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Monsoonal habitats for the people: a pilot geoarchaeological and urban-planning study of land use and water management histories in the highlands of Madagascar

Yijie Zhuang, Tse-Hui Teh, Chantal Radimilahy and Zoë Crossland

Abstract

This article addresses one of the most significant research questions in the archaeology of Madagascar: when and how rice farming began to spread in the highlands. It also explores if it is possible to use this archaeological knowledge in urban codesign. Here we present preliminary geoarchaeological results and interview data from our two pilot field trips around several key archaeological sites along the Ikopa and Sisaony rivers in the Imerina region, near the capital city of Antananarivo.

These first-hand data on land use and water management histories provide fresh insights to understand highly localised erosion events and other ecological consequences of farming, as well as the non-linear evolution of hillslope–valley environments and landscapes in the studied region. Our results suggest that while some erosion might have begun as early as 2000 BP, most erosion events occurred from 500 BP onwards, coinciding with clear evidence of severe soil slaking and increased presence of rice phytoliths. The impact of intensified land use practices on local environments varies significantly between different locations and sites, revealing that the relationship between local ecosystems and human activities was more complicated than generally assumed. In terms of present-day landscape impact, our pilot study also uncovered the ambiguities and discrepancies in policy-making, appreciation and implementation among different stakeholders, rendering communities unaware of the real causes of environmental degradation and vulnerable to future environmental crises. These findings highlight the great potential of integrating archaeological knowledge of ecological and land use histories with the diverse needs of stakeholders for sustainable development and better preparation for future climate-related challenges.

Keywords: Madagascar highlands, water management and land use, geoarchaeology, urban planning, erosion and hillslope–valley evolution, stakeholders

Introduction

Madagascar's rice production and consumption is among the highest in Africa (Diagne et al. 2013). Since its archaeologically documented arrival in the island at least 1,000 years ago (Crowther et al. 2015; Douglass et al. 2019), rice farming has continued to transform landscapes, technologies and life in the country. Today, the urban and peri-urban environment of the capital city, Antananarivo, is dotted with paddy fields and related water management systems that are being overtaken by urban development. These fields represent a distinctive, yet exceptionally sensitive urban ecosystem. Contemporary landscapes in the highlands, where Antananarivo is situated, are characterised by numerous lateritised erosion gullies (*lavaka*) and predominant grassland. Broadly, during the dry season, first-season rice (*vary aloha*) grows in nurseries in low-lying irrigated marshy areas, whereas second-season rice (*vary vakiambiaty*) is sown later in the year at the base of hillslopes and on hillside terraces where it can benefit from rainwater run-off. Both are harvested during the rainy season (Boiteau 1999; Le Bourdiec 1974). The close and intricate relationship between farming and land conservation in the highland region has made it a place where the processes of severe land erosion and humans' role in them have been hotly debated (Brosens et al. 2022; Kull 2000), and where myths and misunderstandings about sustainability prevail (for example, Horning 2012). Some of the long-lasting debates include the question: what are the roles of natural and cultural processes in creating the highlands' characteristic *lavaka*-laden landforms and grass-dominant vegetation (for example, Cox et al. 2009; Vorontsova et al. 2016; Wells and Andriamihaja 1993)? And when and how did rice farming spread across the highlands (see Douglass et al. 2019)?

Two pilot field trips were conducted by the authors and local collaborators to lay the foundations to explore whether past and contemporary knowledge of water management for rice cultivation can be combined to form a sustainable urban and peri-urban water management system that is adaptable to the precarious local hydrology and global climate change. Through our pilot studies, we obtained evidence of late-Holocene sedimentation and land use histories on selected hillslope–valley systems along the Ikopa and Sisaony rivers in the Imerina region outside Antananarivo. We also began to piece together historical and contemporary water management practices and the diverse roles of stakeholders in conserving and evolving such practices. This article summarises key findings from our field trips and their implications for integrating multiple environmental, archaeological and social science evidence. It aims to understand long-term land use transformation and sustainable water management in a rapidly changing world with escalating climate uncertainties.

Patterns and processes of hillslope erosion and land use changes

Among the three hillslope–valley systems that have been investigated (see Figure 1), a total of 10 radiocarbon dates and 19 optically stimulated luminescence (OSL) dates were obtained from both on-site and off-site contexts. This allowed us to reconstruct the chronologies of the onset of local occupation, increasing land use and noticeable hillslope erosion. As shown in Tables 1 and 2, evidence of human activities might be dated to as early as 2000 BP, hinting at an early beginning of scattered burning events around sites such as Ankadivory. However, archaeological evidence of settlement occupation and construction activities is concentrated in the second millennium CE, in accordance with systematic settlement studies from excavation and survey data (Radimilahy and Crossland 2015; Wright 2007). Additionally, OSL dates, many of which were collected from sedimentation layers containing abundant sand or sand-sized particles, provide more detailed information on the onset and timing of ecological disequilibrium caused by erosion and other surface geomorphological processes related to intensifying human land use. Although age-depth models suggest that an evident change of sedimentation rate occurred around 2000 BP, as indicated by changed curves in the model (see Figure 2, lower left), which might not necessarily be caused by human-related activities, most OSL dates of the sandy layers fall into the time span between 500–300 BP (Figure 2, lower right). These results point to a very patchy picture of hillslope erosion and a different path of hillslope evolution during the late Holocene period.

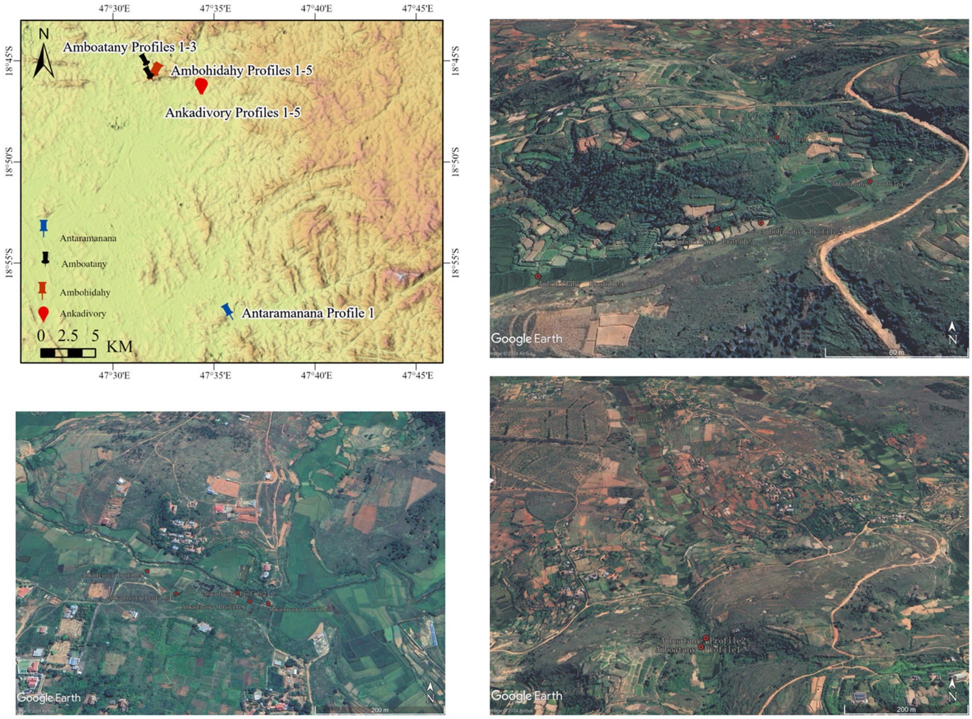

Figure 1 Top left: Locations of the archaeological sites, with coordinates, where geoarchaeological surveys were conducted. Top right, lower left and lower right: Google Earth images of the Ambohidahy, Ankadivory and Amboatany sites, showing sampling locations along the hillslope–valley systems (green belts on the images)

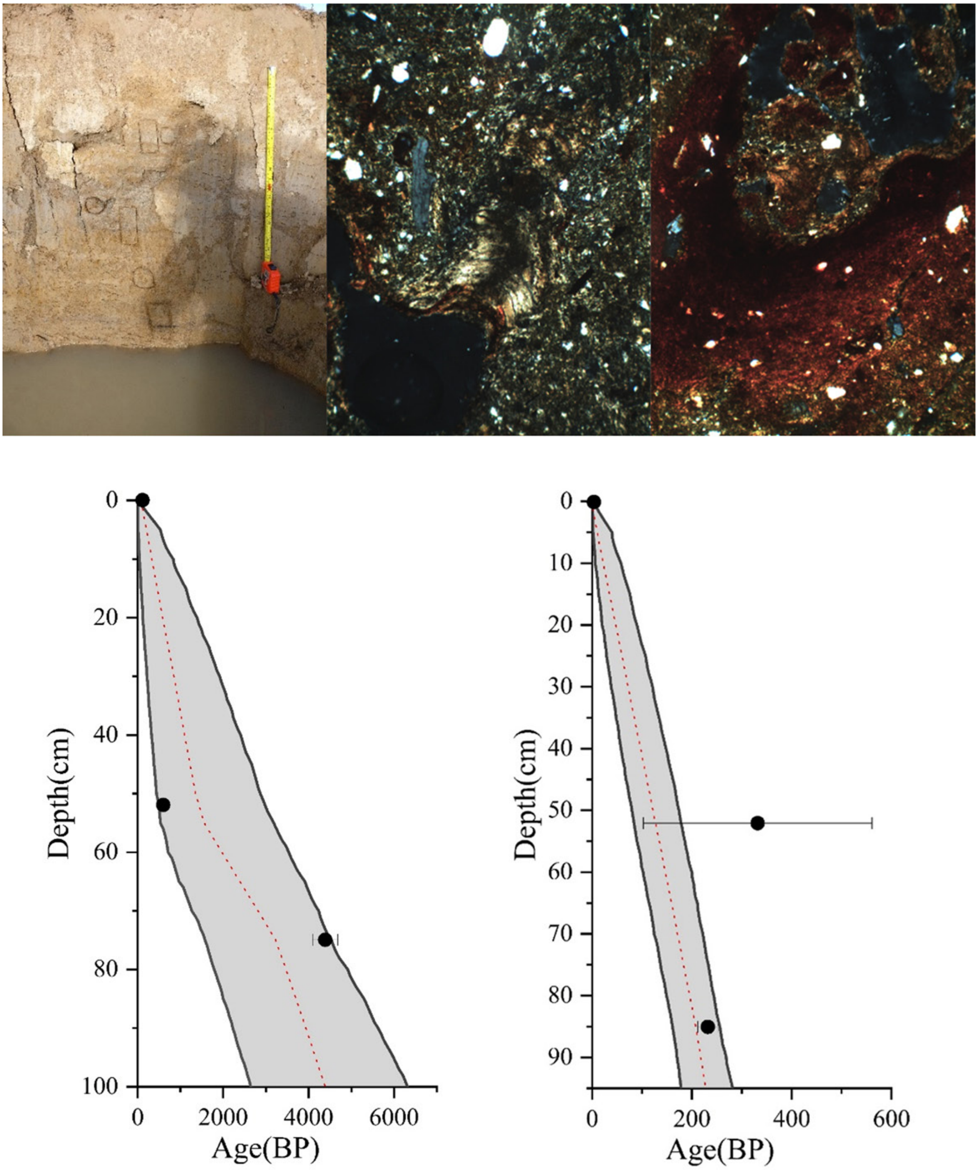

Figure 2 Top left: Ankadivory profile 1, showing where thin section (square) and OSL-dating samples were taken; note the small charcoal lens situated in the bottom square. Top middle: dusty clay coatings with layered structure filling a channel, Ambohidahy profile 2:1. Top right: large area of iron hypo-coating around a void, with clay-rich granular structure, Ambohidahy profile 2:2. Lower left and right: age-depth models for profiles 1 and 2 at Ankadivory, created in R (Baron) software

Table 1 OSL dates from different profiles at Ankadivory (detailed results are to be published in separate articles)

Field code	Lab code	Grain size(µm)	Ge γ-spectrometry (ex situ)			Total Dr (Gy.ka^{-1})	De (Gy)	Age (ka)
			K(%)	Th(ppm)	U(ppm)			
Ankadivory P5:4	GL21086	5–15	0.65±0.09	28.29±1.46	1.30±0.18	3.37±0.14	12.53±0.50	3.72±0.22
Ankadivory P1:2	GL21087	180–250	1.98±0.12	31.50±1.41	2.08±0.15	3.51±0.20	1.71±0.10	0.49±0.04
Ankadivory P1:3	GL21088	5–15	1.60±0.11	27.56±1.25	1.83±0.14	3.89±0.15	16.80±0.95	4.32±0.30
Ankadivory P2:2	GL21089	180–250	1.86±0.12	36.35±1.59	1.95±0.15	4.32±0.25	1.44±1.01	0.33±0.23
Ankadivory P2:4	GL21090	180–250	2.28±0.14	38.28±1.67	2.18±0.16	4.51±0.26	1.02±0.08	0.23±0.02
Ankadivory P4:2	GL21091	5–15	0.55±0.08	30.84±1.54	1.06±0.17	3.47±0.15	22.26±1.13	6.41±0.43
Ankadivory P4:4	GL21092	5–15	0.05±0.06	43.70±2.11	1.75±0.20	5.10±0.23	30.43±1.11	5.97±0.35
Ankadivory P5:2	GL21093	5–15	1.23±0.11	31.24±1.58	1.60±0.18	4.02±0.17	3.67±0.26	0.91±0.08

Table 2 14C dates from Ankadivory

Sample number	Lab code	Material	^{14}C Age (BP)	Calibrated calendar year 95.4% probability
Ankadivory P1-5	Beta - 645047	Carbonate Sediment	1850 +/– 30 BP	(84.1%) (1828–1696 cal BP) (11.3%) (1654–1615 cal BP)
Ankadivory P2-4	Beta - 645083	Charcoal	200 +/– 30 BP	(73.6%) (285–136 cal BP) (13.5%) (116–60 cal BP) (8.3%) (26 – Post BP 0)
Ankadivory P3-2	Beta - 645084	Charcoal	1120 +/– 30 BP	(60.8%) (996–926 cal BP) (34.6%) (1056–1012 cal BP)

These preliminary results are further supported by sedimentological evidence. Results of particle size distribution, and soil micromorphology in particular, reveal frequent fluctuations of sedimentation regimes within and between different examined profiles and hillslope systems. At profile 1, which is located at Ankadivory, in the middle-to-upper part of the valley, the presence of a charcoal lens near the archaeological site, coinciding with an increase of coarse-sized sediments, disrupted clay textural features and abundant micro-charcoal (see Figure 2), might be related to scattered land clearance activities. However, the possibility that it was not anthropogenic cannot be ruled out. The sedimentation in profiles 2 and 4, situated further downstream of the hillslope differ from profile 1. These are both dominated by poorly sorted eroded sediments, pointing to pronounced erosion events. The initiation of these events, however, differs significantly between the two profiles. As revealed by the OSL dates presented above, such processes began and prevailed from *c*. 300 BP in profile 2, whereas those of profile 4 seem to have begun many millennia earlier, taking into account some possible errors in the OSL dates. Located in an even lower position, at profile 5, the sedimentation history saw a clear shift from fine-grained sediments deposited in weak hydrodynamic conditions in the lower part of the profile to one with stronger hydrodynamics, resulting in the deposition of coarser-sized but better-sorted sediments. A similarly patchy and significant intra-hillslope system variation in sedimentation can be seen at other studied sites.

This new chronological and sedimentological evidence prompts us to rethink the mainstream scholarship on the timing and process of gully erosion on the highlands. First, although at some locations (for example, Ankadivory profile 4) erosion began very early, long predating large-scale human occupation, it did not, as suggested by many studies (for example, Cox et al. 2009), cause a continuously accelerating trend of erosion across the entire hillslope–valley system. This calls for a deeper understanding of the non-linear and multifaceted feedback mechanisms between ecological equilibrium and external disturbance. More data are required to further assess this complicated relationship. Second, the erosion rate became much higher from *c*. 500 BP onwards, but it should be noted that such processes were also highly localised and on a variable scale. Different land use practices, such as building terraces and other earthworks, might have evident impact on local erosion and other ecological processes.

Additional evidence of diverse land use practices at these sites comes from soil micromorphological and phytolith analyses. The high ubiquity of rice phytoliths in all the examined profiles (see Figure 3) supports the long-term importance of rice farming on the highlands since at least 1000 BP. Rice phytoliths (*Ehrhartoideae*) were found in 11 out of 12 examined profiles, albeit with varying abundance. Except for samples taken downslope from Amboatany, where rice phytoliths are meagre, all other profiles situated on the middle-to-lower positions of the hillslope–valley systems contain relatively more rice phytoliths than other locations. It is therefore reasonable to suggest that rice farming was more likely to occur at middle-to-lower locations of these places, partly because of their better hydrological conditions to sustain rice farming. Of particular interest are the appearance of bulliform-type phytoliths from the epidermis of rice plant leaves, whose morphometric characteristics, especially the number of so-called fish scale parts, are considered to be a useful indicator of the rice plant's physiological response to field hydrological changes especially in prehistoric rice cultivation of China (for example, Huan et al. 2018). Although such a relationship must be applied with caution to the very different environmental and ecological contexts of ancient rice farming in Madagascar, it points to a fruitful field of research in order to understand how rice farming adapted to the distinctive soils and hydrologies on the highlands.

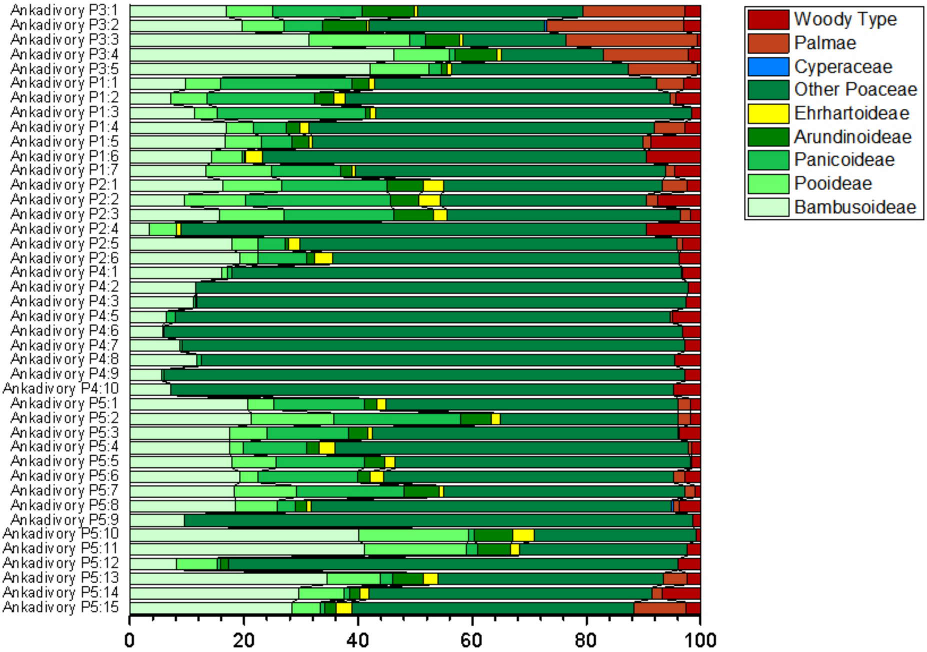

Figure 3 Percentages of different types of phytoliths identified from the Ankadivory site. Ehrhartoideae (yellow bands) refers to rice phytoliths. Note they are completely absent in samples from profile 4

In the thin section slides, the most common micromorphological features related to disturbance to soils through intensified land use include clay textural features caused by mobilisation of clay-sized particles and abundant micro-charcoal and organic matter (see Figure 2). These features are generally caused by the breaking down of soil structure (the soil slaking process) and the addition of heterogeneous material to the soil through repeated tilling, watering and other field farming practices (Macphail and Goldberg 2017). Aligning well with the phytolith evidence, many diagnostic features of intensified land use appear in the middle-to-lower positions of the hillslope–valley systems, indicating that these might be the places with the most intensive farming and other activities since 1000 BP, but particularly after 500 BP. This is not to suggest that other locations were not used. It might be that the intensity and pattern of land use between these places were different. The historical–ecological debate on where the hillslope–valley system was utilised for occupation and farming remains to be further understood.

Practices and problems of peri-urban water management

Associated with the two-season rice farming discussed earlier are two distinctive types of water management and labour organisation between the hillslope and floodplains on the highlands. Grown on the floodplains and marshy land during the dry season, the first-season rice relies on across-the-plain irrigation facilities for reliable yields. Oral history records that the first large-scale canals were built by King Andrianampoinimerina during the eighteenth century, which were used not only for irrigation but also transportation of goods, although there are also accounts of earlier dykes built by previous kings to drain the marshes and allow off-season farming. We might never be able to ascertain the exact date when the main canals running across the plains were built, even though some recent GIS-mapping activities have given new insights on the historical and spatial changes of irrigation structures and rice fields in and around Antananarivo (for example, Ramiaramanana and Teller 2021). Many canals still function well today. Our field surveys in winter (August) 2018 coincided with field preparation before initial early rice transplanting. The main canals running across and flanking the fields supplied water to these fields through small water outlets (see Figure 4). Releasing water from canals to the fields took place within days. At some villages, a combination of modern, concrete structures such as sluice gates and structures built by traditional materials and

Figure 4 Top left: simple, wooden structure barrage on the Mambakely River. Top right: small, temporary water outlet between fields at Amparafara. Middle left: vast rice fields that were just inundated with water released from canal, on low-lying plains near St Paul's Theological College at Ambatoharanana. Middle right: larger-sized barrage at Antaramanana, built of earth and wood, part of it already eroded. Lower: valley and hillslope cultivation and urbanisation, Antananarivo

techniques such as wooden or bamboo barrages were observed. On an even higher level of water system and corresponding social organisation (for example, larger rivers that flow through villages and towns) are different kinds of water control structures using traditional and contemporary techniques (see Figure 4). There is little doubt that a successful operation of this multi-levelled water management system requires effective collaboration between different levels of social organisation, but it faces enormous challenges (see Berg 1981). In addition to commonly encountered issues such as the responsibilities and costs of regular canal dredging and disputes between different villages and households on opening and closing time of canals, new problems have emerged. For instance, the ambiguity, inconsistency and ineffective implementation of local and national rules and laws on water and out-of-date land regulations fail to take into account conflicts of interest between different stakeholders, rendering communities unaware of, or even worse, vulnerable to future water problems. This is further exacerbated by increasingly common industrial water pollution (Bastaraud et al. 2020) and climate change.

The harnessing and utilisation of water on hillslopes, where second-season rice is usually grown, is of a smaller scale but of an equally complicated magnitude. Water here is mainly derived from rainwater in the form of surface runoff, with a few places where spring water is also available. On the top of the hillslope are ponds, which collect rainwater and can be used for first-season rice farming. Small ditches run along the two flanks of the hillslope–valley system, supplying water to the terraced fields. It remains unclear when the terraced fields were built. It is possible that they were built and rebuilt repeatedly. At profile 5 at Ambohidahy, a local farmer recalled his early family history in 1935 when the forest at the site was cleared but it is unclear how old the forest was and what its exact relationship was with the occupation of the site. Abundant sandy sediments, buried about 1 m below the surface in the middle of the valley, might have coincided with this event.

Pressures of urbanisation and lack of water management

That the contemporary landscape of Antananarivo and its surrounding peri-urban area is changing rapidly is an uncontroversial observation. Buildings are shooting up and paddy fields are disappearing. While a system to help urban planners preserve and expand rice cultivation has been developed (Aubry et al. 2012), how inhabitants experience, react to and plan for this change is unknown. We conducted a pilot study consisting of field observations and opportunistic unstructured interviews on a tributary of the Ikopa River in Antananarivo in August 2019. This pilot fieldwork was complemented by two purposeful interviews: one with the Director of Environmental Integration from the Ministry of Water; another with an elderly rice farmer and archaeologist.

Teh, Mr Ramilisonina and a local interpreter did a combination of walking and driving through the valley up to the middle hillslope where rice cultivation stopped (see Figure 4, lower). This was conducted in a criss-cross fashion, following roads and existing walking paths, observing local interactions with the landscape and evidence for recent and past urbanisation, resulting in nine opportunistic interviews with people working on the land. They were asked about their cultivation practices, the challenges that they face, the land use change they have observed and why it had happened.

From the observations of the walk and drive, it was clear that some pre-existing rice paddies were disused because they had been cut off from water sources or drainage. Some places that previously cultivated rice were now waterlogged and could only support the cultivation of cress. Other areas had dried out and the clay ground was used to make bricks, providing further material for urbanisation and less rice cultivation. Most of the fields were small and required manual labour for cultivation. Many plots also cultivated fruits, vegetables and sometimes included a pond to farm tilapia.

The nine unstructured interviews showed that all the people working on the land knew that the current water management system for agriculture was lacking. They could describe changes to their own and neighbouring fields. All nine respondents were aware of land use and their access to water had changed. The reasons given for the conversion of fields to buildings, peat digging and brick making was varied, besides fields becoming uncultivatable; some cited pressure to sell land from government officials; others the increased land value for building; and in one instance, the need for a school building. All respondents seemed resigned to the lack of water management and were focused on coping with whatever problem was at hand for them, rather than putting energy into developing a better system.

We conducted the interviews with the elderly rice farmer and archaeologist on his own cultivation plot. In addition to rice, he grew vegetables, bananas and raised tilapia. He also showed us how the bunds and water channels worked in a valley further from the city. He explained what the ecological cues were for planting *vary aloha*, crop rotation and permaculture practices. He also explained a complex system for the inheritance of land, which also affected the continuity of plot cultivation. Rice cultivation is labour-intensive work, and he felt that some fields were abandoned due to farmers becoming physically incapable of working the land with no younger people interested in the physically demanding work.

Despite younger generations being disinterested in rice cultivation, great emphasis was placed by families on the importance to have and consume their self-grown rice. As an aside, the farmer’s daughter observed that cultivation of the land held a lot of meaning for her father and contributed to his sense of wellbeing, identity and self-efficacy.

From central government, it was identified that there were many rules, but that they were neither implemented nor operationalised. The government focused on fixing problems after they had occurred rather than executing the policies they had set that may prevent problems from arising. It was also felt that there was a conflict between the Ministry of Water and citizens with what was seen as a water priority.

While rapid urbanisation is a worldwide phenomenon, local pressures alter the dynamics of this process. In this case the accelerant to urbanisation is the water requirement for the cultivation of rice. As plots become dry or waterlogged, they are vulnerable to urbanisation. However, the importance of rice and complementary aqua- and agriculture as a food source, as well as a culturally valued practice, decelerate the pace of urbanisation. If the inhabitants of Antananarivo wish to maintain their rich history and practices of rice cultivation in its valleys and hillslopes, new water management systems and new rice cultivars need to be developed in response to urban development and climate change.

Conclusion

The variation in local terrain and recently escalating climatic uncertainty have imposed significant challenges for the feasibility and sustainability of hillslope irrigation and farming practices. Recent studies have shown that the erratic and unreliable rainfall, combined with smallholder farmers' financial inability to invest and improve farming conditions, have significant impact on rain-fed rice farming on hillslopes of the highlands (Bruelle et al. 2014). Climate change has also started to have an impact on sowing and harvesting times and farmers' decisions to interact with these new challenges (for example, Randriamarolaza and Aguilar 2023). Better preparation for such challenges would require a more holistic understanding of the complex and dynamic interaction between patterns of hereditary land ownership, varying soil and hydrology for long-term farming and other related social and economic infrastructures such as why and how land value changes and deference to governmental policies occurs.

How could archaeological insights of past landscape change inform new ways to manage water, develop rice cultivars and evolve practices of rice cultivation in Antananarivo? The evolution and transformation of rice-farming landscapes in the Madagascar highlands is a fascinating but significantly understudied topic. Understanding these processes is crucial not only for the archaeology of the island of Madagascar, as an important node in the broader Indian Ocean trading network, through which rice, goods and populations migrated, but also for the ecological conservation and sustainable development of the area around Antananarivo where rapid urbanisation and intensified land use have imposed critical challenges for both society and the environment. Our preliminary results highlight the complex ecological feedback mechanisms between land use practices and hillslope–valley systems at different sites archaeologically. It is not as simple a story as geomorphologists and other environmental scientists have proposed for the Madagascar highlands (for example, Cox et al. 2009) – that erosion, regardless of the severity, would often lead to irreversible hillslope degradation. Rather, the outcome really depends on the timing, intensity, location and other factors influencing the erosion events. Moreover, while phytolith studies have provided evidence for rice farming across the highlands, many questions remain to be answered. First, a local phytolith reference collection, with samples collected from different habitats, needs to be established to enhance the interpretation of these phytolith results. Second, more robust identification criteria and statistical analysis of archaeological phytoliths are also required, alongside other unsolved issues.

Our pilot geoarchaeological investigation represents an essential shift in recent research, expanding the focus on settlement archaeology and material evidence of regional interactions to reconstructing the environmental and ecological foundations of these important developments that transformed the natural and cultural landscape of the highlands. Achieving this requires careful coordination and collaboration during planning and execution of fieldwork, and integrated sampling processing and analysis. Equally valuable was our experiment to combine archaeology with urban design. While our interviews focused primarily on local farmers' awareness and views about water uncertainties, and only briefly touched on other stakeholders and policies that may have influenced the development of resilient water management practices, our findings revealed both the enormous challenge and potential to develop functional and sustainable ways of utilising and conserving diverse water habitats for people in the present and future.

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Declarations and conflicts of interest

Research ethics statement

Not applicable to this article.

Consent for publication statement

Not applicable to this article.

Conflicts of interest

The authors declare no conflicts of interest with this article. All efforts to sufficiently anonymise the authors during peer review of this article have been made. The authors declare no further conflicts with this article

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