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Geophysics elucidate long-term socio-ecological dynamics of foraging, pastoralism, and mixed subsistence strategies on SW Madagascar

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ABSTRACT

The environmental impacts of human societies are generally assumed to correlate with factors such as population size, whether they are industrialized, and the intensity of their landscape modifications (e.g., agriculture, urban development). As a result, small-scale communities with subsistence economies are often not the focus of long-term studies of environmental impact. However, comparing human-environment dynamics and their lasting ecological legacies across societies of different scales and forms of organization and production is important for understanding landscape change at regional to global scales. On Madagascar, ecological and cultural diversity, coupled with climatic variability, provide an important case study to examine the role of smaller-scale socio-economic practices (e.g., fishing, foraging, and herding) on long-term ecological stability. Here, we use multi-spectral satellite imagery to compare long-term ecological impacts of different human livelihood strategies in SW Madagascar. Our results indicate that the nature of human-environmental dynamics between different socio-economic communities are similar. Although some activities leave more subtle traces than others, geophysics highlight similar signatures across a landscape inhabited by communities practicing a range of subsistence strategies. Our results further demonstrate how Indigenous land stewardship is integrated into the very fabric of ecological systems in SW Madagascar with implications for conservation and sustainability.

1. Introduction

Environmental archaeologists have studied the interactions of human societies and their ecological surroundings for over a century, but most theoretical attention has focused on large-scale societies and intensive land-use strategies (e.g., Harrower and D'Andrea, 2014; Penny et al., 2018; Tarolli et al., 2019). The focus on "large-scale" societies has left the archaeological record pertaining to the earliest human populations understudied and some of the least well documented with respect to anthropogenic impacts to ecosystems (see Stephens et al., 2019). While there is a growing interest in "frontier" and "peripheral" settlements (e.g., Kopytoff, 1987; Lamb, 2022; Lightfoot & Martinez, 1995; Ogundiran, 2014), often these studies frame their analysis in relation to larger urban centers, which limits our ability to understand the patterns and processes of human communities who are mobile and occupy and interact with landscapes at a variety of geographical and temporal scales (e.g., Lamb, 2022).

In systems interactions, there are always feedback effects caused by interactions which occur at and between different spatial and temporal scales (Elsawah et al., 2020; Kohler & Gumerman, 2000; Widlok et al., 2012). The intersection of different interaction scales between different individuals, groups, and their surroundings is therefore crucial to consider in any study of socioenvironmental relationships (Lansing, 2003; Shin et al., 2020; Widlok et al., 2012), and forms the basis of a set of theoretical frameworks which are often collectively referred to as complex systems theory (CST; Davis, 2023; Preiser et al., 2018). CST has been slowly introduced to archaeology and anthropology, more broadly, to investigate human-environmental dynamics that feed into the development of sociocultural systems, human responses to environmental and climatic events, and resilience of these systems (Davis, 2020,

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2023; Marsh, 2016; Ortman et al., 2020; Petrie et al., 2017). As such CST has contributed greatly to understanding human actions and their implications in socio-ecological (in)stability over time.

Archaeological studies have increasingly demonstrated that past land-use practices play a continual role in ecosystem function and biodiversity in the present (e.g., Wright, 2022; Pavlik et al., 2021; McMichael et al., 2023). However, human activities vary, as do their effects on environments. Studies of human modifications to landscapes (or niche construction, see Odling-Smee, 2003, 2024) have made strides in understanding some of these feedback dynamics, but have been most widely applied to study agricultural systems (see Quintus & Allen, 2023). Among small-scale societies with subsistence economies, identifying the role of different land-use practices using the archaeological record is challenging as there is rarely clear separation between these strategies (e.g., foraging, fishing, pastoralism, etc.) (see Crowther et al., 2018; Kusimba, 2005; Terrell et al., 2003). Thus, a question for archaeologists is how can we improve our ability to identify the lasting impacts of past human-environment interaction and distinguish between different practices?

While studying the lasting environmental impacts of ancient foraging and hunting communities has been challenged by poor preservation and/or a misattribution of hunting features with historic period occupations (Lemke, 2021), there have been recent advances focused on predicting and understanding cultural niche construction among hunting/foraging societies (e.g., Davis & Douglass, 2021; Lemke, 2021; Rowley-Conwy & Layton, 2011; Veatch et al., 2021). Pastoralism, in contrast, has received less attention (c.f., Ventresca Miller et al., 2020; Verzijl & Quispe, 2013). On Madagascar, for example, pastoralism is often hypothesized to be a major driver of landscape and ecosystem change (e.g., Domic et al., 2021; Crowley et al., 2017; Godfrey et al., 2019; Razanatsoa et al., 2022). However, other factors like hypervariable climatic change might be responsible in equal or greater measure for some landscape change (e.g., Virah-Swamy et al. 2016). Presuppositions regarding different land-use practices can and do have profound consequences on the design of conservation programs (Ekblom et al., 2019; Hughes et al., 2023; Quiros et al., 2017).

To alleviate these challenges, we present a method using multitemporal and multispectral satellite imagery to examine how different livelihood strategies (i.e., foraging, pastoralism, etc.), including the legacy of past livelihood strategies, impact seasonal variations in vegetation and soil composition. We use SW Madagascar as a case study (Fig. 1) and we pose the following questions:

1) how do different socioeconomic systems (defined by primary subsistence strategies) influence the stability of ecological systems?

2) Do we find differences in the long-term impacts of different human behaviors on ecological resilience and stability?

We hypothesize that both foraging and pastoralist settlements will display distinct characteristics in terms of vegetation and soil composition (indicated by Normalized Difference Vegetation Index (NDVI) values and reflectance values derived from satellite imagery) compared with non-anthropogenic areas. NDVI is a mathematical representation of biomass and vegetation productivity derived from multispectral data. While the connection between pastoralism and land degradation have been challenged in recent decades (e.g., Brierley et al., 2018; Ullah, 2019), the association remains strong in several recent publications focused on Madagascar (e.g., Joseph & Seymour, 2023; Velo et al., 2020).

To critically examine these assumptions, we hypothesize that pastoralist settlements will display lower ecological stability than forager settlements, indicated by higher absolute rates of change in

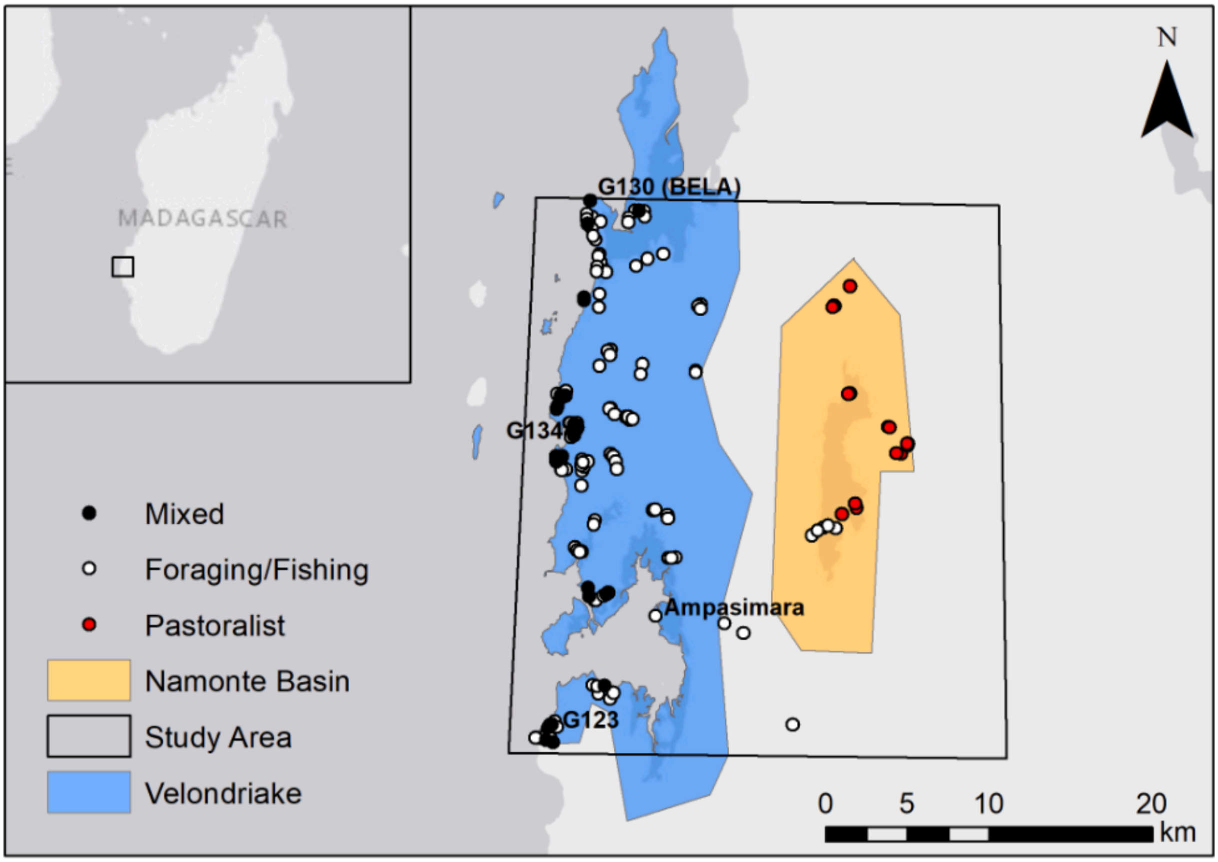

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Fig. 1. Map of the study region and locations of excavated sites mentioned in the manuscript in SW Madagascar.

geophysical signatures between seasons. SW Madagascar exhibits extreme seasonal shifts precipitation and temperature vary widely at different parts of the year. If human landscape modifications served to reduce this variation, the availability of certain resources (vegetation, freshwater, etc.) would become more stable and the resilience of communities can be enhanced by buffering against more drastic shifts in resource availability (e.g., higher vegetative biomass production could support larger year-round cattle herds). Furthermore, we hypothesize that foraging settlements will display greater vegetative diversity (Bliege Bird et al., 2008; Ellis et al., 2021) – indicated by higher NDVI values compared to surrounding contexts – and pastoralism will result in higher levels of soil nutrients and lowered vegetative diversity (McClure, 2015; Ventresca Miller et al., 2020) – indicated by increased electromagnetic reflectance across the green, red, and NIR spectra and lower NDVI values compared with surrounding contexts.

1.1. Background on Madagascar

Archaeological evidence indicates that people have occupied southwest Madagascar for at least the past 1500–2500 years (Douglass et al., 2019; Table 1). The region is home to a culturally diverse set of communities who practice a combination of different subsistence and land-use strategies including fishing/foraging, hunting, pastoralism, and agriculture (Yount et al., 2001). The coast of SW Madagascar is primarily occupied by Vezo fishers who exploit marine ecosystems and migrate throughout the year. Archaeological signatures of these occupations consist of artifact scatters of shell and ceramic materials, as well as animal bones, beads, glass, and ash deposits, representing temporary and permanent villages and campsites. Foraging and hunting are practiced along the coast as well as inland within the spiny forests. Transhumant pastoralism, which is primarily practiced inland in the dry deciduous forest and grasslands, tends to exploit the dry forest ecosystem and rely on introduced plants like spiny cactus and other succulent taxa to feed their herds, as well as cultivate crops in different parts of the year (Kaufmann & Tsirahamba, 2006). Archaeological signatures of communities who practice pastoralism generally consist of cattle pens and low-density scatters of artifacts,including ceramics, shell, beads and ash.

On Madagascar, a great deal of scholarly attention has focused on state formation and the development of settlements in the central highlands (e.g., Dewar & Wright, 1993; Mille, 1970; Parker Pearson, 1992, 1997; Vérin, 1986; Wright, 2007). However, the earliest inhabitants of the island were likely fishers, hunters, and foragers, and limited survey coverage across the island's landmass has resulted in a patchy understanding of the impacts of small-scale communities on ecosystems during the earliest periods of human occupation (Davis et al., 2020; Douglass et al., 2019; Parker Pearson et al., 2010). At the same time, the role of human communities in contributing to megafaunal extinctions and vegetation change across Madagascar has been heavily debated (Dewar, 1984; Godfrey & Douglass, 2022).

On Madagascar, where coastal communities today are at risk from anthropogenic climate change, improving our understanding of long-term human-environment interactions and past human response to environmental change is pivotal for developing effective, equitable and sustainable conservation policies. The southwest of the island, in particular, represents an ideal location to study the intersection of socioeconomic systems and their ecological impacts over the past several millennia, as the region contains an intricate (but fragile) archaeological record and is inhabited by communities that largely identify by their subsistence strategies (Yount et al., 2001). Today, despite a transition towards a cash economy, communities in this region practice many of the same subsistence practices as their ancestors (i.e., foraging, fishing, and agropastoralism). The island experiences two distinct seasons, and the semi-arid southwest of the island has a monsoon-like wet season from November – April and a dry season from May – October. The prolonged dry season in arid- and semi-arid areas has been known to produce periods of nutritional deprivation on livestock (Leggett et al., 2003), which have significant impacts on human populations who rely on them.

These climatic and environmental conditions required the adoption of different livelihood strategies, each of which can affect landscapes in different ways. While a great deal of attention has focused on ecological impacts of human activities, the majority of this literature has focused on larger-scale impacts made by sedentary populations with larger population densities (e.g., Stephens et al., 2019). By shifting attention toward small-scale community environmental impacts, particularly the role that subsistence strategies have on ecological stability and resilience, we can reassess traditional distinctions of "low-impact" and "high-impact" land-use and evaluate how socioecological dynamics compare among communities with different socio-economic practices and provide important insights that can help co-design sustainable land-use policies in the present.

2. Methods

We use a compilation of 98 high-resolution multispectral PlanetScope satellite images collected between 2018–2021 to quantify geophysical signatures associated with foraging and pastoralist archaeological settlements and their surrounding environmental contexts (Supplemental Table 1). PlanetScope data consist of 4 multispectral

Table 1

Results of existing radiocarbon dates from prior work in this region. All calibrations use the SHCAL20 calibration curve (Hogg et al., 2020) unless otherwise indicated.

Lab ID	Description	14C age (BP)	±	Cal BP (2σ)	Reference
D-AMS-012442	worked marine shell from level 3 of rock shelter site NSS2	3086	32	2694–2295*	Douglass, 2017
D-AMS-012441	worked marine shell from level 10 of open air site Antsaragnagnangy	1954	27	1299–973*	Douglass, 2017
D-AMS-012440	charcoal from level 4 of open air site Antsaragnagnangy	915	25	900–726	Douglass, 2017
D-AMS-001950	charcoal from level 2 of rock shelter site TONY	1179	21	1066–962	Douglass, 2017
D-AMS-001951	charcoal from level 1 of rock shelter site TONY	196	26	284-present	Douglass, 2017
D-AMS-001949	charcoal from level 1 of open air site Antsaragnasoa	279	22	434–151	Douglass, 2017
PSU9728	Charcoal (cf. Euphorbiaceae) from level 1 of pastoral village site Namonte	135	15	270–10	Davis et al., 2024
PSU9729	Charcoal (Euphorbiaceae) from level 1 of pastoral village site Namonte	135	15	270–10	Davis et al., 2024
PSU9730	Charcoal (wood) from level 2 of pastoral village site Namonte	80	15	255–34	Davis et al., 2024
PSU9731	Charcoal (wood) from level 1 of cattle pen in pastoral village site Namonte	350	15	475–318	Davis et al., 2024
PSU9732	Charcoal (seed) from level 2 of cattle pen in pastoral village site Namonte	345	20	476–315	Davis et al., 2024
PSU9733	Charcoal (Euphorbiaceae) from level 2 of cattle pen in pastoral village site Namonte	350	15	475–318	Davis et al., 2024
PSU9734	Charcoal (cf. Euphorbiaceae) from level 1 of pastoral village site Amboroke	175	20	289-present	Davis et al., 2024
PSU9735	Charcoal (tuber) from level 2 of pastoral village site Amboroke	240	15	308–155	Davis et al., 2024
PSU9736	Charcoal (wood) from level 2 of pastoral village site Amboroke	−2700	15	(−13)–(−29)**	Davis et al., 2024
PSU9737	Charcoal (wood) from level 1 of pastoral village site Amboroke	−90	15	(−1)–(−9)**	Davis et al., 2024
PSU9738	Charcoal (Euphorbiaceae) from level 1 of pastoral village site Amboroke	120	15	263–26	Davis et al., 2024

Notes: * Calibrated using the MARINE20 curve (Heaton et al., 2020) with estimated δR of 200 years ± 50 (following Douglass, 2017). ** Calibrated using the Bomb13SH12.21 curve (Hua et al., 2021).

bands (Blue, Green, Red, and Near infrared) with 3 m spatial resolution and are freely available to researchers. Following previous studies (e.g., Orengo et al., 2020), we calculate the median value across all of these images to evaluate average environmental signatures (e.g., vegetation, chlorophyll absorption and geology, and biomass characteristics) over time in this area (and subsequently the average impact of human activity). We conducted this analysis using the *raster* (Hijmans, 2019), *sf* (Pebesma, 2018; Pebesma & Bivand, 2023), and *ggplot2* (Wickham, 2016) packages in R (R Core Team, 2020).

To compare geophysical signatures, we use an archaeological dataset from the Velondriake Marine Protected Area consisting of 340 different confirmed coastal archaeological sites (which were primarily occupied by fishing/foraging communities; see Davis, 2022; Douglass, 2016) and 80 confirmed areas without any archaeological materials (i.e., absence of surface scatters of shell, ceramics, faunal remains, and charcoal). The earliest fishing and foraging sites are typically located in cave shelters, with later sites generally consisting of open air villages and camp sites (Douglass, 2016; Table 1). These sites tend to consist of an abundance of marine shell material, including shells used to create tools and remnants of consumption (e.g., burnt shells, fire pit features, etc.). There is limited radiocarbon evidence from other sites that people have occupied this region for the past 3,000 years (see Douglass, 2016, Douglass et al., 2019). Ceramic chronologies and indicate that many of the sites investigated here were occupied within the past 1000 years (Davis et al., 2023).

To further bolster our understanding of settlement timelines, we conducted 1x1 m excavations and obtained datable organic material (i.e., charcoal) from four open air sites consisting of fishing/foraging and mixed subsistence communities (Fig. 1). Excavations were conducted with trowels, and soils were screened using a 2 mm mesh. We excavated using natural stratigraphic changes as level breaks. Soil was described using the Munsell soil color chart. Charcoal materials excavated in situ from each excavation unit were photographed using a Keyence VK-X1100 182(violet) laser scanning microscope for species identification using a reference collection of modern macrocharcoal from southwestern Madagascar housed at Columbia University. All well-preserved, identifiable samples with stratigraphically secure contexts were selected for AMS analysis, following chronometric hygiene procedures (see Douglass et al., 2019). All selected samples were pretreated using an acid-base-acid (ABA) decontamination protocol to remove humates from the charcoal. ABA consisted of washes with 1 N HCl and 1 N NaOH for 20-minute intervals at 70 °C. Pretreatment and graphitization were conducted in the PSU Stable Isotope Geochemistry Laboratory. AMS was conducted at Penn State's Energy and Environmental Sustainability Laboratories Radiocarbon Facility and dates are reported using accepted standards (Stuiver and Polach, 1977). We conducted AMS calibrations using the SHCAL20 calibration curve (Hogg et al., 2020) within OxCal 4.4 (Bronk Ramsey, 2009).

We then compare these data with a total of 16 recorded pastoralist settlements (identified by the presence of domesticated animal bones and/or the presence of architecture like cattle pens) that date to between 450–150 cal. BP and 15 areas without archaeological materials located in the adjacent Mikea Forest (Davis et al., 2024; Table 1). Pastoralist sites are identified both by the presence of domesticated animal bones (primarily zebu [cattle]) and features like cattle pens. These pens are often identified by dark, organic rich soil stains where dung and other material accumulated over time. All sites included in this analysis were assessed using ground survey with individual surveyors spaced at 5 m intervals to maximize recovery of archaeological materials. Because the Mikea Forest and Velondriake Marine Protected Area display quite different baseline environmental signatures (i.e., dense dry forests and coastal dune systems, respectively), we standardize the background values of the data using non-archaeological site locations (see Supplemental Code). Standardized values were calculated using the formula:

$$Standard = Min_y + \frac{(x - Min_x) \times (Max_y - Min_y)}{Max_x - Min_x}$$

Where x and y represent the data being standardized and the standardized dataset, respectively.

The variable rate of rainfall in SW Madagascar presents challenges to traditional views of ecological equilibrium, where carrying capacity of a species is controlled as a ratio of population to resources (Behnke & Scoones, 1992). We can turn to CST and resilience theory to assess whether human activities have affected ecosystem resilience (*sensu* Holling, 1973). Within the context of SW Madagascar, we define stability as the degree of fluctuation in environmental properties between seasonal climatic shifts, and resilience as the constancy of stability over time, following Holling (1973). To measure resilience, we use electromagnetic reflectance properties recorded in PlanetScope imagery at archaeological sites in SW Madagascar associated with foraging and pastoralist communities. Reflectance provides proxies for vegetative diversity and productivity, moisture retention properties, and soil composition (Jensen, 2007).

We calculate resilience as the absolute difference between the median composite PlanetScope images:

$$\Delta_e = |\widetilde{x_w} - \widetilde{x_d}|$$

Where Δ_e is the ecological difference, $\widetilde{x}_w$ is the median wet season value, and $\widetilde{x}_d$ is the median dry season value. Following Holling (1973), we interpret smaller Δ_e values as higher levels of resilience, as this is indicative of prolonged durations of stable ecological conditions.

Distinguishing between targets of interest in remote sensing is often conducted using separability metrics, which use relationships between spectral signatures to try and differentiate between two or more datasets (Crabb et al., 2022). To determine if foraging/fishing and pastoralist settlements present different impacts to soil and vegetative characteristics, we use the M−statistic (Kaufman & Remer, 1994) which is a commonly employed separability metric calculated as:

$$M = \frac{\mu_1 - \mu_2}{\sigma_1 + \sigma_2}$$

Where μ and σ represent the mean and the standard deviation of each target, respectively. The higher the score the greater the separability. Features are said to have good separability when $M > 1$. All analyses are conducted in R (R Core Team, 2020; see Supplemental Files). As a complementary analysis, we also use statistical independence tests to assess differences in the geophysical profiles of different settlement types. We assessed our data for normality using the Shapiro-Wilk test and then chose the Wilcoxon rank sum test because our data are non-normally distributed.

To assess the impacts of different subsistence economies on vegetative health and diversity, we calculate the NDVI using the formula:

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

Where NDVI is a ratio of near infrared (NIR) and red electromagnetic values. While there are many different vegetative indices to choose from, we use NDVI here because it is one of the most commonly used vegetative indices and has been successfully used in prior studies on Madagascar for ecological and archaeological analyses (Davis & Douglass, 2021; Phelps et al., 2022).

The people of SW Madagascar have long practiced a variety of subsistence practices, sometimes engaging in multiple forms at once (see Tucker, 2020; Yount et al., 2001). As such, we also attempt to assess the impacts of mixed subsistence practices and their impacts on geophysical signatures using a subset of the archaeological data discussed previously. Using survey data collected in 2019–2020, we selected 131 archaeological deposits that displayed evidence of primarily/only fishing/foraging (i.e., no domesticated fauna) and 31 deposits that showed

Table 2

Radiocarbon dates from charcoal recovered from excavation units reported in this study. These represent open air village and camp sites. All calibrations use the SHCAL20 calibration curve (Hogg et al., 2020) unless otherwise indicated. Samples were identified using a reference collection of modern macrocharcoal from southwestern Madagascar housed at the Olo Be Taloha African Archaeology Laboratory and the Inside Wood Database (https://insidewood.lib.ncsu.edu/). Dating was conducted at Penn State's Radiocarbon dating laboratory using accelerator mass spectrometry (AMS).

PSUAMS#	Site Name	Description	F^{14}C	±	D^{14}C (‰)	±	Species	^{14}C age (BP)	±	Cal BP (2σ)
10424	BELA (G130)	G130 (BELA) Unit 1 Level 1 Charcoal #1. 13 cm.	1.1911	0.0021	191.1	2.1	Tree	200	15	283–107
10425	BELA (G130)	G130 (BELA) Unit 1 Level 1 Charcoal #2. 20 cm.	0.9878	0.0016	−12.2	1.6	Tree	200	15	283–107
10426	BELA (G130)	G130 (BELA) Unit 1 Level 1 Charcoal #3. 18 cm.	0.9847	0.0016	−15.3	1.6	Tree	205	15	283–141
10427	BELA (G130)	G130 (BELA) Unit 1 Level 1 Charcoal #4. 21 cm.	0.9974	0.0017	−2.6	1.7	Tree	125	20	253–0
10428	BELA (G130)	G130 (BELA) Unit 1 Level 2 Charcoal #5. 20 cm.	0.9866	0.0017	−13.4	1.7	Tree	155	15	262–0
10429	G123	G123. Unit 3 Level 2 Charcoal #2. 20 cm.	0.9897	0.0018	−10.3	1.8	Wood	415	15	495–331
10430	G123	G123. Unit 3 Level 1 Charcoal #1. 16.5 cm.	0.9333	0.0018	−66.7	1.8	Tree	555	20	549–509
10431	G123	G123. Unit 2 Level 1 Charcoal #3. 22 cm.	0.9499	0.0017	−50.1	1.7	Cf. *Adansonia*	85	15	132–26
10432	G123	G123. Unit 2 Level 1 Charcoal #2. 16 cm.	0.9755	0.0017	−24.5	1.7	Cf. *Adansonia*	110	15	242–23
10433	G123	G123. Unit 2 Level 1 Charcoal #1. 14 cm.	0.9753	0.0017	−24.7	1.7	Wood	20	15	58–27
10434*	Ampasimara	Ampasimara. Unit 1 Level 1 Charcoal #1. 8 cm.	0.9746	0.0017	−25.4	1.7	Wood	−1400	15	−6 – −40
10435	Ampasimara	Ampasimara. Unit 1 Level 1 Charcoal #2. 26 cm.	0.9844	0.0019	−15.6	1.9	Tree	100	15	239–25
10436	Ampasimara	Ampasimara. Unit 1 Level 2 Charcoal #3. 27 cm.	0.9810	0.0016	−19.0	1.6	Tree	125	15	252–5
10437	G134	G134. Unit 1 Level 1 Charcoal #1. 21 cm.	0.9868	0.0016	−13.2	1.6	Wood	105	15	240–24
10438	G134	G134. Unit 1 Level 1 Charcoal #2. 20 cm.	0.9903	0.0017	−9.7	1.7	Tree	80	15	129–26
10439	G134	G134. Unit 1 Level 1 Charcoal #3. 19 cm.	0.9855	0.0017	−14.5	1.7	Tree	120	15	251–7
10440	G134	G134. Unit 1 Level 1 Charcoal #4. 34 cm.	0.9848	0.0017	−15.2	1.7	Tree	125	15	252–5
10441	G134	G134. Unit 1 Level 1 Charcoal #5. 38 cm.	0.9935	0.0015	−6.5	1.5	Tree	55	15	59–26
10442	G134	G134. Unit 1 Level 1 Charcoal #6. 38 cm.	0.9918	0.0018	−8.2	1.8	Tree	65	15	125–27
10443	G134	G134. Unit 1 Level 1 Charcoal #7. 43 cm.	0.9852	0.0017	−14.8	1.7	Unidentified	120	15	251–7
10463	G134	G134. Unit 1 Level 1 Charcoal #8. 40 cm.	0.9882	0.0018	−11.8	1.8	Tree	95	15	256–33
10444	G134	G134. Unit 1 Level 2 Charcoal #10. 43.5 cm.	0.9788	0.0016	−21.2	1.6	Possible tuber	170	15	272–0
10445**	G134	G134. Unit 1 Level 2 Charcoal #11. 47 cm.	0.6988	0.0016	−301.2	1.6	Tree	2880	20	3062–2867
10446	G134	G134. Unit 1 Level 2 Charcoal #13. 50 cm.	0.9857	0.0016	−14.3	1.6	Possible shrub	115	15	246–22
10447	G134	G134. Unit 1 Level 2 Charcoal #14. 50 cm.	0.9870	0.0022	−13.0	2.2	Possible shrub/ cactus	105	20	251–7
10448	G134	G134. Unit 1 Level 3 Feature 1 Charcoal #1. 57 cm.	0.9777	0.0019	−22.3	1.9	Tree	180	20	279–0
10449	G134	G134. Unit 1 Level 3 Feature 2 Charcoal #1. 65 cm.	0.9866	0.0017	−13.4	1.7	Possible Tuber	110	15	242–23
10450	G134	G134. Unit 1 Level 4 Charcoal #15. 68 cm.	0.9854	0.0018	−14.6	1.8	Possible shrub	120	15	251–7
10451	G134	G134. Unit 1 Level 4 Charcoal #16. 66 cm.	0.9858	0.0017	−14.2	1.7	Cf. *Adansonia*	115	15	246–22
10452	G134	G134. Unit 1 Level 4 Charcoal #17. 68 cm.	0.9832	0.0016	−16.8	1.6	Tree	135	15	253–0
10453	G134	G134. Unit 1 Level 4 Charcoal #18. 68 cm.	0.9799	0.0019	−20.1	1.9	Tree	165	20	273–0
10464	G134	G134. Unit 1 Level 4 Charcoal #19. 68 cm.	0.9846	0.0019	−15.4	1.9	Tree	125	20	268–14
10465	G134	G134. Unit 1 Level 4 Charcoal #20. 69 cm.	0.9806	0.0018	−19.4	1.8	Possible shrub/ cactus	160	15	283–0
10466	G134	G134. Unit 1 Level 4 Charcoal #23. 71 cm.	0.9875	0.0017	−12.5	1.7	Possible shrub	100	15	256–33
10467	G134	G134. Unit 1 Level 4 Charcoal #24. 71 cm.	0.9836	0.0018	−16.4	1.8	Tree	135	15	270–10
10468	G134	G134. Unit 1 Level 4 Charcoal #26. 73.5 cm.	0.9860	0.0018	−14.0	1.8	Possible Palm Tree	115	15	259–30
10469	G134	G134. Unit 1 Level 5 Charcoal #22. 76 cm.	0.9768	0.0020	−23.2	2.0	Possible shrub	190	20	291–0
10470	G134	G134. Unit 1 Level 5 Charcoal #23. 72 cm.	0.9800	0.0019	−20.0	1.9	Possible shrub	160	20	284–0
10471	G134	G134. Unit 1 Level 5 Charcoal #25a. 82 cm.	0.9885	0.0019	−11.5	1.9	Tree	95	20	257–33
10472	G134	G134. Unit 1 Level 5 Charcoal #25b. 82 cm.	0.9768	0.0017	−23.2	1.7	Shrub	190	15	290–0
10473	G134	G134. Unit 1 Level 5 Charcoal #26. 77 cm.	0.9786	0.0019	−21.4	1.9	Unidentified	175	20	289–0
10474	G134	G134. Unit 1 Level 5 Charcoal #27. 79 cm.	0.9836	0.0017	−16.4	1.7	Unidentified	135	15	270–10
10475	G134	G134. Unit 1 Level 5 Charcoal #28. 78 cm.	0.9739	0.0019	−26.1	1.9	Tree	210	20	303–0
10476	G134	G134. Unit 1 Level 5 Charcoal #29. 84 cm.	0.9760	0.0018	−24.0	1.8	Tree	195	20	293–0
10477	G134	G134. Unit 1 Level 5 Charcoal #30. 82 cm.	0.9776	0.0018	−22.4	1.8	Tree	180	15	286–0
10478	G134	G134. Unit 1 Level 6 Charcoal #31. 85 cm.	0.9694	0.0019	−30.6	1.9	Tree	250	20	422–151
10479	G134	G134. Unit 1 Level 6 Charcoal #32. 81 cm.	0.9818	0.0017	−18.2	1.7	Tree	145	15	278–6
10480	G134	G134. Unit 1 Level 6 Charcoal #33. 90 cm.	0.9846	0.0018	−15.4	1.8	Tree	125	15	265–22
10481	G134	G134. Unit 1 Level 6 Charcoal #34. 90 cm.	0.9807	0.0019	−19.3	1.9	Tree	155	20	283–0
10482	G134	G134. Unit 1 Level 6 Charcoal #35. 92 cm.	0.9765	0.0018	−23.5	1.8	Tree	190	15	290–0
10483	G134	G134. Unit 1 Level 6 Charcoal #36. 89 cm.	0.9772	0.0018	−22.8	1.8	Not Euphorbiaceae	185	20	290–0
10484	G134	G134. Unit 1 Level 6 Charcoal #37. 96 cm.	0.9718	0.0016	−28.2	1.6	Cf. Euphorbiaceae	230	15	207–151
10485	G134	G134. Unit 1 Level 6 Charcoal #38. 87 cm.	0.9853	0.0018	−14.7	1.8	Not Euphorbiaceae	120	15	263–26
10486	G134	G134. Unit 1 Level 6 Charcoal #39. 96 cm.	0.9725	0.0018	−27.5	1.8	Tree	225	20	309–0
10487	G134	G134. Unit 1 Level 7 Charcoal #41. 110 cm.	0.9766	0.0018	−23.4	1.8	Tree	190	15	290–0
10488	G134	G134. Unit 1 Level 7 Charcoal #42. 115 cm.	0.9794	0.0018	−20.6	1.8	Tree	165	15	285–0
10489	G134	G134. Unit 1 Level 8 Charcoal #43. 129 cm.	0.9769	0.0017	−23.1	1.7	Tree	190	15	290–0
10490	G134	G134. Unit 1 Level 8 Charcoal #44. 144 cm.	0.8983	0.0019	−101.7	1.9	Cf. *Adansonia*	860	20	792–722

Notes * Calibrated using the Bomb13SH12.21 curve (Hua et al., 2021). These samples contain post-bomb carbon, indicating a modern date. **This sample is an outlier with all other dates from this site, and may represent long-lived wood that predates the cultural contexts of this site.

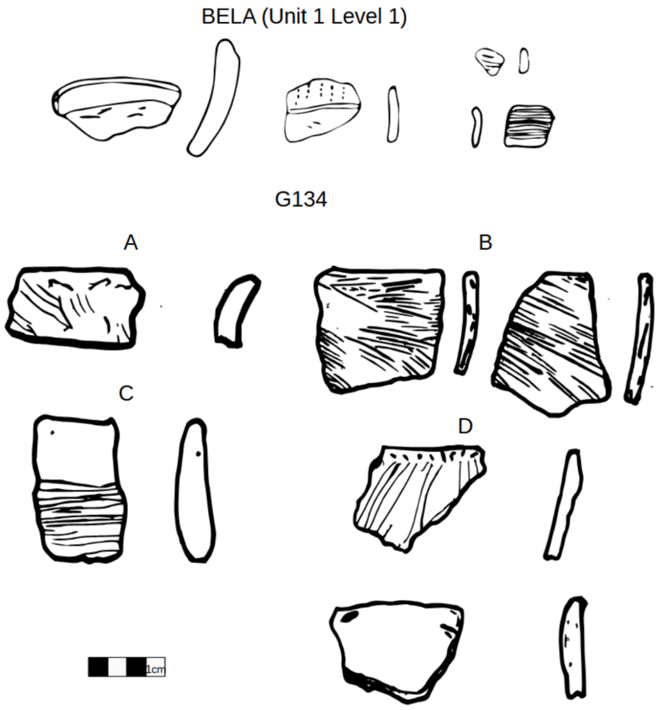

Fig. 2. Ceramic rims from BELA Level 1 and G134 Level 3 (A), Level 5 (B), Level 6 (C) and Level 8 (D). Shell combing found on sherds from BELA and G134 Level 3 and 5 correspond with the past 250 years, but punctation marks correspond with older periods, largely disappearing after about 200–250 BP. G134 shows this progression well, with the youngest layers (via ^{14}C dates) corresponding with shell combed ceramics, and later layers containing evidence of punctation and incising.

evidence of both fishing/foraging and pastoralism (i.e., mix of marine shells, domesticated fauna, etc.). We then compare these datasets with pastoralist settlements in the Mikea Forest to assess pastoralism's long-term ecological impacts using the same process as highlighted above.

3. Results

Excavations carried out between 2021–2022 at four open-air village sites consisting of fishing/foraging and mixed subsistence communities show that people occupied this region extensively for the past 1000 years, with settlement density increasing over the past 300–500 years (Davis, 2022; Table 2). Radiocarbon data from prior excavations at pastoralist sites further demonstrate an influx of settlements beginning ca. 450 years ago (Table 1). AMS dates over the past 300 or so years have significant error ranges associated with their calibration. As such, further confidence in these dates is provided by ceramics recovered from several of these sites and their associated chronologies (see Davis et al., 2023).

Prior research (e.g., Hixon et al., 2021; Wright et al., 1996; Douglass, 2016; Parker Pearson et al., 2010) has established that punctation marks and incising are associated with older assemblages between ca. 850–250 BP, while shell combing decorations are more recent (ca. 250–50 BP). When examining ceramics from our excavations, we find that shell combing and other earlier decorative forms like punctation and incising are found among excavation layers dated within the past 250–300 years (Fig. 2). This provides added confidence that these sites fall closer to the 200 year age range, rather than a modern occupation.

Coastal fishing/foraging occupations display close similarities to inland pastoralist villages, as both sets of settlements display increased reflectance properties in the Green, Red, and NIR spectra compared to their non-anthropogenic surroundings in the dry season (Fig. 3). These reflectance properties correspond with vegetation, chlorophyll absorption and geology, and biomass characteristics, respectively. In the dry season, coastal communities and inland pastoralists display decreased reflectance in these spectra, but mixed subsistence communities showed increased reflectance in the Green and Red spectra, and specifically fishing/foraging settlements were increased in the Green only (Fig. 4). M−statistic scores demonstrate that coastal foraging and inland pastoralist settlements display limited separability based on their spectral characteristics, as all electromagnetic bands return M−scores of < 1 in both seasons (Table 3). Separability is highest for the Blue and Green bands in both seasons, but only the Blue band attains an M−score > 1 during the wet season.

We also find that fishing/foraging and pastoralist settlements display lower seasonal shifts in geophysical properties compared to surrounding

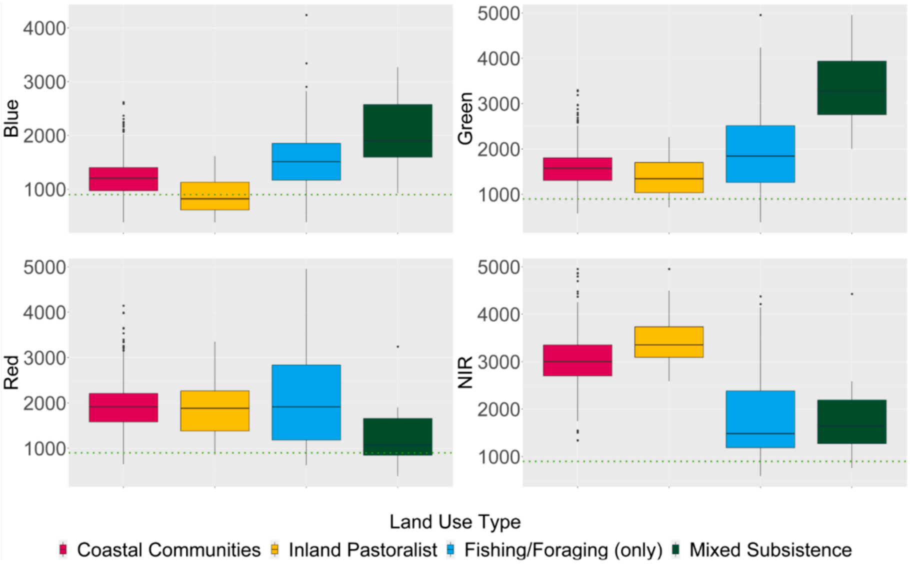

Fig. 3. Shows reflectance values in the dry season for coastal archaeological settlements in the Velondriake Marine Protected Area alongside inland sites and surrounding areas in the Mikea Forest, SW Madagascar. Reflectance values were standardized by non-archaeological signatures in the Mikea Forest. Patterns show that in both environments, human settlement presents elevated reflectance values compared to average non-anthropogenic signatures (green-dotted-line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

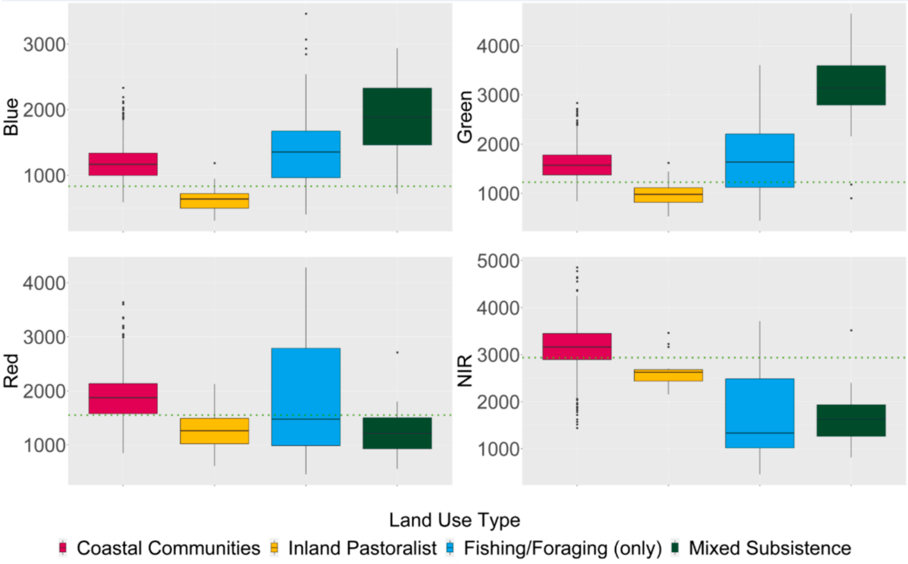

Fig. 4. Shows reflectance values in the wet season for coastal and inland settlements. Patterns show that in pastoralist settlement presents lower reflectance values than the average non-anthropogenic signatures (green-dotted-line) while foraging and mixed subsistence show higher reflectance in the blue and green wavelengths but lower reflectance in the red and NIR compared to non-anthropogenic areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
M−score separability tests between Inland Pastoralist and Coastal Fishing/Foraging Settlements (scores > 1 are bolded) in the Velondriake Marine Protected Area.

Season	Band	M−score
Dry	1 (Blue)	0.490
Dry	2 (Green)	0.262
Dry	3 (Red)	0.089
Dry	4 (NIR)	0.298
Wet	**1 (Blue)**	**1.029**
Wet	2 (Green)	0.906
Wet	3 (Red)	0.672
Wet	4 (NIR)	0.558
Annual	1 (Blue)	0.417
Annual	2 (Green)	0.616
Annual	3 (Red)	0.693
Annual	4 (NIR)	0.137

areas (Fig. 5). Mixed subsistence areas appear to have higher seasonal shifts in the Blue and Green spectra than their non-archaeological surroundings, and pastoralist settlements display shifts that are higher in the NIR than other subsistence strategies. M−statistics further show that these slight differences display weaker spectrally separablity, as M−scores are < 1 (Table 3).

3.1. Statistical independence between geophysical signatures

Despite low spectral separability, different socioeconomic strategies do display statistically independence in both the dry (Table 4) and wet (Table 5) seasons. The greatest differences are noticeable in the dry season across the blue and green electromagnetic spectra. Red and NIR are also distinct but not year-round.

3.2. NDVI and vegetative characteristics

When examining NDVI values, pastoralist villages display slightly lower values (but statistically insignificant, $p > 0.4$ in the wet season, $p > 0.05$ in the dry season) compared with non-archaeological surroundings, while coastal foraging/fishing and mixed subsistence villages display statistically significantly higher NDVI values ($p < 0.001$ in the wet season) than non-archaeological surroundings (Fig. 6 and Fig. 7). These differences are statistically insignificant for all subsistence strategies in the dry season ($p > 0.08$). Coastal settlements, overall, display lower NDVI values than non-anthropogenic areas in the wet season (Fig. 7). In terms of NDVI stability between seasons and over several years of satellite observation (2018–2022), however, coastal sites show less change in NDVI values than pastoralist villages and non-archaeological areas, while pastoralist villages display nearly identical change to non-archaeological surroundings (Fig. 8).

4. Discussion

We find that the patterns between different socioeconomic systems are similar in terms of their geophysical profiles compared to non-archaeological contexts in the surrounding area, but there are some differences that can be identified. While only small-to-moderate separability exists between foraging and pastoralism in the wet season (making it difficult to visualize differences), there are statistically significant distinctions between subsistence strategies across both seasons and multiple electromagnetic wavelengths. As such, the reflectance profiles between primarily fishing/foraging, pastoralist, and mixed-economy settlements are distinct, but this distinction is not always strong enough to reliably separate these land-use types using remote sensing imagery alone. Our greatest ability to discern differences appears to be in assessing resilience factors and overall geophysical variability between seasons, and in the wet-season, specifically (Figs. 4-5). It is in this temporal scale where we may be able to quantify different land-use strategies across the landscape using semi-automated approaches paired with ground-based investigation, but this will constitute a future research agenda.

Previously, Davis and Douglass (2021) conducted a similar remote sensing analysis of archaeological settlements within the Velondriake Marine Protected Area, which also identified distinct geophysical properties among coastal foraging villages and campsites. When evaluating these signatures, we find very similar patterns to what is seen in the Namonte Basin. Closer analysis of these patterns in the Namonte Basin demonstrates that they are related to changes in soil mineralogical composition, but also to changes to vegetation moisture retention and species diversity present on and around archaeological zones that span several centuries (Domic et al., 2021; Davis et al., 2024). Along the

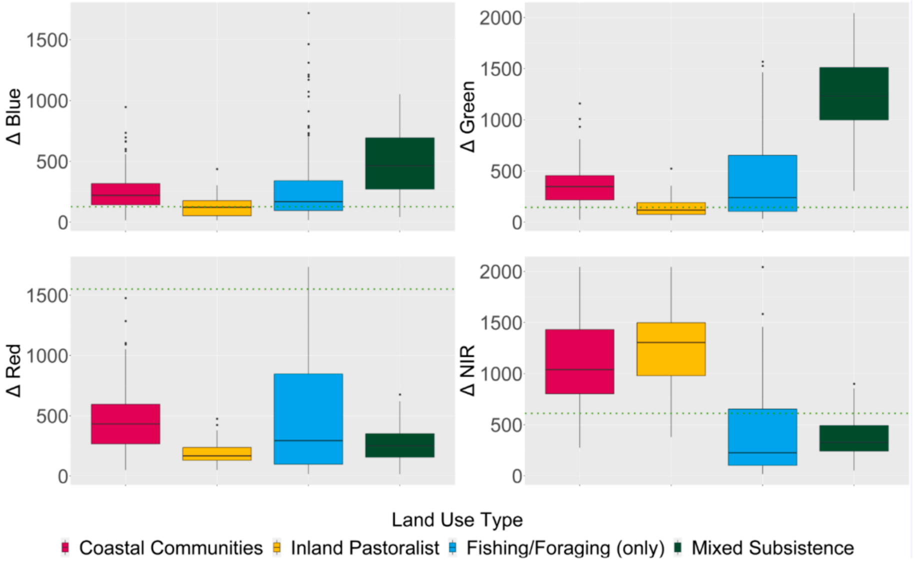

Fig. 5. Shows absolute difference between reflectance values in the wet and dry seasons for coastal and inland settlements. The lower the difference, the more stable the geophysical environmental conditions. Average non-anthropogenic geophysical signatures are represented by the green-dotted-line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Dry Season (bolded entries are statistically significant; *italicized* entries are NOT statistically significant).

Comparison	Band	W	p-value
Pastoral – Foraging	**Blue**	**365.5**	**8.415 e-6**
	Green	**664**	**0.006045**
	Red	*1066*	*0.6572*
	NIR	**2108**	**3.46 e-8**
Mixed – Foraging	**Blue**	**2864**	**0.001234**
	Green	**3695**	**3.321 e-11**
	Red	**1076**	**4.552 e-5**
	NIR	*2075*	*0.9967*
Pastoral – Mixed	**Blue**	**27**	**4.429 e-8**
	Green	**4**	**3.712 e-11**
	Red	**351**	**0.004125**
	NIR	**450**	**1.571 e-9**

Table 5
Wet Season (bolded entries are statistically significant; *italized* entries are NOT statistically significant).

Comparison	Band	W	p-value
Pastoral – Foraging	**Blue**	**228**	**1.123 e-7**
	Green	**464**	**6.174 e-5**
	Red	*876*	*0.08233*
	NIR	**1904**	**8.931 e-5**
Mixed – Foraging	**Blue**	**1117**	**1.591 e-5**
	Green	**552**	**8.159 e-11**
	Red	**2860**	**0.01588**
	NIR	*1856*	*0.1438*
Pastoral – Mixed	**Blue**	**7**	**9.077 e-11**
	Green	**14**	**1.025 e-9**
	Red	*251*	*0.8107*
	NIR	**455**	**1.837 e-8**

coast, these differences also correspond with changes in plant taxa present around archaeological sites, and while paleoecological data is not yet available for Velondriake, changes to soil composition are also likely present. This is the focus of ongoing research.

Returning to our initial hypotheses, we do find that foraging and pastoralist settlements display distinct characteristics in terms of reflectance values compared with non-anthropogenic areas. However, NDVI values are less distinct. While pastoralist villages display lower NDVI values than other areas, the assumption that pastoralist settlements would display lower ecological stability than foraging settlements was not supported by our analysis. In contrast, pastoralist settlements display congruent changes in NDVI signatures in areas with no surface evidence of archaeological activity, but slightly higher changes compared to sites associated with foraging. All subsistence practices appear to have been well integrated into the ecological system of this region (i.e., at equilibrium), as they display very similar geophysical and vegetative patterns to the surrounding landscape. Pastoralist sites appear especially well integrated as fluctuations in seasonal NDVI values are statistically insignificant (W = 148, p-value = 0.28), while coastal sites display statistically significant differences with their surroundings (W = 8146, p-value = 0.008).

Pastoralist settlements also show increased NIR signatures in the dry season. Pastoralist villages actually depreciate in their NIR signature during the wet season, which supports ethnographic and historic accounts about when these villages were occupied and when cattle herders used the wider forest for pasture (Kaufmann & Tsirahamba, 2006). Water is scarcer in the dry season, keeping people (and their animals) closer to villages near lake beds, but more abundant in the wet season, allowing animals to graze further from villages and lakes. In sum, we find very few differences in the long-term impact of different socioeconomic strategies in SW Madagascar. Conversely, our results suggest that fishing/foraging, pastoralist, and mixed subsistence strategies present many similarities when we account for scalar differences between them.

These findings are important as they provide new ways to evaluate landscape use across different societies practicing varied subsistence strategies. The importance of scale has been emphasized by researchers to trace similarities between archaeological and modern cities (e.g., Bettencourt et al., 2008; Ortman et al., 2014), and by those studying socioecological systems interactions (e.g., Baggio et al., 2016; Bradtmöller et al., 2017; Davis, 2023). The evaluation of small scale societies can benefit from this same treatment by examining the ways some behaviors are comparable or different across scales of interaction.

4.1. Socio-ecological resilience and hypervariable climatic and political history

This study has further implications for understanding the role of human niche construction in persisting through intense shifts in climatic

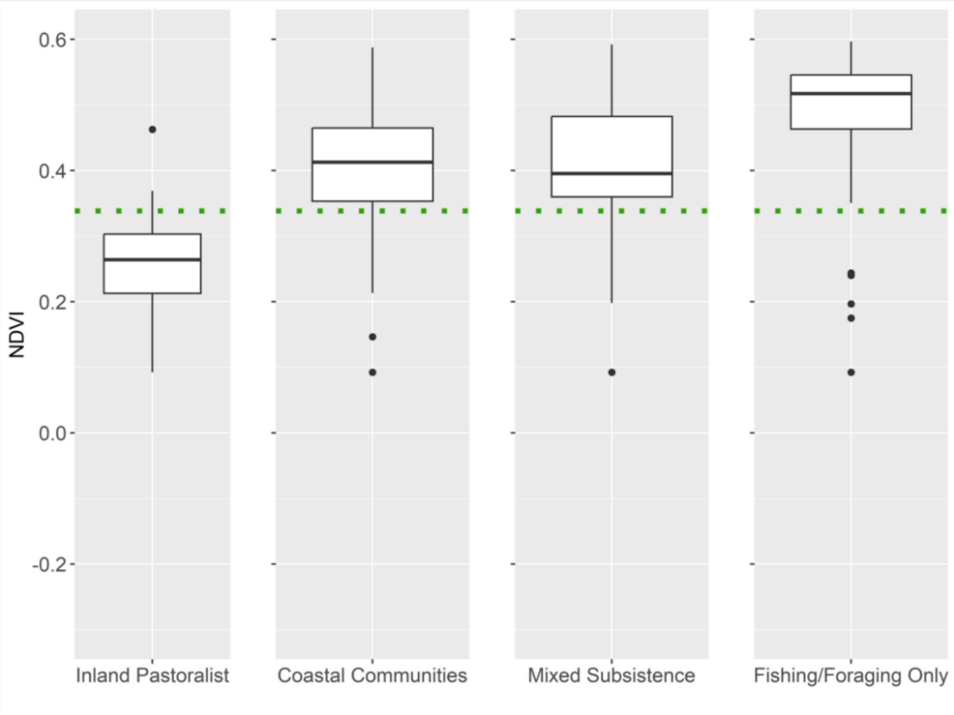

Fig. 6. NDVI values for the wet season. Average non-archaeological values shown in green-dotted line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

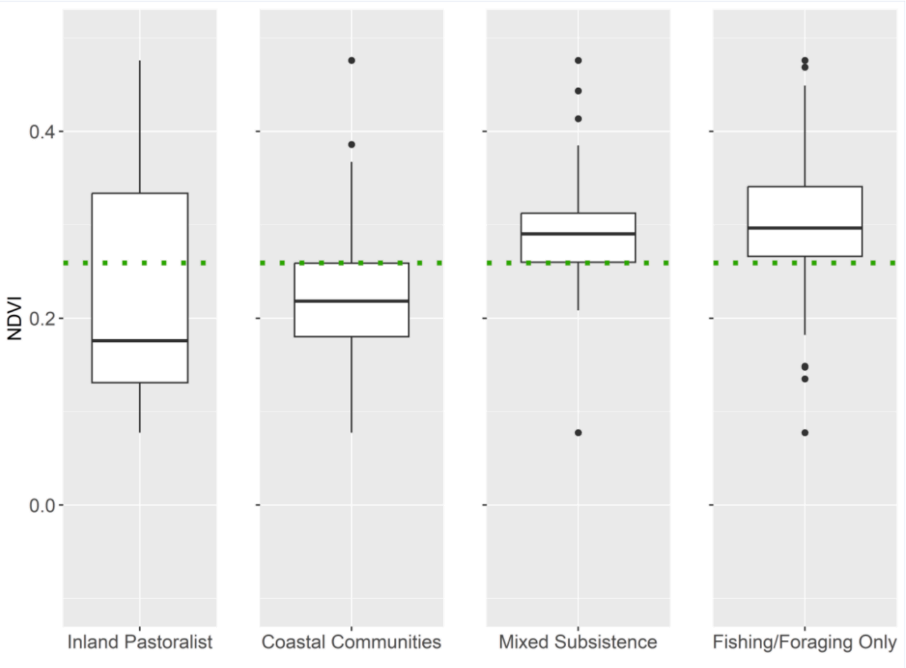

Fig. 7. NDVI values for the dry season. Average non-archaeological values shown in green-dotted line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and sociopolitical conditions. Ceramic and radiocarbon evidence from archaeological sites in the Velondriake and Mikea regions suggest sustained human presence through a series of climatic and sociopolitical shifts (Davis et al., 2023). Beginning around 450B.P., intergroup warfare, polity formation, and the slave trade became widespread in southwest Madagascar (Grandidier and Grandidier, 1903, 1904). This period also coincided with considerable drought conditions (Hixon et al., 2021; Razanatsoa, 2019), but there were consistent fluctuations between very wet and dry conditions every few decades during this time. Beginning around 250B.P., climatic conditions began to stabilize but slave raiding and colonial violence continued (Grandidier and Grandidier, 1906, 1907). Despite these stressors, occupation of the Velondriake coast and Mikea forest continued and communities adopted semi-nomadic liveway strategies to cope with insecurity and variability during certain periods (Table 1 and 2).

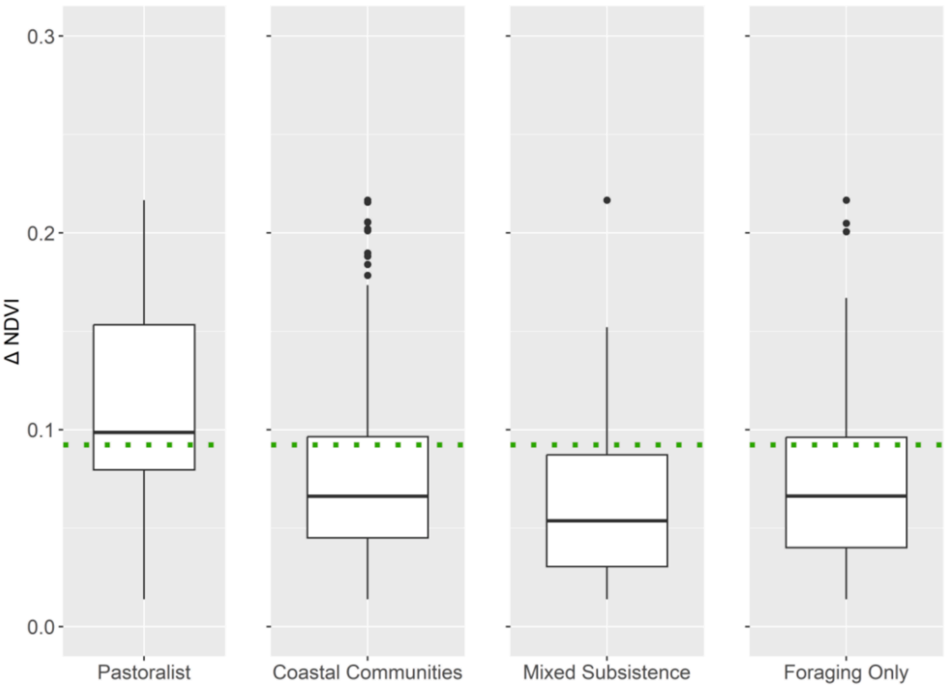

Fig. 8. Absolute difference in NDVI across seasons and years – pastoralist sites have nearly identical rates of change in NDVI values compared to average non-archaeological values (green-dotted-line), while coastal foraging/fishing and mixed subsistence sites appear to present lower vegetative changes seasonally and over time. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our analysis demonstrates that even when faced with extreme change events, the creation of a human ecological niche resulted in more stable environmental conditions in SW Madagascar which were passed down over time, continuing into the present. Likewise, social networks, although forced to adapt and reorganize due to external pressure, also persisted over millennia, potentially acting as a risk mitigation strategy (Davis et al., 2023). Importantly, the remote sensing data analyzed in this study coincide with periods of increased drought and decreased precipitation (Ollivier et al., 2023; Randriatsara et al., 2022), and yet fluctuations of ecological conditions appear to have been buffered by historical human land-use.

The broader significance of this finding is that remote sensing archaeology provides an important way to examine the varying legacies of different human land-use histories on a global scale (also see Alders et al., 2024; Raab et al., 2022; Mohr et al., 2024). Many recent studies emphasize the importance of archaeological and historic land-use for ecological planning and conservation in the present (e.g., Ellis et al., 2021; McMichael et al., 2023; Pavlik et al., 2021; Raab et al., 2022). Yet, characterizing these effects, particularly among groups that practiced a variety of land-use strategies simultaneously, remains difficult to discern (Stephens et al., 2019). Advances in geochemistry approaches have explored such legacy impacts (e.g., Storozum et al., 2021) and remote sensing has great potential to enhance local ground-based investigations to quantify the ways in which past land use continues to impact ecosystems in the present (e.g., Mohr et al., 2024). Such work also provides clear examples of how archaeology can make real-world impacts to contemporary challenges facing society like climate change and environmental conservation (e.g., Altschul et al., 2017).

4.2. Limitations

There are some important caveats to the findings in this study. First, the sample sizes for pastoralist and foraging villages are uneven, with a far greater sample size achieved for coastal foraging/fishing settlements (n = 131) compared to mixed subsistence (n = 31) and inland pastoralist ones (n = 16). This relates to the limited amount of archaeological fieldwork conducted in the Mikea Forest, and as more data are collected the results may change. Conducting archaeological surveys in this region is difficult due to the spiny vegetation that obscures visibility of surface deposits. As of now, this study uses all the available archaeological data from this region. The results offer new insights that should spur on further research. Second, this study relies solely on geophysical signatures. It is our goal to conduct follow up research using sediment samples to assess the connection between geophysical characteristics explored here and geochemical changes to the study area.

5. Conclusions

This research suggests that the relationship between human land-use strategies and environmental impacts are similar among communities practicing different socioeconomic strategies. Foraging, in particular, is often viewed as “low impact”, compared to strategies like pastoralism which are often assumed to drive massive ecological shifts like deforestation and grassland expansion. Although some activities leave more subtle traces than others, when presented with high enough resolution data (spatially, spectrally, and temporally) we can see that the nature of human landscape modification is very similar across different kinds of subsistence practices.

Understanding long-term ecological legacies is particularly important for sustainability and conservation planning in the present. Studies like this help demonstrate how Indigenous land stewardship often become integrated into the very fabric of ecological systems and serve as a stabilizing factor for ecosystems (e.g., McMichael et al., 2023). By removing traditional land use practices, socioecological systems dynamics can be upended, leading to problematic or disastrous outcomes for sustainable land and resource management (Razanatsoa et al., 2021). Future work will examine material and zooarchaeological assemblages from excavated sites combined with sediment analyses to provide greater insight into the subsistence strategies employed and the impacts of human activity on soil composition over longer time scales.

CRediT authorship contribution statement

Dylan S. Davis: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Alejandra Domic:** Writing – review & editing, Validation, Formal analysis. **George Manahira:** Writing – review & editing, Validation, Resources, Project administration, Investigation, Conceptualization. **Kristina Douglass:** Writing – review & editing, Supervision, Methodology, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jaa.2024.101612.

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