Sorghum and finger millet cultivation during the Aksumite period: insights from ethnoarchaeological modelling and microbotanical analysis.

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ABSTRACT

For centuries, finger millet (*Eleusine coracana* Gaertn.) and sorghum (*Sorghum bicolor* (L.) Moench) have been two of the most economically important staple crops in the northern Horn of Africa. Nonetheless, their agricultural history is poorly documented due to preservation issues faced by macrobotanical remains and the small number of systematic archaeobotanical research programs in the region. In this paper, we explore the potential extent of finger millet and sorghum agriculture in the northern Horn of Africa region during the Aksumite Kingdom (ca. 50 BCE-CE 800), that is, the period when finger millet and sorghum are first documented in the macrobotanical record. To do so, we employ a methodology that combines cross-cultural modelling, ethnoarchaeology and phytolith analysis. Together, these proxies allow us to propose and test hypotheses about past agricultural practices in the northern Horn. According to our models, the agriculture of finger millet and sorghum was possible around the main Aksumite sites in the region, likely under extensive-rainfed cultivation regimes. These results are supported by the phytolith assemblage from Ona Adi, which records the presence of water-stressed Panicoideae and Chloridoideae grasses since the beginning of the site's occupation during the Late Pre-Aksumite period (ca. 600-400 BCE).

Keywords: C4 agriculture, cross-cultural modelling, ethnoarchaeology, phytoliths, Kingdom of Aksum, Horn of Africa.

Introduction

Over 500 million people are thought to be fed globally by sorghum (*Sorghum bicolor* (L.) Moench) and finger millet (*Eleusine coracana* Gaertn.). These are drought-resistant crops that can grow in a variety of environmental conditions, including regions with poor soils and erratic rainfall (Ruiz-Giralt et al. 2023a). In the northern Horn of Africa, finger millet and sorghum have been cultivated since at least the Aksumite period, ca. 1,500 years ago, and represent a significant component of local agricultural economies, as they are well-suited to the semi-arid climate of the region. Despite their long presence in the northern Horn, little is known about the beginnings of the agricultural history of these crops in the region, even though mentions of finger millet and sorghum as indigenous to the Horn of Africa are present in the literature of the 20th century (e.g., Vavilov 1926, 1951, Harlan 1969, 1971, Dogget 1991) and the specific area in which they were first domesticated has been extensively debated (e.g., Harlan and Stemler 1976, Hilu and de Wet 1976, and references therein). Recent evidence has built some consensus around eastern Sudan as the area of domestication of sorghum (see Winchell et al. 2018), whereas the domestication locale of finger millet remains unclear – although most authors recognize the highlands of eastern Africa, including the Ethiopian and Eritrean highlands as the most likely area of domestication (see Fuller and Hildebrand 2013, Fuller 2014). The earliest available archaeological evidence of finger millet and sorghum in the highlands of northern Ethiopia and Eritrea dates to the 1st and 3rd centuries CE respectively. On the one hand, carpological evidence of finger millet has been documented at Ona Nagast (D'Andrea 2008), where one grain has been identified in deposits from the Early Aksumite phase (ca. 50 BCE-CE 150). Sorghum, on the other hand, has only been documented after the 3rd century CE at Aksum: one grain was found at the Tomb of the Brick Arches (dated from cal. CE 239-561) and, it has been interpreted by Boardman (2000) to date to the Classic Aksumite period (ca. CE 150-330). Another seed was found in the Late Aksumite deposits from the D-site in Aksum (ca. CE 500-700). Despite the limited number macrobotanical remains, isotopic analysis on human remains of one individual from Etchmare East (dated from cal. 465-197 cal. BCE) have shown C$_4$ plants to represent 20% of their diet (D'Andrea et al. 2011). More recently, phytoliths of Panicoideae (C$_4$ grass subfamily including sorghum) and Chloridoideae (C$_4$ grass subfamily including finger millet), as well as starch grains associated with the Andropogoneae (Panicoideae tribe including sorghum) and Eragrostideae (Chloridoideae tribe including finger millet and t'ef) tribes have been found in the microbotanical records from Mezber and Ona Adi, demonstrating that these grasses were continuously exploited from the Initial Pre-Aksumite phase at Mezber (ca. 1600-900 BCE) to the abandonment of Ona Adi (ca. CE 700) and the subsequent Post Aksumite occupation of the site (Ruiz-Giralt et al. 2023b). These proxies, however, cannot generally identify plants to the species level, and more research is needed on the phytolith and starch production of the C$_4$ wild members of these subclades to securely identify specimens to the genus level (however, see Liu et al. 2019, Lucarini and Radini 2020).

The scarcity of carpological evidence of C$_4$ small-seeded cereals, as well as recurrent inconsistencies in the presence of these crops between macro- and microbotanical assemblages in different parts of the world (e.g., Liu et al. 2014, Madella et al. 2014, Lucarini et al. 2016, Out et al. 2016, Laugier et al. 2022), have shown the importance of developing alternative approaches to study the history of these cereals in the archaeological record (see Madella et al. 2016). The preservation issues of finger millet and sorghum except in extreme conditions (e.g., desert environments, see Mercuri et al. 2018, Beldados 2019) have long been recognized (see Young and Thomson 1999). Indeed, experimental studies have shown that finger millet seeds rarely survive temperatures over 250-300°C (Terefe and Beldados 2021, Mueller et al. 2022), while the identification of sorghum remains is significantly hindered after being exposed to 300-350°C (Varalli et al. 2023, Beldados and Ruiz-Giralt in review). Even when they survive, the degree of charring and the moisture content of the grains can greatly impact their preservation (Wright 2003, 2014). Other authors have highlighted the importance of cereal processing activities in the survival of these crops: for example, Young and Thomson (1999) noted that cereals such as sorghum and finger millet are generally underrepresented in archaeological deposits, as they do not need to be parched before pounding to release the grain from the chaff because they are dried under sunlight rather than over a fire. In this regard, Lyons and D'Andrea (2003) were told by local informants from Tigrai (northern Ethiopia) that only wheat, barley and chickpeas are commonly roasted for consumption. Sorghum is sometimes roasted, but finger millet grains are never exposed to fire. Further, both cereals are commonly used in traditional brewing, which involves the baking of flour but never of grains (see Lee et al. 2015, Wayessa et al. 2015). Fuller and Stevens (2018) note that the biggest challenge for the study of the history of sorghum in Africa has been the small number of systematic archaeobotanical sampling programs as

well as poor preservation at some African sites, the latter worsened by the effect of bioturbation in tropical soils. These same considerations can be extended to finger millet.

In this paper, we focus on the agriculture of finger millet and sorghum during the Aksumite period in the northern Horn of Africa. We aim to explore whether the cultivation of these crops was feasible around the main Aksumite archaeological sites identified to date, and to investigate potential agricultural practices, including cultivation intensity and watering regimes, that might have been in place based on the surrounding environmental conditions. We approach these issues using a combined methodology that includes ethnoarchaeological modelling and phytolith analysis. To do so, we have developed the following workflow (Figure 1): 1) creation of models on traditional agrosystems using available ethnographic literature, 2) cross-validation of the models using first-hand ethnographic data from the study area, 3) application of the model to archaeological sites from the Aksumite period, and 4) evaluation of the results by comparison with the phytolith data from one of the analysed sites. This approach is based on the theoretical consideration that, by examining the main environmental factors influencing modern traditional agrosystems, we can improve our understanding of past agricultural practices. This is because traditional agrosystems are often the result of very long-term processes of ecological adaptation that have resulted in highly resilient socio-ecological systems known to have been in place for hundreds or thousands of years. Even though it is true that sociocultural phenomena often play a role in shaping traditional agriculture, we argue that human communities can only adopt a finite number of agricultural solutions under specific ecological conditions and with a specific set of technological implementations, regardless of culturally imbued preferences (Ruiz-Giralt et al. 2023a).
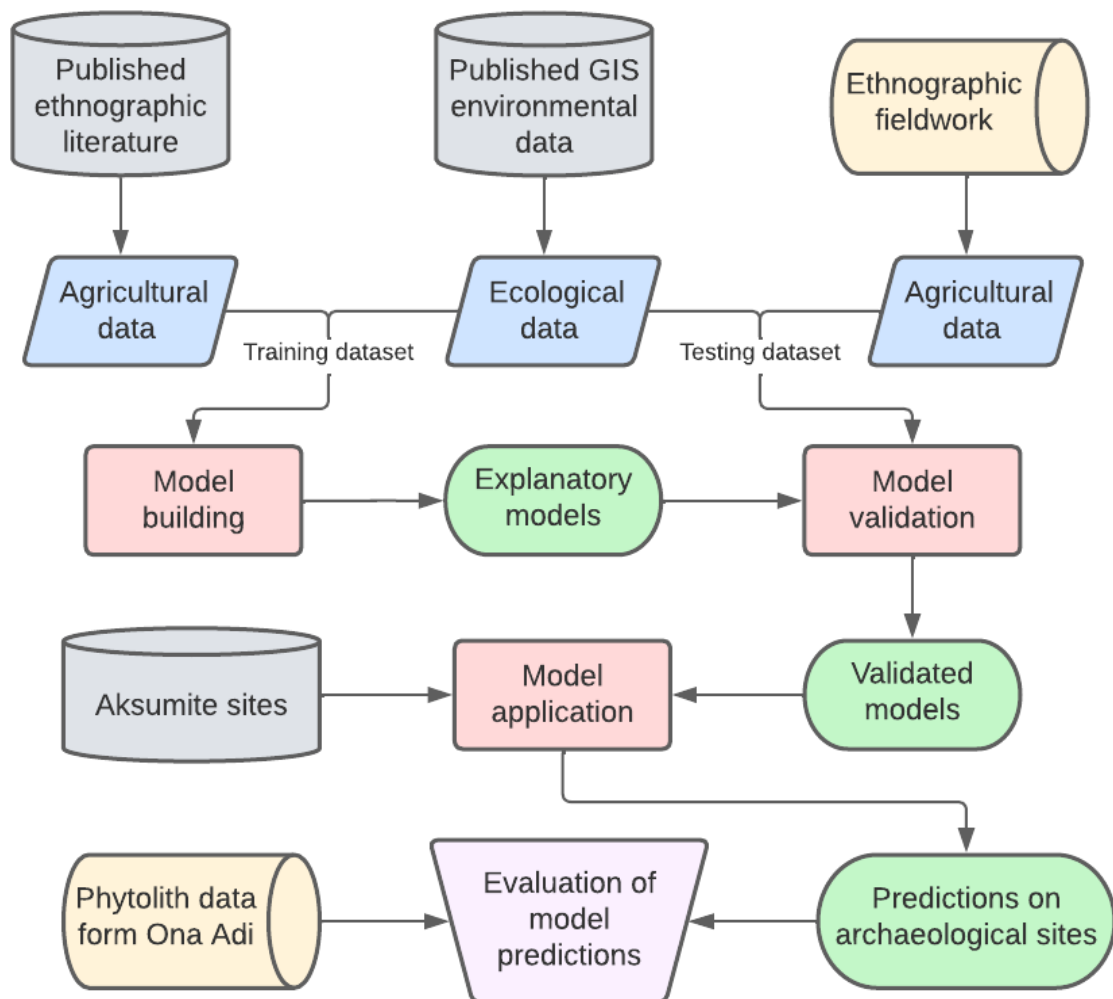

Figure 1 - Workflow used in this study. Grey boxes represent previously published data. Yellow boxes contain new data. Blue shapes represent datasets. Processing data steps in R software 4.2.2 (R Core Team 2021) are red rectangles. Green shapes represent the results of R processing.

Study area

Environmental setting of the highlands

The highlands of northern Ethiopia and Eritrea are nowadays characterised by an arid to semi-arid climate (Aridity Index ranges from 0.098 to 0.652, Hagos et al. 2019) and strong seasonality, with a primary rainy season from mid-June to mid-September. The landscape of the area is dominated by an irregular plateau ranging from 1,000 to 3,500 metres above sea level (masl) resulting from the volcanic activity associated with the East African Rift. These topographic variations have produced a mosaic of microclimates within very short distances, which show significant variation in temperature (annual means vary between 15 and 25ºC) and rainfall (annual means ranging between 500 and 750 mm per year). The region is known to have experienced significant environmental changes during the Late Pleistocene, showing a general tendency towards aridification that extended until the East African Humid Period (ca. 9000-3600 BCE), when a climatic optimum was reached (Hoelzmann et al. 2004, Nyssen et al. 2004). Despite the prevalence of wet conditions during these moister millennia, dry events also occurred (e.g., Marshall et al. 2011), eventually leading to a period of landscape instability and reduced precipitation that extended until ca. 2200 BCE (Lanckriet et al. 2017). It was during this time that the present-day climatic conditions were established, following a last abrupt change in the region's ecological conditions between 5,000-4,000 years ago (Tierney and de Menocal 2013). Since then, climate conditions remained relatively stable, showing alternating periods of landscape degradation and recovery occurring at the local level (see Bard et al. 2000, Darbyshire et al. 2003, Sulas et al. 2009, Ruiz-Giralt et al. 2021). Although Machado et al. (1998) considered that these fluctuations were the result of increased aridity, more recent studies by French et al. (2009, 2017) have argued that significant landscape degradation did not uniformly occur until the 15th or 16th centuries. Indeed, analysis of stable isotopes have shown no indication of widespread, major alterations in climate in the region during the Pre-Aksumite (1600-50 BCE) and Aksumite (50 BCE-CE 700) periods (Terwilliger et al. 2011, 2013). Instead, landscape modification during these centuries appears to be related to land clearing practices associated with agricultural activity (Terwilliger et al. 2011, 2013, French et al. 2017, Blond et al. 2021, Ruiz-Giralt et al. 2021).

Human occupation and subsistence economies during the Aksumite period (50 BCE-CE 700)

The Kingdom of Aksum originated during the late-1st millennium BCE in the Aksum area, specifically on Bieta Giyorgis hill, which was the centre of a polity known as "Proto-Aksumite" (400-50 BCE) (Fattovich and Bard 2001). By 50 BCE, the focus of political power shifted from the hilltop to the plain in the south, marking the beginning of the Aksumite Kingdom (Fattovich 2010, 2019, Phillipson 2012). Despite being a small kingdom at the beginning of the Common Era, its regional and interregional influences were rapidly consolidated, extending its political and economic control towards the Red Sea, the Eastern Desert, and possibly the Upper Nile Valley, and incorporating previously distinct populations (Phillipson 2012). Further territorial expansion occurred during the 3rd century CE and following periods, when various Aksumite kings annexed surrounding regions as far as the Red Sea coastal plain and extended to the Middle Nile region and South Arabia. Aksum developed into an increasingly centralised state which adopted Christianity in the early-4th century CE (Fattovich 2019). In this regard, several systematic surveys during the last 20 years (Michels 2005, Schmidt et al. 2008a, Sernicola 2008, D'Andrea et al. 2008, Sernicola and Phillipson 2011, Harrower and D'Andrea 2014, Gaudiello and Yule 2017, Benoist et al. 2020, Harrower et al. 2022) have identified the presence of Aksumite sites over much of present-day region of northern Ethiopia and Eritrea, suggesting that the Aksumite territory comprised the entire highlands of the northern Horn of Africa, from the Red Sea coast and the edge of the Rift Valley in the East, to the Rora Laba mountain in northern Eritrea, the Tekeze River in western Tigrai and the Amba Alagi mountain in southern Tigrai (Fattovich 2010, 2019).

The territory controlled by the Aksumite kingdom was exceedingly diverse. The results of intensive archaeological surveys and excavations demonstrate a pattern of occupation characterised by the absence of a strong political centre of settlement articulation (Schmidt 2009, Curtis 2010, Harrower and D'Andrea 2014, Graniglia et al. 2015, Harrower et al. 2022). Geospatial analysis of Aksumite settlement patterns points to a general lack of spatial clustering and site-size hierarchies, suggesting a heterarchical rather than hierarchical pattern of political organisation (Harrower and D'Andrea 2014, Harrower et al. 2022). In this regard, Harrower et al. (2022) have shown that, besides the capital city of Aksum, other large urban sites such as Ona Adi, Matara, Wakarida, and Beta Samati also acted as local centres of settlement organisation during the Aksumite period, surrounded by an increasing number of hamlets and villages as a result of significant population growth

(Harrower et al. 2022). A similar situation was probably extended to the city port of Adulis (Peacock et al. 2007, Zazzaro et al. 2014), as well as to other important Aksumite sites such as Adi Ahoune (Anfray 1973, Godet 1977, D'Andrea et al. 2008), Qohaito (Wenig and Curtis 2008, Wenig 2010), Qwiha (Breton and Ayele 2018), Enda Sellassie (Finneran and Phillips 2005, Moy 2019), Hawelti-Melazo (Menn 2020), Emba Derho (Schmidt et al. 2008b), Agoula (Anfray 1970), Debarwa (Littmann et al. 1913 cited in de Contenson 1961), Daqqa Mahare (Littmann 1907) and Edaga Hamus[1]. Further GIS-based settlement pattern analyses in eastern Tigrai have shown statically significant associations between sites and their surrounding environment, including preferential selection of sediment slope and valley bottom landform classes as well as water-rich areas with greater agricultural potential (Harrower and D'Andrea 2014). An analogous situation has been recorded in central Tigrai by Sernicola (2008, Sernicola and Sulas 2012), where a settlement preference for altitudes over 2,000 masl has been recorded. According to Harrower and D'Andrea (2014) such conditions offered increased agricultural productivity for cultivation and grazing, but they would have also mitigated the risks of periodic drought.

Subsistence was based on the agriculture of Near Eastern C$_3$ cereals (including emmer wheat (*Triticum dicoccum* L.), free-threshing wheat (*Triticum durum* L. and *T. aestivum* L.), barley (*Hordeum vulgare* L.), linseed/flax (*Linum usitatissimum* L.) and lentil (*Lens culinaris* Medik.), which were combined with indigenous crops, including finger millet and sorghum, as well as t'ef (*Eragrostis tef* (Zucc.) Trotter), noog (*Guizotia abyssinica* (L.f.) Cass.), and possibly the semidomesticated Ethiopian oat (*Avena abyssinica* Hochst.) (Boardman 2000, D'Andrea 2008, Meresa 2017, Delle Donne 2021, Ruiz-Giralt et al. 2023b). It is worth noting that the Pre-Aksumite emphasis on cereal agriculture shifted during the Aksumite period as an important range of pulses – namely, chickpeas (*Cicer arietinum* L.), horse bean (*Vicia faba* L.), grass pea (*Lathyrus sativus* L.), and pea (*Pisum sativum* L.) – and geophytes – including members of the Brassicaeae, Zingiberaceae and possibly Dioscoreaceae families – as well as other economic crops such as cress (*Lepidium sativum* L.), gourds (Cucurbitaceae), cotton (*Gossypium* sp.) and grapes (*Vitis* sp.) were introduced (Boardman 2000, D'Andrea 2008, Meresa 2017, Ruiz-Giralt et al. 2023). Regarding agricultural practices, woodland clearance was carried out to open new agricultural crop fields (Terwilliger et al. 2011, Ruiz-Giralt et al. 2021), although the extent of such activity remains unknown. According to Sulas et al. (2009, Sulas 2014, 2018), Aksumite farmers engaged in a cultivation cycle governed by a bi-modal climate with long dry seasons and short rainy periods that allowed farmers to engage in other productive activities during several months each year. In this sense, some scholars have speculated that such labour cycles might have been controlled by the central state (Sulas et al. 2009, Sulas 2014), in relation to long-distance trade based on the exploitation of natural resources over a wide area, together with control of labour on an unprecedented scale (Phillipson 2012). Regarding animal husbandry and herding activities, the zooarchaeological record is dominated by domesticated bovids (including cattle, sheep and goat) and chicken (Cain 2000). Information derived from inscriptions and rock art highlight the importance of cattle in Aksumite agriculture as work animals (Finneran 2007: 93). It is noteworthy that recent studies have found no indication that large-scale irrigation was in practice during the Aksumite period (Sulas et al. 2009, Sulas 2014, 2018, Harrower et al. 2020), contrary to earlier hypothesis (Kobishchanov 1979, Butzer 1981, Bard et al. 2000, Michels 2005). As noted by Harrower et al. (2020), the available archaeological evidence indicates that irrigation played a supplemental role (if any) rather than a central role in Aksumite agriculture. Instead, authors argue that Aksumite populations were able to thrive by utilising rainfed agriculture, terraces, and small-scale irrigation techniques (mostly used for horticulture) that are similar to the ones still in use in the region today (Harrower et al. 2020, see also Biagetti et al. 2022).

Study case: Ona Adi

The site of Ona Adi is situated close to the modern villages of Menabeity and Etchmare, in Tabia Shewit Lemlem, at an altitude of 2,452 masl. The pottery recovered from the site reveals five phases of occupation: 1) Mid/Late Pre-Aksumite (ca. 750-400 BCE), 2) Pre-Aksumite to Aksumite (PA-A) transition (ca. 400 BCE-CE 1), 3) Early Aksumite (ca. CE 1-330), 4) Middle Aksumite (ca. CE 330-500) and Late Aksumite (ca. CE 500-700)

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[1] Edaga Hamus refers to a large Aksumite settlement (ca. 19.9 ha) recorded around the church of Ta'kot Debre Tsion (Tigrai, Ethiopia). It likely represents a major settlement centre at least during Classic Aksumite times, ca. CE 150-330.

(Mekonnen 2019: 339). Ona Adi is one of a few sites known to have been occupied during the PA-A transition, a time of cultural transformation that witnessed leadership changes and the abandonment of settlements in the regional centres of Yeha and Aksum (D'Andrea et al. 2008). Archaeological excavations by the Eastern Tigrai Archaeological Project (ETAP) (D'Andrea et al. 2008) have identified Ona Adi as an Aksumite urban centre, covering a total area of approximately 10 hectares (Harrower and D'Andrea 2014). The site has buildings with stepped wall construction and ceremonial pottery that suggest the presence of elite residences. The ceramics, lithics, and grinding stones recovered at the site demonstrate the advanced technical knowledge of artisans who had honed their craft. Two coins depicting Aksumite kings were also discovered, possibly indicating the presence of one or more leaders of the heterarchical polities that appeared during the Aksumite period.

Carpological analyses by Meresa (2017) have shown a diverse assemblage that included both domestic and wild plant species: the domesticated fraction comprises wheat, barley, lentil, flax, noog, t'ef, and finger millet, whereas the weeds and wild species assemblage was dominated by indeterminate Poaceae and *Lolium* sp, (Meresa 2017). It is worth noting that the presence of t'ef and finger millet was only attested after the Early and Late Aksumite periods respectively. By contrast, the results of phytolith analysis from grinding stones have recorded a clear predominance of C_4 morphotypes (30 to 40%) over C_3-related morphotypes (1 to 5%) – note that 60% were classified as herbaceous indeterminate (Poaceae/Cyperaceae) (see Ruiz-Giralt et al. 2023b for further details). Microbotanical analysis have also recorded the presence of starch grains associated to grasses from the subfamilies Panicoideae (including Andropogoneae and Paniceae types), Pooideae and Chloridoideae (including an Eragrostideae type), as well as legumes and various geophytes, which were being consistently processed at Ona Adi throughout the entire occupational sequence of the site (Ruiz-Giralt et al. 2023b).

Materials and methods

Ethnoarchaeological models

Global models on crop selection, finger millet (FM) and sorghum (SB) cultivation by Ruiz-Giralt et al. (2023a) were applied to assess FM and SB agriculture in the northern highlands of Ethiopia and Eritrea. These models were constructed using data from ethnographic literature on traditional agrosystems around the world, and they study the interaction between environmental variables and agricultural practices. Training datasets were obtained from Ruiz-Giralt et al. (2023a, S1 Appendix, Table S3), which extracted physio-climatic and edaphic data from published GIS data (Zomer et al. 2008, Hiederer and Köchy 2011, Estima et al. 2013, Shangguan et al. 2014, EROS 2017, Fick and Hijmans 2017). All training response datasets were transformed using Hellinger's transformation (Legendre and Gallagher 2001, Legendre and de Cáceres 2013), whereas the explanatory datasets were standardised (by subtracting the variable mean to each value and then dividing it for the standard deviation) to create comparable scales. The crop selection model was used to assess cultivation viability of FM and SB. The original models in Ruiz-Giralt et al. (2023a) included pearl millet (*Pennisetum glaucum* (L.) R.Br), which was excluded from the response dataset as its cultivation has not been recognized in the study region. The models on FM and SB agriculture were applied to investigate cultivation intensity (casual, extensive, or intensive agriculture) and watering regimes (rainfed, flood or irrigated agriculture) (Table 1). All models were computed following the methodology applied by Ruiz-Giralt et al. (2023a): Redundancy Analysis (RDA) (Legendre and Legendre 2012) with adjusted-R2-based forward selection (FS) (Blanchet et al. 2008) was used to identify and select significant explanatory variables and reduce collinearity. Linear trend (LT) and distance-based Moran's eigenvector maps (dbMEM) analyses were performed to test for spatially structured variance (Borcard et al. 1992, 2004, 2018, Legendre et al. 2012). The statistical significance of all models and submodels was tested by 1000 permutations.

Table 1 - Definitions of agricultural practices considered in this study.

Variable	Definition	References
Casual Agriculture	Slight or sporadic cultivation of food or other plants incidental to a primary dependence upon other subsistence practice	Murdock 1981: 98
Extensive Agriculture	Or shifting cultivation, as where new fields are cleared annually, cultivated for a year or two, and then allowed to revert to forest or brush for a long fallow period	Murdock 1981: 98

Intensive Agriculture	On permanent fields, utilizing fertilization by compost or animal manure, crop rotation, or other techniques so that fallowing is either unnecessary or is confined to relatively short periods	Murdock 1981: 98
Rainfed Agriculture	Water is provided by rainfall alone (directly or as run-off), cultivation occurs far from any permanent water sources and without any water harvesting	Lancelotti et al. 2019: 1027
Décrue Agriculture	Or floodplain cultivation, as where water is provided by natural inundation, typically from major river systems.	Lancelotti et al. 2019: 1027
Irrigated Agriculture	Water is provided to crops at regular intervals throughout the growing season by human intervention	Lancelotti et al. 2019: 1027

The reduced models were first evaluated by assessing their capacity to blindly predict their own training dataset using performance measures: accuracy (correctly classified entries / total number of cases), precision (positive samples that were correctly classified / total number of positive predicted cases), recall (positive entries correctly classified / total number of positive cases), and F1-score (evaluation of the classification performance through calculation of the harmonic mean of precision and recall) (Tharwat 2018). Model fitting predictions were classified as 0 or 1 using various classification thresholds (CT) calculated on the training data, including: 1) sensitivity-specificity equality approach (Sens=Spec), 2) sensitivity-specificity sum maximisation approach (MaxSens+Spec), 3) overall prediction success maximisation approach (MaxPCC), 4) predicted-observed prevalence equality approach (PredPrev=Obs), and 5) the ROC plot-based approach (MinROCdist) (see Manel et al. 2001, Liu et al. 2005, Nenzén and Araújo 2011 for further details). F1-score was used to choose between CTs. Second, the models were cross validated against ethnographic data from Tigrai (27 semi-structured interviews conducted during May-June of 2019, see Biagetti et al. 2022 for further details) to evaluate the model's performance at a local level in the region. The environmental datasets used for the Tigrayan interviewees were generated utilising an area of 50-km radius from the GPS coordinates of their respective households as noted by Ruiz-Giralt et al. (2023a). The selection of this area was based upon information provided by the interviewees regarding the location of their cultivated fields, which ranged from 0 to 40-50 km from their homes (Biagetti et al. 2022). The testing explanatory dataset was standardised before predictions, using the mean and standard deviation of the training dataset in order to preserve data structure and distribution (Hastie et al. 2009). The same methods detailed above were applied to formulate and evaluate the predictions on the ethnographic data.

After cross-validation, the three models (crop choice, FM cultivation and SB cultivation) were applied to the core region of the Aksumite Kingdom, the highlands of northern Ethiopia and southern Eritrea, specifically to the main Aksumite sites listed by Fattovich (2019) complemented by some more recently investigated sites such as Qwiha (Breton and Ayele 2018) and Beta Samati (Harrower et al. 2019). The studied sites included Ona Adi, Aksum, Beta Samati, Matara, Adulis, Wakarida, Adi Ahoune, Qohaito, Qwiha, Enda Sellassie, Hawelti-Melazo, Edaga Hamus, Agoula, Debarwa, Daqqa Mahare and Emba Derho (Figure 2). The area of analysis was established at 1, 5, 10, 25, 50, 100 and 200 km around the geographical position of the archaeological sites to evaluate different spatial scales. The same explanatory dataset of subactual environmental variables used by Ruiz-Giralt et al. (2023a) was employed, as the last abrupt change in the region's ecological conditions occurred ca. 4,500 years ago, before the chronology considered in this study (see above). The same methods detailed above were applied to formulate predictions on the archaeological sites. Presence-absence predictions were made using the CT with the best performance measures when classifying ethnographic cases (MaxPCC, see Table 2 below). Statistical analyses were executed using R software 4.2.2 (R Core Team 2021). The full code and data (Supplementary Information, Datasets 1 and 2) are available at https://doi.org/10.5281/zenodo.7859673.
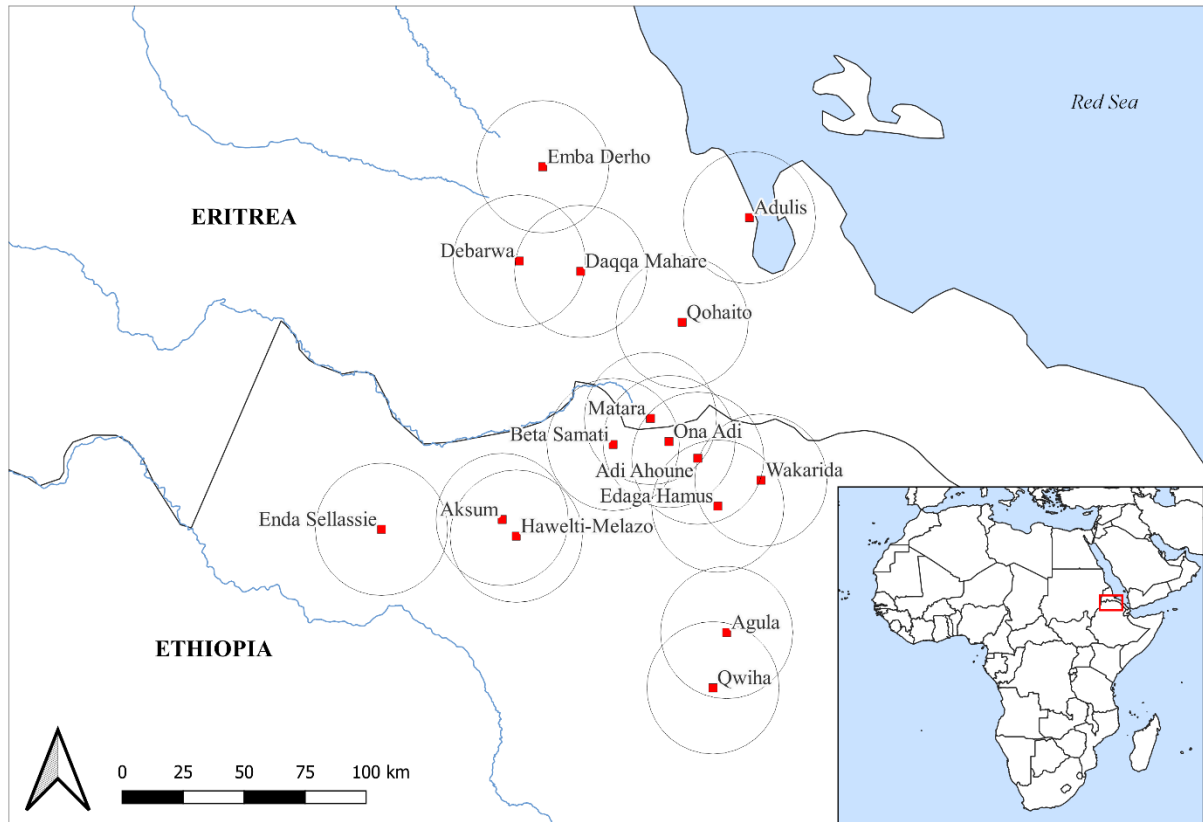
Figure 2 - Map of the sites included in the model represented with the areas within a 25-km radius.

Phytoliths

A total of 46 phytolith samples from Ona Adi were analysed. Samples were selected according to stratigraphical criteria to cover the entire occupational sequence of the site, including contexts characterised as fills, middens, floors, and ash accumulations. Phytoliths were extracted following the protocol described by Madella et al. (1998), adapted to reduce the effect of highly concentrated chemicals during long periods of exposure following Cabanes et al (2011) (e.g., concentration of hydrochloric acid reduced to 5%), and to calculate the Acid-Insoluble Fraction (AIF) (Albert and Weiner 2001). Sonication was introduced during the removal of soil organic matter and clay with hydrogen peroxide and sodium hexametaphosphate, respectively, in order to facilitate their separation from the mineral fraction as proposed by Lombardo et al. (2016). Phytolith slides were prepared with a permanent medium (Entellan®), and they were analysed and photographed using a Euromex iScope microscope at 400x magnification with an Euromex scientific camera sCMEX-6. Phytolith descriptions were conducted according to the International Code for Phytolith Nomenclature (ICPN) 2.0 (Neumann et al. 2019). A minimum of 250 single cell phytoliths were identified in each sample and multicell phytoliths (silica skeletons) were counted separately. Taxonomical and anatomical interpretations follow Ruiz-Giralt et al. (2023b). Pearson's correlation coefficient between phytolith concentration and number of morphotypes identified was utilised as an indicator for the impact of taphonomic processes on the phytolith assemblages (Madella and Lancelotti 2012). Kruskal-Wallis H test was used to analyse differences between samples grouped by archaeological phase and type of context.

An adaptation of the experimental model for assessing plant water availability on C_4 plants by D'Agostini et al. (2023) was implemented to assess watering practices at Ona Adi. This model was built using the modern phytolith assemblages from leaves extracted from five traditional landraces each of finger millet, pearl millet and sorghum experimentally grown under different watering conditions (see D'Agostini et al. 2022 for further details). Using stepwise selection in a binomial Generalised Linear Model (GLM), D'Agostini et al. (2023) identified blockies, stomata and polylobate phytoliths as the best explanatory variables (stepwise AIC = 84.51) to establish if archaeological phytolith assemblages derive from well-watered (WW) or water stressed (WS) crops. In the experimental assemblage, blocky phytoliths were identified as the phytoliths formed by

precipitation of silica in bulliform cells of the leaves. In the present study, however, the blocky morphotype also included silicified cells other than leaf bulliforms (for further discussion see Ruiz-Giralt et al. 2023b, Supplementary Information) as it is common in archaeological contexts (Neumann et al. 2019). Therefore, blockies were excluded from the experimental training data. As a result, the stepwise selection included saddle, cross and polylobate as the best predictors (stepwise AIC = 54.52). When applying the model to the archaeological samples, all morphotypes uniquely belonging to C_3 species and all morphotypes exclusively produced in inflorescences were excluded from the archaeobotanical dataset to obtain a dataset comparable with the experimental one, as recommended by D'Agostini et al. (2023). All statistical analyses were performed using R software 4.2.2 (R Core Team 2021). The full code and data (Supplementary Information, Datasets 3 and 4) are available at https://doi.org/10.5281/zenodo.7859673.

Results

Model building and cross-validation

The results of RDA with adjusted-R2-based FS showed that the new crop selection model retains 44.9% of the total inertia. The most significant predictors identified included mean altitude, mean topsoil pH (0 to 0.3 metres), variance of subsoil pH (0.3 to 2.5 metres), mean precipitation concentration index and mean topsoil volumetric water content at -10 kPa. All variables were found to be statistically significant and showed no collinearity. LT and dbMEM analyses showed no spatial patterns in the training dataset. Regarding FM and SB cultivation models, the full results are reported by Ruiz-Giralt et al. (2023a). On the one hand, the most important variables for finger millet cultivation included mean subsoil sulphur content, mean precipitation concentration index and topsoil mean phosphorus content (adjusted R2 = 0.61). On the other hand, sorghum cultivation was found to be determined by the mean of growing cycle duration, the variance of both topsoil and subsoil cation exchange capacity and the mean soil organic carbon (adjusted R2 = 0.24). All variables were identified as statistically significant and showed no collinearity nor spatial patterns.

At validation, all the reduced models were found to be well fitted using different classification thresholds – meaning that they could predict their own training datasets despite drastically reducing the number of explanatory variables. In all cases, the MaxPCC approach showed to be the best CT for model fitting (Table 2). Using MaxPCC, all models achieved over 85% accuracy and showed the highest classification strength (F1-score), ranging from 0.84 to 0.95. A similar situation was observed during model cross-validation against ethnographic data from Tigrai, as all models reached their highest accuracy and classification strength with the MaxPCC approach. For crop selection, the model was able to correctly predict 89% of the ethnographic cases. Despite not scoring the highest true positive rate, the model was able to identify all the positive cases, hence showing the highest classification strength using the MaxPCC approach (F1-score = 0.94). In the case of FM cultivation, all performance measures scored slightly below 0.5. This is because the model failed to predict cultivation intensity in all testing cases even though it correctly predicted 96% of the watering regimes. Finally, the SB cultivation model correctly predicted 98% of the testing cases, also showing the highest classification strength (F1-score = 0.98).

Table 2 - Performance measures of model fitting and cross-validation using different classification thresholds (Acc. = Accuracy, Prec. = Precision, Rec. = Recall, F1 = F1-Score).

Model	Method	Model fitting				Cross-validation			
		Acc.	Prec.	Rec.	F1	Acc.	Prec.	Rec.	F1
Crop choice	Sens=Spec	0.77	0.84	0.75	0.80	0.63	0.89	0.67	0.76
	MaxSens+Spec	0.81	0.94	0.73	0.82	0.54	0.93	0.52	0.67
	MaxPCC	**0.85**	**0.85**	**0.92**	**0.88**	**0.89**	**0.89**	**1.00**	**0.94**
	PredPrev=Obs	0.82	0.86	0.84	0.85	0.89	0.89	1.00	0.94
	ObsPrev	0.76	0.93	0.64	0.76	0.54	0.93	0.52	0.67
	MinROCdist	0.81	0.91	0.74	0.82	0.54	0.93	0.52	0.67
FM cultivation	Sens=Spec	0.95	0.95	0.95	0.95	0.49	0.48	0.49	0.48
	MaxSens+Spec	0.95	0.95	0.95	0.95	0.49	0.48	0.49	0.48

	MaxPCC	**0.95**	**0.95**	**0.95**	**0.95**	**0.49**	**0.48**	**0.49**	**0.48**
	PredPrev=Obs	0.95	0.95	0.95	0.95	0.49	0.48	0.49	0.48
	ObsPrev	0.62	0.75	0.35	0.48	0.4	0	0	0
	MinROCdist	0.95	0.95	0.95	0.95	0.49	0.48	0.49	0.48
SB cultivation	Sens=Spec	0.8	0.67	0.78	0.72	0.73	0.6	0.67	0.63
	MaxSens+Spec	0.78	0.63	0.85	0.72	0.71	0.55	0.7	0.62
	MaxPCC	**0.89**	**0.85**	**0.84**	**0.84**	**0.98**	**0.98**	**0.98**	**0.98**
	PredPrev=Obs	0.86	0.79	0.79	0.79	0.93	0.93	0.85	0.89
	ObsPrev	0.63	0.44	0.35	0.39	0.41	0.03	0.02	0.02
	MinROCdist	0.79	0.64	0.81	0.72	0.67	0.5	0.57	0.53

Model building and cross-validation

The results of the application of the crop selection model showed variation at different spatial scales (Table 3). First, the results showed that FM could be cultivated in over 80% of all Aksumite sites at 1, 5, 10, 25, 50 and 200 km scales (Range = 87.5 to 93.75%). At 100 km, however, only 62.5% of the sites were positively classified. FM appeared to be absent from the port site of Adulis at all scales. By contrast, the model showed FM cultivation to be possible at all spatial scales only at the sites of Ona Adi, Aksum, Matara, Qwiha, Edaga Hamus, Agula, Adi Ahoune, Enda Sellassie, and Hawelti-Melazo. Regarding SB, the model predictions were 18.75% at a 1km-radius, 31.25% at 5 km, 43.75% of the sites at 10- and 25-km, 87.5% at 50-km and 100% at 100- and 200-km radiuses. In this case, three sites were always positively classified, including Beta Samati, Adulis, and Agoula, whereas no site was always classified as zero. SB is recurrently absent under 10km for Ona Adi, Matara and Adi Ahoune, under 50 km for Aksum, Debarwa and Daqqa Mahare and under 100 km at Enda Sellassie and Hawelti-Melazo.

Regarding FM cultivation model, the results showed a clear predominance of extensive-rainfed (EXT-RF) over intensive-rainfed (INT-RF) and intensive-irrigated (INT-IRR) agriculture at all spatial scales, encompassing over 66% of all sites where FM cultivation was recognized viable by the first model (Table 3). This situation was recorded at the 1, 5, 10 and 25 km scales (>90%), where all sites were classified as EXT-RF except for Wakarida, predicted to be INT-RF. The lowest percentage of EXT-RF was encountered at 50 km, where a third of the sites were classified as INT-RF (including Wakarida, Qohaito, Edaga Hamus, Emba Derho, and Adi Ahoune). After that, the EXT-RF predominance was recovered at the 100-km and 200-km radius scale, except for Emba Derho. It is worth to note that FM cultivation at Ona Adi was always predicted as potentially extensive-rainfed, except for 1-km radius where not enough environmental data were available.

Table 3 - Summary of the results of the model application to 16 archaeological sites in percentage. The full results are available as Supplementary Information, Table S1 (FM = Finger millet, SB = Sorghum, CAS = Casual, EXT = Extensive, INT = Intensive, RF = Rainfed agriculture, DEC = *Décrue* / Flood agriculture, IRR = Irrigated agriculture). Note that length of growing cycle was not used for FM as it was not retained by the model as a significant explanatory variable.

Model		1 KM	5 KM	10 KM	25 KM	50 KM	100 KM	200 KM
Crop choice	FM	93.75	93.75	87.5	87.5	93.75	62.5	93.75
	SB	18.75	31.25	43.75	43.75	87.5	100	100
FM cultivation	EXT-RF	91.67	92.86	92.31	92.86	66.67	90.91	93.33
	INT-RF	8.33	7.69	7.69	7.14	33.33	9.09	6.67
	INT-IRR	0	0	0	0	0	0	0
SB cultivation (90 days)	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	0	0	0	0	0	0	0
	INT-RF	0	0	0	0	0	0	0
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	100	100	85.71	100	100	93.75	100

	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	0	0	0	0	0	0	0
SB cultivation (120 days)	INT-RF	33.33	33.33	71.43	75	64.29	75	100
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	66.67	80	28.57	25.0	28.57	12.5	0
	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	0	0	0	0	0	0	0
SB cultivation (150 days)	INT-RF	100	100	100	100	100	100	100
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	0	0	0	0	0	0	0
	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	0	0	28.57	25	0	0	0
SB cultivation (180 days)	INT-RF	100	100	71.43	62.5	85.71	93.75	100
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	0	0	0	0	0	0	0
	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	33.33	40	71.43	62.5	78.57	100	100
SB cultivation (210 days)	INT-RF	66.67	66.67	28.57	37.5	28.57	18.75	0
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	0	0	0	0	0	0	0
	CAS-RF	0	0	0	0	0	0	0
	EXT-RF	100	100	100	100	100	100	100
SB cultivation (240 days)	INT-RF	33.33	20	0	12.5	0	0	0
	INT-DEC	0	0	0	0	0	0	0
	INT-IRR	0	0	0	0	0	0	0

The duration of growth cycle was retained as a significant variable in the crop model for SB, so the SB model was applied using six different growing cycle durations, that is 90, 120, 150, 180, 210 and 240 days to represent the broad spectrum between the fastest- and slowest-growing varieties of sorghum recorded in the wider NE African region (Biagetti et al. 2022). Overall, the most common predicted practice was INT-RF (Table 3). However, there were important differences according to the duration of the growing cycles: for example, almost all sites were categorised as INT-IRR when modelling 90-day sorghum at all spatial scales, with the exceptions of Ona Adi at 10 km and Enda Sellasie at 100 km, which were not classified under any group. A similar situation was observed when using the 120-day growing cycle, though in this case INT-IRR was less common amongst sites, reaching its highest percentage at 5-km radius around the sites (80%), but rapidly decreasing when augmenting the radius (28.57% at 10- and 0% at 200-km radius). By contrast, when using the slowest growing cycles (210 and 240 days), most of the sites were classified as EXT-RF. This pattern is less clear in the 210-day growing cycle, which shows a relatively balanced distribution between EXT-RF and INT-RF at the scales below 50-km radius, favouring EXT-RF predictions after augmenting the site distance to 100-km radius. In the case of 240 days, all sites were predicted to potentially use EXT-RF agriculture to cultivate sorghum, with the additions of Agula at 1 and 5 km and Wakarida at 25 km in which both EXT-RF and INT-RF regimes were included. Regarding the intermediate growing cycles, most sites were classified as INT-RF: whereas at 150 days, 100% of the sites were classified as INT-RF; at 180 days, some were considered EXT-RF, gradually decreasing in favour of INT-RF as radius area increased. It is worth noting that the model did not produce any prediction of casual-rainfed (CAS-RF) or intensive-décrue (INT-DEC) agriculture. Overall, a general pattern could be identified: increasing growing-cycle duration was associated with decreased cultivation intensity and potential irrigated agriculture rate. This tendency was accentuated by the extent of the area analysed: the smaller the radius, the higher the cultivation intensity and rate of irrigation. In the case of Ona Adi, this pattern was clearly identified, although no major differences were recorded in association to site radius size.

Phytoliths from Ona Adi: validating the results against archaeological evidence

During the analysis, 59 single-cell morphotypes and 23 silica skeleton types were identified. Additional taxonomic classification resulted in 19 groups for single cells and 8 groups for articulated cells. For a detailed discussion of each morphotype and its taxonomic and anatomic association, see Ruiz-Giralt et al. (2023b, Supplementary Information: 52-114) – also available at https://zenodo.org/record/7731566. Phytolith concentration ranged between 0.39M and 4.86M phytoliths per gram of AIF. The Kruskal-Wallis H test did not highlight significant differences amongst phases or types of contexts. No correlation between phytolith concentration and number of morphotypes was found (Pearson's r = -0.02). This indicates that taphonomic processes did not have a significant impact on the general composition and representativeness of the phytolith assemblage.

Single-celled phytoliths

Table 4 includes the results of the analysis of the single-celled phytolith assemblage from Ona Adi (raw data available as Supplementary Information, Dataset 5 at https://doi.org/10.5281/zenodo.7859673). Morphotypes associated with indeterminate herbaceous plants (Poaceae/Cyperaceae and Poaceae) encompassed between 56.1% and 59.8% of all the assemblage. C_4 grass subfamilies (Panicoideae and Chloridoideae) represented 18.1 to 19.7% of all phases, whereas C_3 Pooideae ranged between 3.4 and 4.4%. Palms, herbs, and other plants represented 0.9 to 2.1%, and dicotyledonous ranged between 1.2 and 2.6%. The remaining 14.8 to 16.9% of the assemblage was associated with non-diagnostic morphotypes.

C_4 water availability model.

The results of the application of the stepwise model using saddle, cross and polylobate as explanatory variables are shown in Figure 3, where 0 indicates water-stressed conditions and 1 indicates well-watered conditions (full results available as Supplementary Information, Dataset 6 at https://doi.org/10.5281/zenodo.7859673). Most samples ranged between 0 and 0.25, meaning that the assemblage was likely derived from plants growing in water-stressed conditions. There were four outliers, including samples #961, #228, #1621 and #2509. These fell between 0.409 and 0.585 and therefore were difficult to consider as either well-watered or water stressed.

Figure 3 - Plot of the probability of Ona Adi's archaeological phytolith samples to be derived from a well-watered crop-phytolith assemblage.

Table 4 - Summary of results from single-celled phytolith analysis grouped by taxonomic categories.

Archaeological Context	n samples	Indeterminate Herbaceous		C4							C3	Palms and Herbs			Weeds					
		Poaceae/Cyperaceae (%)	Poaceae (%)	Andropogoneae (%)	cf. Aristidoideae (%)	Panicoideae/Chloridoideae (%)	cf. Panicoideae/Chloridoideae (%)	Panicoideae (%)	Chloridoideae (%)	cf. Chloridoideae (%)	Pooideae (%)	Arecaceae (%)	Zingiberales (%)	cf. Zingiberales (%)	Cyanotis sp. (%)	Commelina sp. (%)	Commelinaceae (%)	Cyperaceae (%)	Dicotyledonous (%)	Non-diagnostic (%)
Late Pre-Aksumite	4	29.4	28	0	0	7.4	1.4	0.2	9.3	0.3	4.3	0.2	1	0	0.1	0	0	0	2.6	15.6
PAA transition	10	24.3	31.7	0.1	0.04	7.7	1.1	0.3	10.2	0.2	4.4	0.3	1.4	0.2	0	0.2	0	0	2	15.9
Early Aksumite	9	24.7	35.1	0.04	0.04	8.1	1.2	0.1	9.2	0.1	3.4	0.2	1.4	0	0.04	0	0	0	1.6	14.8
Middle Aksumite	9	28.5	30.5	0	0	10.1	1.1	0.2	7.7	0.4	3.5	0.3	1	0	0	0.4	0.04	0.04	1.2	14.8
Late Aksumite	14	31.1	26.9	0	0	10	0.4	0.1	7.5	0.2	4.2	0.2	0.6	0.03	0.03	0.1	0	0	2	16.9
Total Ona Adi	46	27.7	30.4	0.02	0.02	9	0.9	0.2	8.6	0.2	4	0.2	1	0.04	0.02	0.1	0.01	0.01	1.8	15.7

Discussion

Building ethnoarchaeological models

The results of the model on finger millet and sorghum agriculture show that the most determining factors for the selection of these crops are altitude, precipitation concentration, soil acidity and soil water retention capacity. Our model shows that modern rural communities preferentially cultivate sorghum in regions characterised by relatively higher soil water pH, whereas finger millet is more commonly selected in highland areas with higher soil water-retention. Altitude is known to be a factor in crop choice in modern Tigrai, as farmers change to barley as the main cereal crop as fields approach 3,000 metres above sea level. Further, finger millet and sorghum appear to be preferred in areas with moderate to irregular precipitation distribution. As noted by Ruiz-Giralt et al. (2023a, and references therein), the importance of these variables in the cultivation of finger millet and sorghum have been already recognized by agronomists hence highlighting the scientific value of traditional agrosystems. Moreover, the absence of spatial patterns indicates that cultural transmission was not the main factor in shaping the studied traditional agrosystems, but that local processes of adaptation were likely more important. This is an important point regarding the applicability of the models to the archaeological record, as past agrosystems were most likely also the result of long processes of ecological adaptation at the local to regional levels.

The validation of the models produced consistent comparable results to the original study (Ruiz-Giralt et al. 2023a). More importantly, they showed an overall better performance when cross-validated against the ethnographic data solely from Tigrai, with the unique exception of the cultivation intensity of finger millet agriculture. This situation can be attributed to the current national land management strategies in relation to demographic growth, which have prompted an intensification of agricultural systems in order to sustain the increasing population. Apart from this specific case, the models were able to correctly predict over 90% of the validation cases –including crop preferences and sorghum cultivation intensity and watering practices, but also the watering regimes used in finger millet agriculture– showing an outstanding performance when working at the regional and local levels. Indeed, such capability enables us to confidently apply the models to archaeological sites in the highlands of the northern Horn, especially given the fact that environmental conditions have not significantly changed for over 4000 years (see above).

Modelling agricultural practices in the past

The application of the crop choice model to the main Aksumite sites in the highlands of the northern Horn of Africa shows that the agriculture of finger millet and sorghum was generally viable around these locations, especially in the case of finger millet. The results of this first model show that finger millet agriculture was possible at different spatial scales around most of the studied archaeological sites, including Ona Adi. Indeed, previous studies have shown Aksumite populations to preferentially located their settlement in highland water-rich valleys (Sernicola 2008, Sernicola and Sulas 2012, Harrower and D'Andrea 2014). Altitude and soil water-retention are also the main factors determining the choice of finger millet as identified by our crop choice model, hence explaining the generalised predicted presence of finger millet in the studied sites. Regarding cultivation intensity and watering practices, the ethnoarchaeological models indicate that most sites would have had to opt for extensive-rainfed regimes if cultivating finger millet. The model shows that this type of agriculture is presently the most common practice in areas with erratic rainfall like the highlands of the northern Horn. By contrast, more intensive regimes, including irrigated agriculture, not only need more concentrated precipitation but also agricultural fields with more fertile soils to sustain recurring cultivation. These fields are nowadays used in Tigrai for the cultivation of crops with higher input requirements, mainly barley and wheat, but also t'ef. In the past, similar land management practices were likely to have been in place, as Near Eastern C_3 cereals were very important staples during Aksumite times as well (Boardman 2000, D'Andrea 2008). Nonetheless, at this moment it is difficult to evaluate past land cultivation intensity, especially given the poor results of the model when predicting modern-day cases. Overall, our data highlight the potential economic value of finger millet agriculture in the past. The low water and soil-nutrient requirements of finger millet when cultivated under extensive-rainfed regimes means that Aksumite people might have cultivated it in fields unfit for barley and wheat agriculture, but also during the aforementioned episodes of landscape degradation.

In the case of sorghum, the first model shows an interesting pattern: the wider the radius around the sites, the more sites are classified as potentially cultivating sorghum. This would indicate that Aksumite communities were less likely to cultivate sorghum in their immediate surroundings, but that the agriculture of sorghum was viable in the wider region. The results of the crop choice model indicate that sorghum was likely preferred in the coastal lowlands, as exemplified by the site port of Adulis (Zazzaro et al. 2014), as well as in areas located away from the main settlements, often with less agricultural potential (Harrower and D'Andrea 2014). When cultivated in the near vicinity of the sites, we argue that sorghum would have played a similar role as finger millet within Aksumite economy, and that the use of one or the other likely depended on more local, specific factors such as soil pH, as well as cultural preferences of the different local communities – for example in association with beer making activities. In relation to the intensity of cultivation and watering practices, the length of the growing cycles seems to be the most important factor in determining sorghum agriculture. According to our model, fast-growing sorghum varieties grown in traditional agrosystems demand more intensive agricultural regimes and even the use of irrigation. These types of landraces, which mature in 120 days or less, are often the result of long processes of human selection and they are unlikely to have been available to farmers during the Aksumite period. Instead, slower maturing types comparable with the traditional landraces observed today (over 180 days, see Biagetti et al. 2022) were much more likely to be present. According to the sorghum cultivation model, these varieties could have been cultivated under extensive-rainfed conditions in a manner similar to what the ethnoarchaeological models predict about finger millet agriculture.

Phytolith analysis as a tool for hypothesis evaluation
The very limited presence of sorghum and finger millet in the macrobotanical remains found in archaeological contexts of the northern Horn of Africa, seem to contradict the prediction of the ethnographic models. However, the general scarcity of macro-remains of these grass species and other member of the Panicoideae and Chloridoideae families has been attributed to the limited number of systematic archaeobotanical programs on the continent (Fuller and Stevens 2018) and the preservation issues faced by their seeds in the archaeological record (Young and Thomson 1999), especially t'ef (D'Andrea 2008) and finger millet (Terefe and Beldados 2021, Mueller et al. 2022). Recent studies have turned to the analysis of microbotanical remains as an alternative to explore the agricultural history of these crops around the world (e.g., Liu et al. 2014, Lucarini et al. 2016, Out et al. 2016, Lucarini and Radini 2020, Goldstein et al. 2021, Cagnato et al. 2022, González-Rabanal et al. 2022, Laugier et al. 2022, Le Moyne et al. 2023, Ruiz-Giralt et al. 2023b).

The phytolith assemblage from Ona Adi shows an important presence of the Panicoideae and Chloridoideae C_4 grass subfamilies in the site. Today, the most important species of these subfamilies in the northern Horn agriculture are sorghum (Andropogoneae, Panicoideae), t'ef and finger millet (both Eragrostideae, Chloridoideae). Even though phytoliths do not allow for taxonomic classification to the species level, these crops – and their wild and semi-domesticated relatives – are the most likely taxa represented at Ona Adi. Indeed, similar results have been obtained from microbotanical residues (both phytoliths and starch grains) from grinding stones at Ona Adi (Ruiz-Giralt et al. 2023b) indicating that C_4 plants were processed and consumed at the site, and that the presented assemblage is not only a result of the surrounding vegetation. It is worth noting that recent studies have found that C_4 plants were an important part of the region's economy since the mid-2nd millennium BCE (Ruiz-Giralt et al. 2023b, Beldados et al. 2023), showing an extended period of interaction with local communities who eventually would have incorporated them as agricultural products. In this regard, the phytolith results from Ona Adi confirm the significant presence of C_4 plants during Aksumite times, and thereby lend some support for the results of the ethnoarchaeological models, which indicate that both finger millet and sorghum agriculture was viable in the surrounding area of the main Aksumite sites, including Ona Adi.

The results of the application of the C_4 water availability model by D'Agostini et al. (2023) to Ona Adi's phytolith sample indicate that the C_4 plants found at the site grew in water-stressed conditions. This was rather consistent throughout the occupational phases of the site, and outlier samples only appeared after the beginning of the Aksumite period. As such, the phytolith data support the hypothesis produced by the ethnoarchaeological models, which consistently classified watering practices at Ona Adi as rainfed regimes, both for finger millet and sorghum –with the sole exception of the 90-day-sorghum variety. Since phytoliths are a direct proxy of plant water availability, our results reinforce the previous hypothesis that C_4 crops

would have been cultivated in rainfed conditions during the Aksumite period in the highlands of northern Ethiopia and Eritrea. Indeed, recent studies that have argued that large-scale, intensive irrigation was not necessary to ensure food security during the Kingdom of Aksum (Sulas et al. 2009, Sulas 2014, 2018, Harrower et al. 2020) contrary to previous theories that considered it to be an indispensable factor in the establishment and development of the Aksumite polity (e.g., Kobishchanov 1979, Butzer 1981, Bard et al. 2000, Michels 2005). Indeed, it was believed that crop irrigation was necessary to sustain increasing Aksumite populations, and that the technology was likely introduced from Yemen, where large-scale hydraulic infrastructures have been identified (see Harrower 2009 for a review). To date, the only evidence of Aksumite water management is the presence of water reservoirs at sites such as Aksum or Qohaito, which have been recently reinterpreted as sources of water supply for people, animals and other domestic activities, including the watering of house-level gardens and plots (see Sulas 2014, 2018 for further details). A similar structure has been identified immediately to the south of Ona Adi, although in this case it is impossible to determine its age or if it existed during the Aksumite occupation of the site. In any case, archaeological evidence of large-scale irrigation structures has not yet been found in the region, despite the increasing number of systematic archaeological surveys (e.g., Michels 2005, Schmidt et al. 2008a, Sernicola 2008, D'Andrea et al. 2008, Sernicola and Phillipson 2011, Harrower and D'Andrea 2014, Gaudiello and Yule 2017, Benoist et al. 2020, Harrower et al. 2020). Altogether, our current understanding is that irrigation, if present, was likely used in similar fashion to what can be observed in modern-day Tigrai, where it is rare and generally small-scale (Harrower et al. 2020), and mostly limited to horticulture and maize cultivation (Biagetti et al. 2022). Overall, the data we have presented support the hypothesis of an Aksumite agrosystem primarily based on the rainfed cultivation of cereals, which would have included African C_4 crops such as finger millet and sorghum.

Concluding remarks

Ethnoarchaeological models are a useful tool to generate hypotheses from the present, especially when they can be validated using direct archaeological data. In this paper, we have presented a methodology that combines ethnography, cross-cultural modelling, ethnoarchaeology and archaeobotany to build, test, apply and validate a set of models that aim to evaluate past agricultural practices related to the cultivation of finger millet and sorghum in the northern Horn of Africa. The results show that the cultivation of these crops was viable in the surroundings of the most important Aksumite sites known to date. Furthermore, the models demonstrate that, when practised, the cultivation of finger millet and sorghum was most likely extensive-rainfed. The phytolith data from one of these sites, Ona Adi, generally agrees with the model predictions, reinforcing the scientific potential of the presented approach. At the same time, our results underline the importance of implementing systematic archaeobotanical research programmes that include microbotanical sampling and analyses into future archaeological projects in the northern Horn. This is related to the preservation issues faced by the macrobotanical remains of many C_4 plants, which have significantly hindered our current understanding of Aksumite agricultural economies. Overall, the presented results indicate the cultivation of finger millet and sorghum during Aksumite times might have been much more significant than previously considered.

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Data, scripts, code, and supplementary information availability

Conflict of interest disclosure

The authors declare that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

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