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Traditional land use is integral to ecological function in SW Madagascar

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Historic land-use practices are important for understanding present-day patterns of ecological productivity and resilience. A longstanding challenge, however, has been how to discern different land-use activities across landscapes from archaeological and historic data. Here, we show how multispectral satellite imagery and machine learning can identify different subsistence strategies of past human land-use. Looking at coastal, southwest Madagascar, a location often cited as an example of how human land-use has degraded the island's ecosystems, we show that centuries of traditional land-use practices are positively correlated with ecosystem function. Therefore, future actions to address contemporary ecological degradation on Madagascar, and elsewhere, should consider historic land-use practices and their long-term effects on ecosystem function. Such relationships are fundamental for protecting environmental systems.

Ecology students, as noted in the introduction to *Braiding Sweetgrass*[1], commonly believe that all human impacts on ecosystems are negative. Despite this common belief, research reveals that humans have complex, negative and positive influences, affecting future land-use resilience and sustainability. For example, while there is little doubt that modern industrialization has had negative impacts on ecological systems, blame is often also placed on local communities practicing traditional livelihood strategies[2–4]. Pastoralist communities, in particular, have been blamed for deforestation[5–7] despite recent research repeatedly demonstrating that grazing is critical in sustaining ecological systems[8–10]. Yet, negative connotations persist in policy decisions around the world[11,12].

A common thread among most narratives of ecological degradation is the practice of specific economic systems for exploiting resources. Assessing the role of different land-use practices in the past on environmental change is challenging, however, as there is rarely clear evidence separating subsistence economies in the archaeological record[13–15]. However, advances in quantifying differences in landscape-scale land-use patterns using spatial modeling and remotely sensed datasets are starting to alleviate these issues by isolating different behavioral patterns and geochemical signatures between land-use strategies[16,17].

On Madagascar, issues of sustainability have been at the forefront of research, development, and policymaking for decades[2,18]. As a global "biodiversity hotspot" with at least two millennia of human occupation, landscape modification, and climate change[19–21], Madagascar provides an important case study for evaluating human–environment dynamics across different scales of human societies. While the timing of human arrival is debated[22,23], current archaeological data suggests that the earliest human inhabitants were likely foraging societies, and by ca. 1500 B.P. the introduction of cattle and other domesticates became widespread[24,25]. Chronological evidence supports the notion that these earlier human occupations had lower population and settlement densities and many relied heavily on fishing, hunting, and gathering[20]. This observation has led many researchers to assert that the introduction of domesticated species and the spread of agropastoralism were major drivers of deforestation and grassland expansion on Madagascar[26–29].

There is global archaeological evidence that demonstrates the importance of past land-use practices in fostering biodiversity and ecological productivity in the present[8,30–32]. As such, history suggests that human subsistence activity may be integral to sustainable ecosystem functioning. The ability to understand the connection between historic land-use and ecological change is invaluable for local communities, state governments, and international organizations, as the consequences of removing integral species from an ecosystem can be catastrophic[33–35]. If people are an integral part of Madagascar's ecosystem, conservation policy strategies must be attuned to the role of people and their socioeconomic practices in facilitating sustainability and resilience.

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Today, pastoralism is understood as a key component of many ecosystems, contributing to sustainability and resilience[8–10]. Nonetheless, notions of "destructive" pastoralism and "pristine" hunter-gatherer societies persist in the present and these conceptions can skew policy development and lead to unfair penalties on traditional land-use practices with disastrous effects (see[11],[12]).

Humans and the broader ecological system engage in feedback cycles where actions have cascading effects that can have time-delays[36–38], sometimes on the order of centuries[37,39,40]. Time lags inherent in many human–environment interactions mean that to fully grasp the impacts of a given activity requires a firm understanding of historic events and memories of social practices and their consequences on the environment (Fig. 1). For example, researchers have found that millennia of swidden (slash-and-burn) forestry practices in the Amazon have led to greater soil fertility ([41], also see[42]). Numerous studies from around the world have uncovered historical land-use legacies and their effects on contemporary ecological conditions and the conservation efforts[43–45].

One significant global question that Madagascar can help to address is how legacies of early human activity have contributed to contemporary ecological contexts. Remote sensing data can provide an important way to explore cumulative environmental change, as modern landscapes represent a palimpsest—a layered history of human and natural events that have shaped an environment's present state[46]. In fact, prior remote sensing research from SW Madagascar concluded that vegetation surrounding archaeological sites are more stable than plants growing further away from archaeological sites[47].

In this study, we build from this prior research to ask, do traditional land-use practices of Malagasy communities have lasting, cumulative impacts on ecological health and productivity? To address this question, we look at remotely sensed measures of net primary production (NPP), a common measure of energy availability in an ecosystem that can be transferred through a food web. We hypothesize that if traditional human activities led to lower ecological productivity, we will see overlap between areas with land-use legacies related to archaeological activities and zones of low NPP compared with areas lacking these archaeological land-use histories.

In southwest Madagascar, we have collected information related to past human settlement patterns and land-use, but there are imbalances in data acquisition across land-use types. For example, we have only a few

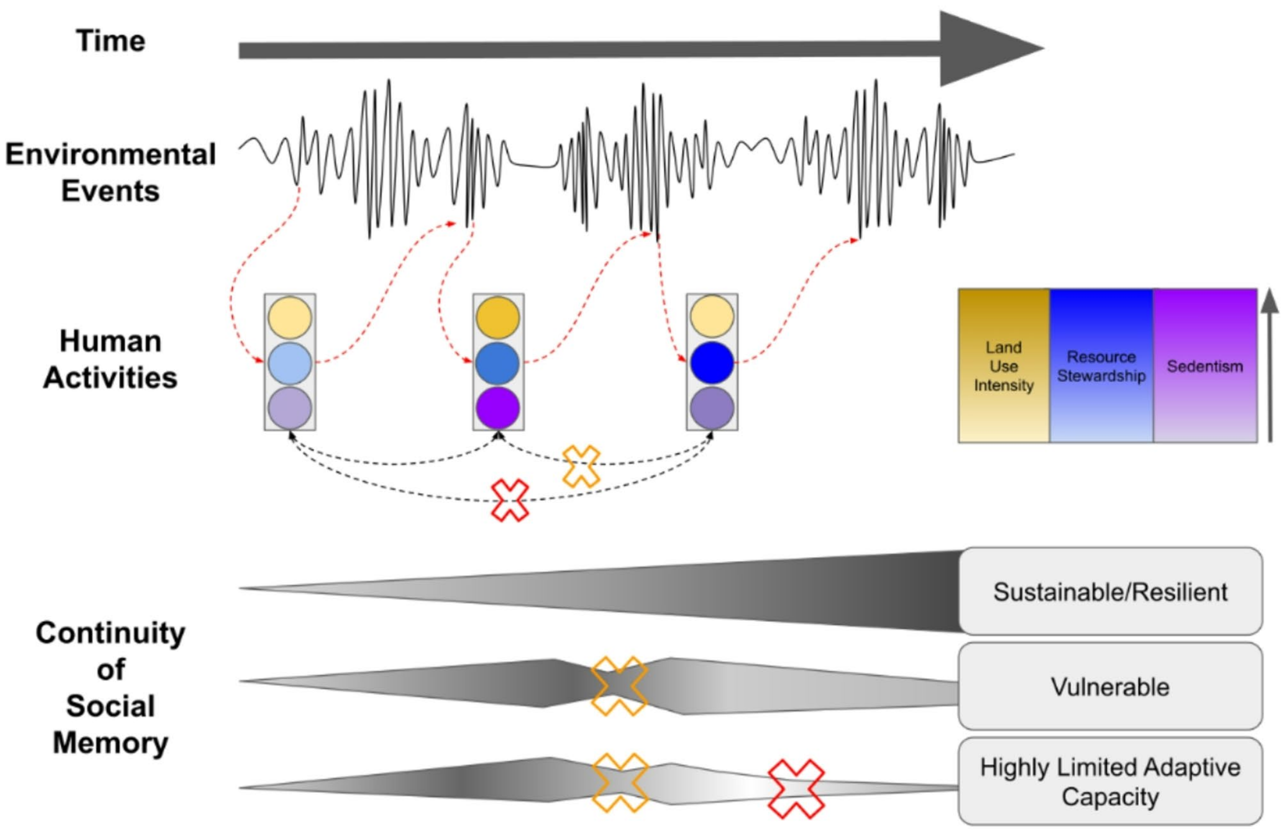

Fig. 1. A conceptual diagram of legacy land-use impacts. Changing environmental and climate conditions result in human responses that create a socio-ecological feedback cycles that connect the past and present. Human activities (e.g., land use and mobility strategies, resource stewardship practices, among others) impact both the future environmental system (via biophysical changes and land-use legacies) and the future social system (via transferred social memory of successful and unsuccessful adaptive strategies). When social memory and traditional ecological knowledge are retained, feedback dynamics between past and present conditions are retained, leading to increased socioecological resilience. If social memory is lost, these positive feedback loops become severed, resulting in increased socioecological vulnerability, as knowledge from past generations is lost.

dozen areas where we know that pastoralism was the predominant economic practice, but over 150 areas where fishing and foraging were predominant. In this study, we employ machine learning and remote sensing datasets alongside archaeological data to identify geophysical signatures on today's landscape that are associated with past human land-use activities (pastoralism, foraging, fishing, etc.) across SW Madagascar. Altogether, this study presents an updated evaluation of human-ecological impacts over the past several centuries in SW Madagascar (Fig. 2), where indigenous communities practice a range of economic activities and occupy an array of ecological systems[48,49]. Our study demonstrates that future actions to address ecological degradation on Madagascar, and elsewhere, must consider historic and archaeological land-use and its impact on modern ecosystem function.

Results

Machine learning helps identify patterns of historic land use

Prior remote sensing analyses on Madagascar demonstrate that archaeological sites display more stable geophysical signatures over time when compared with areas lacking archaeological materials, indicating greater ecological stability[17]. This effect is distributed relatively evenly across different economic practices at these sites, including foraging/fishing, agropastoralism, and mixed economies.

Our machine learning analysis compared three algorithms, Maximum Entropy (MaxEnt), support vector machine (SVM) and random forest (Table 1). The greatest overall accuracy was achieved by MaxEnt and it displayed the least overfitting and highest overall classification agreement. The Random Forest algorithm produced slightly better recall, but was less precise when evaluating new information. As such, we view MaxEnt as the best performing model. A total of 29 archaeological sites from our study area were withheld from the training and validation data, as they have evidence of a mix of subsistence strategies, encompassing foraging and pastoralism. All of the 29 sites were identified as archaeological by the MaxEnt model, and 13 were located in areas that contained (or were within 50 m of) both pastoralist and foraging signatures.

Further verification of MaxEnt predictions comes from survey data collected in 2017 by the Morombe Archaeological Project team which were not used to train the model. A total of 8 coastal sites contained evidence of zebu (*Bos indicus*) in the faunal assemblages, with three of these sites containing evidence of mixed subsistence (zebu and marine shell materials). When examining the placement of these sites alongside our machine learning classification, all except for one were within 80 m of an identified location with pastoralist and foraging/fishing signatures (Fig. 2).

Performance of automated methods (e.g., accuracy), when paired with other datasets and analytical methods, do not need to be exceptionally high to be useful[50,51]. By comparing our automated results with prior archaeological and ethnographic sources and manual verification, our machine learning dataset is able to provide generalized information about land-use and where different subsistence economies were predominant over time (Fig. 2). We manually cleaned the MaxEnt classification to generate information designating regions where different subsistence economies were most prevalent. During this process, we removed any errors identified in the classification when it conflicts with other confirmed archaeological or historical data. In regions where signatures showed a mixture of pastoralist and foraging/fishing signatures, we labeled these areas as mixed subsistence strategies (Fig. 2). The output is not meant to serve as a prospection tool, but rather an aid in understanding broad, regional level land-use practices in the region over the past millennium.

Historic land use practices correlate with modern ecosystem function

When examining the results of our machine learning classification and archaeological datasets against modern landscape trends, general linear models (GLMs) indicate that archaeological land-use practices have a strong positive association with Net Primary Production (NPP) (Table 2; also see Fig. 3). Bootstrapping simulations reaffirm these relationships (see Supplemental File). While there are differences between land-use types, all land-use strategies exhibit strong, positive correlations with NPP while non-anthropogenic locations have a weaker relationship (Table 2). This provides evidence that places with histories of human land-use are well integrated into the natural environment in this region and do not result in ecological degradation or decreased ability to rebound from climate disruptions compared with non-anthropogenic areas (e.g.,[31],[32], also see[52]).

Discussion

Traditional land management practices are often important components of ecological systems, with global examples indicating how humans are crucial players in ecosystem function and conservation[30,52]. Nonetheless, distinguishing between different kinds of land-management practices societies engaged with is challenging[8]. Subsistence economies are often muddled without clear separation and classifying particular groups or practices into categories is often difficult and contentious[13–15]. Our study demonstrates the capacity for remote sensing and machine learning to identify and distinguish between different intensities of land-use and their resulting patterns. This will permit archaeologists, landscape ecologists, and others the ability to greatly expand their understanding of socioeconomics, land-use practices, and landscape change, which is lacking in many regions around the world, especially for early periods of human history[52].

Our analysis of NPP shows that human land-use practices in SW Madagascar exhibit strong positive associations with ecological productivity, while regions without evidence of human land-use express a weaker correlation. This finding suggests that traditional subsistence economies are well integrated into this region's ecosystem and are important contributors to ecosystem functioning. This follows other recent studies that have shown vegetation health to be greater with higher levels of stability over time at archaeological sites than surrounding regions[17,44].

Our analysis also exemplifies that human activities are not spatially constrained to areas of intense occupation, but affect much larger biogeographic regions beyond individual settlements[8,53–55]. This study shows how

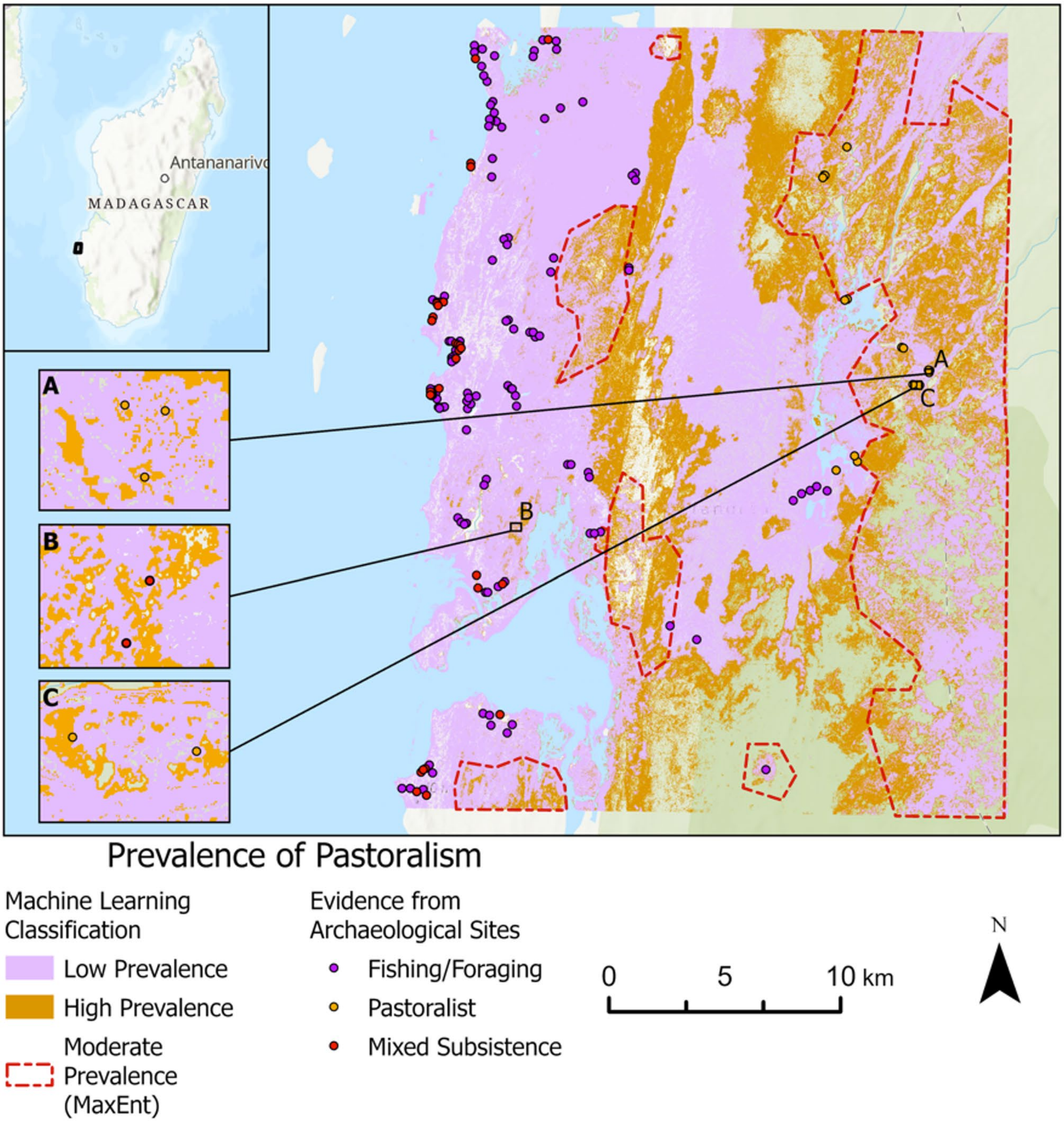

Fig. 2. Map of the study area, recorded archaeological sites, and results of Maximum Entropy classification. Areas identified as "low prevalence" of pastoralism can be interpreted as zones where fishing and foraging were more dominant. Mixed subsistence classifications were manually evaluated after machine learning training. Inset maps A, B, and C show ground verification of mixed subsistence and pastoralist archaeological sites and their corresponding classification. Service Layer Credits: Esri, TomTom, Garmin, FAO, NOAA, USGS, CGIAR, OpenStreetMap contributors, Foursquare, METI/NASA**.** Figure created by the author (DSD) using ArcGIS Pro (v. 3.4, https://pro.arcgis.com/).

signatures found at archaeological sites display similarities with adjacent regions that spread, geographically, throughout large swaths of the study area. While archaeological sites provide important insight to the kinds of bioecological, geochemical, and geophysical signatures associated with human activities, these signatures often persist well beyond individual sites and can illuminate broader patterns of socio-environmental interaction.

Algorithm	Overall accuracy	Precision	Recall	F1	K-coefficient
MaxEnt	0.7714	0.636	0.628	0.632	0.6456
SVM Radial Basis Kernel	0.6944	0.495	0.575	0.532	0.533
Random Forest	0.6842	0.614	0.670	0.641	0.5284

Table 1. Results of Machine learning analyses. MaxEnt performs best and displays the least evidence of overfitting.

Coefficient	Estimate	Standard error	z-Value	*p*-value
(Intercept)	6.479689	0.001822	3555.68	< 2e-16
Moderate Prevalence of Pastoralism (Mixed Economy)	0.970355	0.002277	426.17	< 2e-16
Non Anthropogenic	0.269349	0.003595	74.91	< 2e-16
High Prevalence of Pastoralism	0.911469	0.002423	376.23	< 2e-16

Table 2. Results of GLM assessing NPP as a function of archaeological economic activities. This includes confirmed archaeological and non-archaeological data as well as machine learning generated datapoints.

Economic diversity may have buffered communities against socio-environmental instability in SW Madagascar

For hundreds of years, Malagasy communities practiced a diverse, but interconnected series of economic strategies that made use of different resources and components of the landscape[48]. We know from prior investigations of social networks that there were close connections between different communities, but these connections were disrupted and reorganized during periods of socioecological instability[56]. Our analysis can also shed light on the role socioeconomic strategies play in the emergence of social networks.

Examining our machine learning classification maps against archaeological site networks (identified by Ref[56]), we can see that the earliest social networks consist of communities practicing the same economic strategies (low prevalence of pastoralism), while networks during the preceding periods consist of communities practicing different or mixed strategies (Fig. 4).

The climatic and environmental conditions from 1150 to 450 BP were fairly consistent and predictable, but from 450 to 50 BP sociopolitical instability became dominant and climate conditions became more erratic, shifting between dry and wet conditions. Hypervariability would have affected people's ability to acquire different resources and could have influenced changes to social networks[56]. As such, these conditions could help explain why social networks began to integrate different communities that practiced different resource acquisition and exploitation strategies.

Our analysis demonstrates that humans constructed a highly diverse cultural niche with fuzzy boundaries between economic systems. This may have served to buffer against social and environmental instability by fostering high levels of interaction between inland agropastoralists and coastal fishing/foraging communities. Oral history records indicate that individuals living within single villages often practiced a mix of different subsistence strategies, in a variety of locations, so as to exploit regional environmental heterogeneity while reducing crowding on limited resources[47,48,58]. Stories describe "pasture territories" (*Toets-aombe*, literally, "cattle places,") in the dense deciduous forest, where cattle browsed tree leaves, and strategies of temporary nomadic foraging when wild foods were exhausted close to home. Those who primarily farmed, and those who primarily fished, exchanged goods at designated places. These were elements of diversified household portfolios rather than economic specializations. By flexibly distributing household labor across landscapes and subsistence modes according to fluctuating conditions, households may have facilitated sustainable resource use over centuries. The expansion of the capitalist market economy after European colonization to the present limited mobility, and resulted in limited fallow time for resources, and unsustainable resource use[59]. Studies have shown that the most extensive deforestation in Madagascar (including within the SW) occurred over the past 40 years, in reaction to market incentives[60–62]. Our analysis here suggests that traditional ecological practices are integral to both ecological and social resilience.

Limitations of the study

Several potential limitations of this research should be acknowledged. First, machine learning models were trained to predict subsistence priority using our knowledge of site locations, but this knowledge is limited due to the absence of a complete archaeological survey and the incomplete nature of the archaeological record due to preservation biases and taphonomic processes. Foraging for wild tubers, the staple for terrestrial foragers, leaves scant archaeological traces, so that these sites are probably underrepresented in our database. Our analysis does not consider agriculture, due to a lack of evidence at archaeological sites, despite frequent descriptions of cultivation in oral histories. Second, there are some complicated questions of causality. We argue that subsistence activities cause higher NPP, citing mechanisms such as the accumulation of manure and its use as fertilizer. Simultaneously, people are more likely to locate their sites where NPP is high. High NPP may be both a cause and an effect of subsistence activities, consistent with niche construction theory. More temporal information will be needed to trace changes in NPP through time to establish ultimate causation. Finally, although we classify

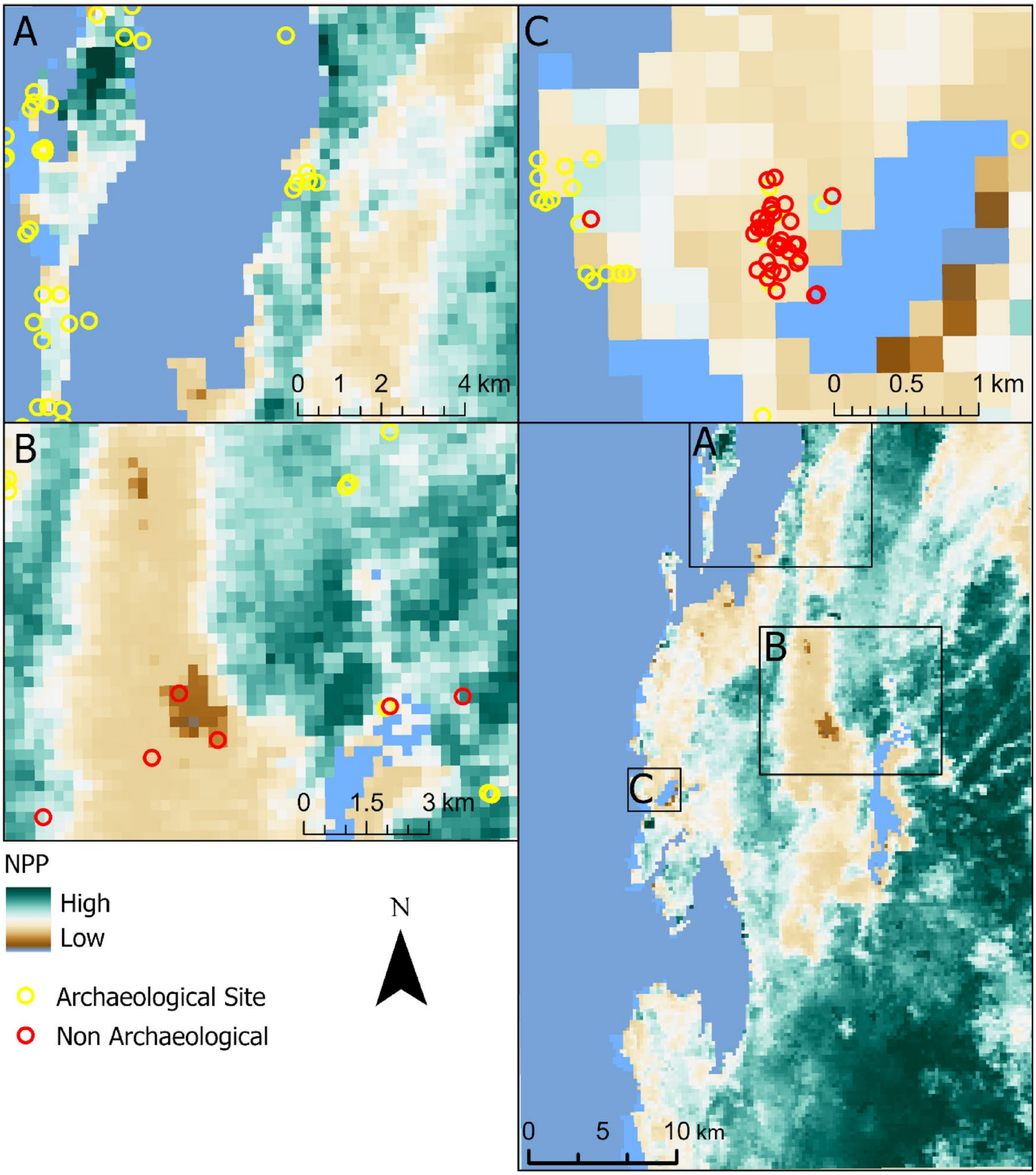

Fig. 3. Visual representation of NPP measurements relative to the locations of archaeological sites and surveyed areas with no evidence of archaeological activities. Figure created by the author (DSD) using ArcGIS Pro (v. 3.4, https://pro.arcgis.com/).

sites as having more or less evidence of pastoralism, the people who lived at these sites probably had a mixed economy spread across the landscape, as described above.

Conclusions and lessons for the future

We find that contemporary ecological productivity is higher within archaeological sites practicing traditional subsistence economic strategies in southwest Madagascar. This follows other recent studies that demonstrate the prolonged impacts of human presence on landscapes (e.g.,[31]). As such, it appears that current threats of biodiversity loss and deforestation within the study region cannot be explained by centennial and millennial legacies of cumulative human impact. Rather, many ecological issues (e.g., deforestation) facing Madagascar and other parts of the world today are the result of climate change (e.g., rising temperatures and lowered precipitation), modern economic practices driven by capitalist markets[61,62], and the absence of infrastructure and the disappearance of traditional ecological practices. Conservation policies that ignore traditional ecological knowledge are likely to perpetuate these issues[63–66].

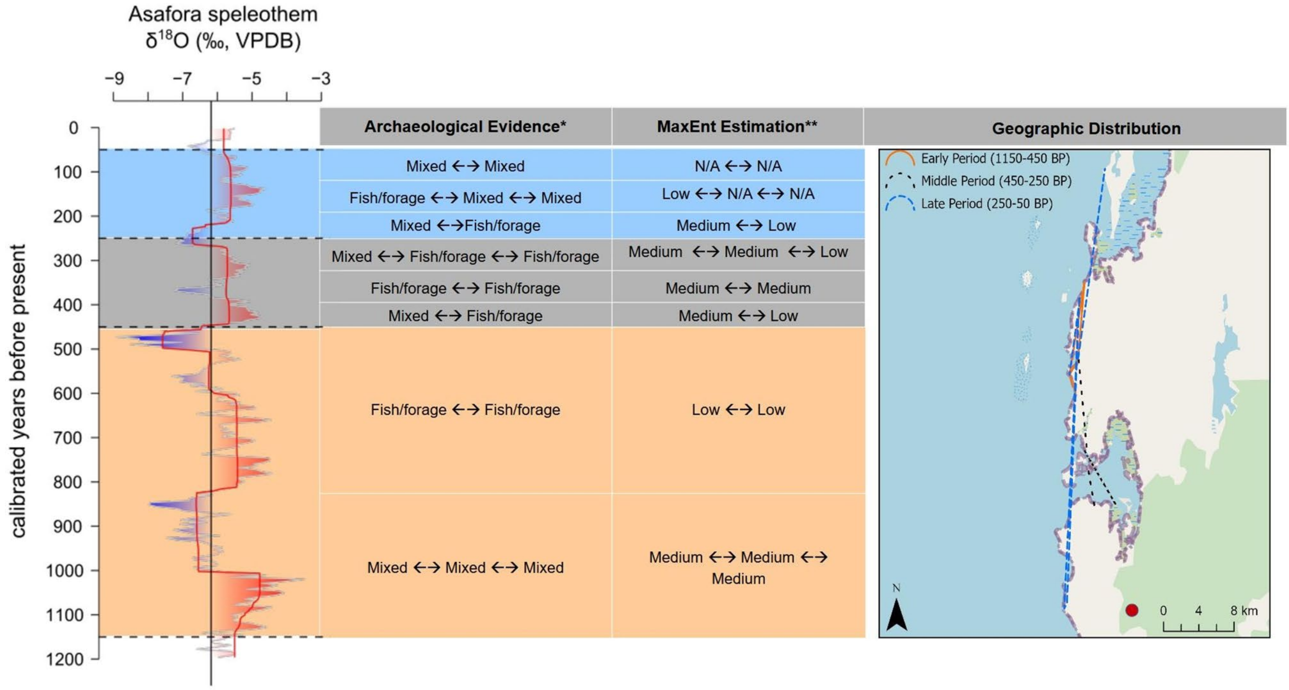

Fig. 4. Diagram of paleoclimate conditions recorded from speleothems at Asafora cave (red dot) by Faina et al.[57] and corresponding archaeological site networks. Each site is labeled by its primary subsistence strategy, identified by archaeological evidence and the MaxEnt prediction of the degree of pastoralist activity. *Archaeological evidence of mixed subsistence refers to presence of zebu bones and evidence of fishing/ foraging (e.g., marine shells). **N/A indicates that the sites fell outside the bounds of the study area where the MaxEnt model was applied.

On Madagascar, as in other places around the world, mobility and intercommunity trade were key strategies for past human resilience and sustainability. While the modern world makes this kind of transhumance difficult (or incompatible) with land-tenure systems and property boundaries, including the boundaries of national parks and protected reserves, a compromise should be sought that permits for freer movement of communities over time and space in order to allow resources to regenerate and human pressures to ease within areas currently experiencing ecological problems. For example, Madagascar National Parks restrict subsistence activities to managed occupation zones. Our evidence suggests that some of the human activities park policies wish to limit or constrain are the same ones that created the diverse, highly productive environments that we now seek to protect. Mobility is also currently hampered by poor security measures and infrastructure throughout much of the southwest. Prioritizing improvements to the region's infrastructure may aid in efforts to increase ecological productivity and sustainability. When security measures are poor, less land can safely be accessed for use, putting pressure on a smaller portion of land with negative consequences.

For instance, current conservation policy in Madagascar, including the "managed occupation zones" (zones d'occupation contrôlée) established by Madagascar National Parks (MNP), tends to limit subsistence activities such as pastoralism, forest product harvesting, and small-scale agriculture within park boundaries. These restrictions are often based on generalized degradation narratives rather than context-specific ecological evidence[66,67]. However, our findings suggest that traditional subsistence activities—including mobile cattle herding and seasonal foraging—are positively associated with ecological productivity, and may play a role in sustaining ecosystem function. Conservation planning that incorporates these histories could reframe controlled mobility and rotational land use not as threats, but as tools for maintaining resilience in highly variable environments.

Similar frameworks are emerging globally. In Tanzania, for example, pastoralist land use has been re-evaluated as ecologically sustainable under revised community-based conservation programs[12]. The (International Union for Conservation of Nature's (IUCN) Protected Area Guidelines[68] also now emphasize the integration of Indigenous and local knowledge systems into conservation management, aligning with our call for greater flexibility and historical grounding in protected area design.

These realizations have global implications for conservation. Efforts that seek to preserve biodiversity need to have a firm understanding of the history of human land-use in the areas they seek to protect. Our study joins a growing literature that illustrates the importance of past land-use in current ecosystem function ([30],[32], e.g.,[64]) and provides a new approach to achieving the integration of archaeological and ecological data. Rather than treat all of humanity as a monolith, nuance is needed to develop sustainable futures.

Methods

Machine learning for identifying archaeological land-use

Here, we use PlanetScope imagery, which is freely available for education and research purposes by Planet Inc. and contains 3 m spatial resolution, 4 spectral bands (blue, green, red, and near infrared), and a temporal resolution of 1 day. Madagascar has two distinct seasons: a dry season (from May–October), and a wet season (from November–April). Prior research (Davis et al.[17]; Davis and Douglass[75]) demonstrates that pastoralist and foraging sites are most distinguishable during the wet season, so we compiled 56 4-band multispectral PlanetScope satellite images from the wet season between 2018 and 2021 (Supplemental Table S1). We calculate the median value across all of these images (following Orengo et al.[76]; Davis et al.[17]) to evaluate average geophysical signatures over time. We conducted this analysis using the *raster*[69], *sf*[70,71], and *ggplot2*[72] packages in R[73].

Previous research has also demonstrated that the use of short-wave infrared (SWIR) data can improve archaeological detection tasks due to its increased sensitivity to moisture and mineralogical changes[74,75]. We used Google Earth Engine, following Orengo et al.[76] (see supplemental code) to compile a 6-year composite average of Sentinel-2 SWIR imagery between 2017 and 2022 to enhance our spectral resolution. SWIR data was imported into R and pansharpened from 20 to 3 m using PlanetScope imagery and a principal components procedure (following[75]). The two datasets are co-registered and spectrally compatible, allowing for pan sharpening to take place in R using the *raster* package[69].

Next, we created a single raster stack of PlanetScope and pansharpened Sentinel-2 SWIR and ran a series of machine learning algorithms to classify archaeological sites based on their primary subsistence strategies. Because of the high degree of overlap between land-use practices in this region, we classify settlements based on their prevalence of pastoral activities, with lower prevalence often corresponding with foraging and fishing villages, moderate prevalence corresponding with mixed subsistence strategies, and high prevalence corresponding with agropastoral communities. We evaluated primary subsistence at archaeological sites using material assemblages recovered at each location during surveys and excavations. Sites with a low prevalence of pastoralism are defined by an abundance of marine shells and archaeobotanical remains with a total lack of evidence of domesticated animals (e.g., Zebu). Sites with high prevalence of pastoralism are defined by the presence of domesticated animal bones (e.g., Zebu) and the presence of structures like cattle pens. Sites with moderate prevalence of pastoralism (or mixed subsistence) were defined as those containing evidence of both domesticated fauna and marine resource exploitation.

Three different machine learning algorithms were tested: Maximum Entropy, Random Forest, and Support Vector Machine with a Radial Basis Kernel. Maximum entropy (MaxEnt) is a method for making predictions from incomplete datasets[77] and operates under the concept of entropy, a measure of choice involved in the selection of an event[78,79]. Under maximum entropy, it is assumed that decisions have a uniform distribution of choices based on a set of known measurements (or training data). As such, MaxEnt models only make assumptions about known data, and do not require absence information to make predictions[77,80]. The constraints imposed on entropy by training datasets lead the model to come to the most conservative estimate of presence data, which also helps to avoid overfitting[80].

Random Forest (RF) models classify data using decision trees and bootstrapping and also perform well with smaller amounts of training information[81]. RF is a non-parametric supervised classification and regression method and operates as a collection of decision trees which all act independently to parse through and classify information. This helps to reduce overfitting as each tree "votes" with their classification choice and the most popular outcome is selected.

Support Vector Machine (SVM) is a non-parametric classification technique that identifies optimal class separations and can achieve high accuracy with small training datasets[82]. One of the strengths of SVM is that it has strong regularization properties, or an ability to generalize to new data, thereby avoiding the pitfalls of overfitting[83]. When datasets are non-linear, SVMs require the addition of a kernel function which transforms data by projecting information in additional dimensions (e.g., 1D–2D), allowing for data that is not separable linearly to become separable[83]. Here, we use a radial basis kernel function, which is one of the more popular kernels that computes the similarity of data points, where the more similar two points are, the closer they are in distance, and the more dissimilar, the greater the distance[84].

We trained each of these models using a dataset consisting of 245 ground-tested points (non-anthropogenic = 121; low pastoralism = 113; high pastoralism = 16). Non-anthropogenic sites represent those locations that have no evidence of archaeological or human activities, while the other classifications (low and high pastoralism) represent different kinds of archaeological sites. Training data was divided using a 80/20 split for training and validation, respectively and we tuned each model automatically using the "tune_length" parameter in the caret package in R (see supplemental file). Tuning is used to alleviate overfitting issues. We set the tune_length to 1 for all models. These analyses were conducted in R v. 4.2.3[73] using the RSToolbox, caret, MIAMaxEnt, and randomForest packages[85–88]. MaxEnt and RF algorithms, in particular, were chosen because they tend to work well with incomplete datasets and smaller sample sizes.

A total of 29 additional archaeological sites were withheld from the training and validation data, as they have evidence of a mix of subsistence strategies (moderate prevalence of pastoralism), encompassing foraging and pastoralism. To explore how our best performing model handles mixed classifications, we evaluated the classification results against these 29 sites. These sites were not added as another class because of spectral overlap with existing classes and the small number of data-points available.

Assessing cumulative ecological impact of archaeological activities

To assess the role of past human economic activities on modern day ecosystem function, we use the Water Productivity through Open Access of Remotely sensed derived data (WaPOR) dataset created by the Food and Agriculture Organization (FAO) of the United Nations[89]. WaPOR contains information on Net Primary Production (NPP), which reflects the amount of biomass produced by plants in an area subtracted by respiratory costs, and is available on Google Earth Engine (GEE) (https://developers.google.com/earth-engine/datasets/catalog/FAO_WAPOR_2_L1_NPP_D#description). NPP data generated by WaPOR is measured in g/m^2, has a decadal temporal resolution calculated between 2009 and 2022, and a spatial resolution of 250 m. We downloaded a portion of this dataset containing our study region and imported the file into ArcGIS 10.8.1.

Next, we generated a random sample of 1000 points throughout the study region in ArcGIS 10.8.1 using the generate random points tool and classified them according to our best performing machine learning analysis categories (MaxEnt). For regions where insufficient archaeological evidence exists to verify our machine learning classification, points were removed, leaving us with 907 data points. Then, we extracted NPP values from the WaPOR data for each point in both a ground verified dataset of archaeological and non-anthropogenic areas (n = 245) and the data points generated by machine learning to compare ecological legacies resulting from specific archaeological economic practices with contemporary metrics of ecological productivity. NPP values were extracted using the Extract Multivalues to Points tool. Data was then exported as a CSV into R where we conducted further statistical analysis.

We used General Linear Models (GLMs) to evaluate possible relationships between archaeological economic activities and contemporary ecological function because they can handle moderate levels of non-normality and describe relationships even when they are non-linear[90]. We also ran a check for data skew in R using the *olsrr* package[91] (which uses linear models as input), and found that the residuals are slightly right skewed for archaeological data, but normal for the simulated data (Supplemental Document). We proceeded by constructing GLMs to assess the relationship between NPP and Archaeological Economic Practice and overall archaeological presence/absence. We used a Likelihood Ratio Test (LRT) to assess different model types. We ran our models using the confirmed data (n = 245), the machine learning generated data (n = 907), and a combination of the two datasets and assessed results using bootstrapping with 10,000 simulations to account for possible biases introduced by these different datasets using the *boot* package[92,93].

Data availability

Spatial coordinates for archaeological sites are not publicly available due to ethical concerns and agreements with local communities. These data can be made available upon reasonable request. Planet Inc data is proprietary and cannot be shared, but all information regarding the images used is provided in our supplemental files. Interested users with educational affiliations can request access to Planet imagery through their Education and Research program. All other data discussed and generated within this manuscript, including code used to conduct machine learning and statistical analyses, is available via Zenodo at https://doi.org/10.5281/zenodo.15483771 and Github at https://github.com/d-davis/Madagascar_Legacy_Niche_Construction.

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Author contributions

Project was designed by DSD and KD. Methods were developed and performed by DSD. DSD Wrote the main manuscript with input from KD, GM, and BT. DSD prepared figures with input from BT. All authors reviewed the manuscript.

Declarations

Competing interests
The authors declare no competing interests.

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