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REVIEW ARTICLE

The Role of Environmental Changes in the Development of the Agricultural Economy During Pre-Aksumite and Aksumite Cultures

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Abstract The northern highlands of Ethiopia and Eritrea (NHE) hosted the earliest agricultural and urban societies in sub-Saharan Africa: the Pre-Aksumite and Aksumite cultures. However, the role of environmental shifts in the transition from hunting-gathering to agriculture and state formation remains unclear. This study reviews 95 peer-reviewed articles on paleoenvironmental data from the NHE and adjacent regions (6000–1000 BP), integrating recent archaeobotanical and archaeological findings. We draw three main conclusions: (1) Paleoenvironmental conditions during this transition were highly variable, with differing tempos and magnitudes of change across the region. (2) The emergence of early agriculture and Pre-Aksumite societies in the NHE was not directly driven by environmental changes around 3500 BP. Instead, social dynamics and interactions among local human groups provided a more plausible explanation. (3) The NHE highlands experienced a shift towards higher humidity during early Aksumite period, specifically between 2500 and 2000 BP and 1500 and 1000 BP. This climatic shift likely enhanced agricultural productivity, facilitating food surpluses that underpinned the expansion of the Aksumite Kingdom. These results suggest that while early agriculture was culturally driven, later state development was more closely tied to environmental factors. To understand the interplay between environmental and socio-cultural factors in the NHE, we recommended interdisciplinary approach integrating, paleoenvironmental, archaeological, and archaeobotanical and genetic studies. This will enhance data resolution, mitigate geographical biases, and refine our understanding of complex societies in the Horn of Africa.

Time Period – Holocene Period.

Region discusses—Horn of Africa (Ethiopia, Eritrea, Djibouti, Somalia, South Sudan, Sudan), Egypt, and Yemen.

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Résumé Les hautes terres du nord de l’Éthiopie et de l’Érythrée (NHE) ont abrité les premières sociétés agricoles et urbaines d’Afrique subsaharienne: les cultures pré-aksoumites et aksoumites. Cependant, le rôle des changements environnementaux reste flou dans la transition d’un mode de vie fondé sur la chasse et la cueillette à un mode de vie agricole qui voie aussi la formation de lÉtat. Cette étude passe en revue 95 articles dans des revues à comité de lectures portant sur les données paléoenvironnementales des NHE et des régions adjacentes (6000 à 1000 BP), in-

tégrant les récentes découvertes archéobotaniques et archéologiques.
Nous tirons trois conclusions principales: (1) Les conditions environnementales au cours de cette transition étaient très variables, avec des rythmes et des ampleurs de changement différents dans la région. (2) L'émergence des premières sociétés agricoles et pré-aksoumites dans le NHE n'a pas été directement motivée par des changements environnementaux autour de 3500 BP. Au lieu de cela, la dynamique sociale et les interactions entre les groupes humains locaux ont fourni une explication plus plausible. (3) Les hautes terres du NHE ont connu une évolution vers une humidité plus élevée au début de la période aksoumite, en particulier entre 2500 et 2000 BP et 1500 à 1000 BP. Ce changement climatique a probablement amélioré la productivité agricole, facilitant les excédents alimentaires qui ont soutenu l'expansion du royaume aksoumite. Ces résultats suggèrent que si l'agriculture primitive était motivée par la culture, le développement ultérieur de l'État était plus étroitement lié aux facteurs environnementaux.
Pour comprendre l'interaction entre les facteurs environnementaux et socioculturels dans le NHE, nous recommandons une approche interdisciplinaire intégrant des études paléoenvironnementales, archéologiques, archéobotaniques et génétiques. Cela améliorera le niveau de résolution des données, atténuera les biais géographiques et affinera notre compréhension des sociétés complexes de la Corne de l'Afrique.

Keywords Paleoenvironment · Northern highlands of Ethiopia · Aksumite · Horn of Africa · Origins of agriculture

Mots clés Paléoenvironnement · Hautes Terres du Nord de l'Ethiopie · Aksumite · Corne de l'Afrique · Origines de l'agriculture

Introduction

The northern highlands of Ethiopia and Eritrea (NHE) have witnessed a succession of different polities throughout pre- and proto-history, making them a crucial region for understanding the development of complex societies in the Horn of Africa. The Pre-Aksumite and Aksumite civilizations were among the earliest urban societies in Africa outside Egypt (Fattovich, 1990; Phillipson, 2000). The initial phase of the Pre-Aksumite civilization emerged around 3500 BP as one of the first documented agricultural and sedentary societies in sub-Saharan Africa (D'Andrea et al., 2023). The subsequent Aksumite civilization flourished around 2,100 BP (Anfray, 1973; Bard et al., 2000; Fattovich, 1990; Munro-Hay, 1991; Phillipson, 1998, 2000).

In the NHE, agriculture integrated indigenous crops (i.e., crops that are native to and domesticated within Ethiopia) with Southwest Asia (SWA) and African domesticates (i.e., crops domesticated in Africa but outside Ethiopia) (Bard et al., 2000; Harlan, 1982, 1992). Consequently, the area has long been recognized as a significant hub of agricultural innovation and plant domestication (Vavilov, 1926, 1951), although little is known about the domestication process of local crops and the high genetic diversity of those domesticated elsewhere (a phenomenon already noted by Nikolai Vavilov (1996) in the early twentieth century).

Over just a millennium, the NHE transitioned from hunting-gathering and pastoralism to a fully developed agricultural system capable of sustaining a large kingdom. Hence, the use and exploitation of wild plants continue (Meresa et al., 2024). However, it is unclear why agriculture emerged so late in the region, despite its existence in neighboring areas, and how it was so rapidly adopted once it appeared.

The development of an agriculture-based economy relies on water resources, fertile soils, and agricultural techniques that enable the production of food surplus (Bard et al., 2000; Butzer, 1981; Munro-Hay, 1991). In turn, water availability for agriculture is contingent upon the climate and environmental characteristics of a region, and this availability is greater in the NHE than in the surrounding lowland regions, where pastoralism was dominant and agriculture was limited (Bard et al., 2000; Butzer, 1981). Recent research, however, challenges this view. For instance, Biagetti et al. (2022) demonstrate that agricultural systems can thrive in drylands without reliance on irrigation or proximity to major water sources. Their findings highlight the potential of alternative cultivation strategies in arid environments.

Paleoclimatic studies of the NHE provide additional context, suggesting a dry Early Pre-Aksumite period, followed by increased rainfall during the rise of the Aksumite civilization, which may have facilitated its development (Berakhi et al., 1998; Butzer, 1981; Marshall et al., 2009). However, other perspectives propose persistent aridity with only intermittent wetter intervals until approximately 1300 BP (Terwilliger et al., 2011). These differing interpretations underscore the complexity of climatic influences on agricultural and societal development in the region.

Establishing causal relationships between cultural and climatic changes is hindered by the limited availability of archaeological data in this region (Bard et al., 2000). Comparative analyses of past environmental changes in the NHE and neighboring regions are crucial for understanding the emergence of agriculture and the development of complex societies. Thus, this study reviews paleoenvironmental evidence and correlates it with archaeobotanical, archaeological, and genetic studies to address a key question: Is agricultural development and urbanization in the NHE explained by climate change or cultural and social factors?

Current Hypothesis on the Emergence of Agriculture in the NHE

Understanding the development of agriculture and complex societies in this region requires examining the antecedent cultures of surrounding regions. To explain the emergence of farming practices in the NHE, three primary hypotheses have been proposed (sections "North-West of NHE" to "Locally"; Fig. 1). These hypotheses are evaluated within the context of paleoenvironmental data spanning ~ 6000–1000 BP, with a focus on assessing how environmental changes may have influenced or shaped each proposed pathway.

North-West of NHE

Among the cultures north-west of the NHE were nomadic people from the Nile Valley of Sudan, near the present-day Ethio-Sudanese border, named after their pottery style, the ACT. They have occupied most of the plains in eastern Sudan since 7000 BP (Fattovich, 1991, 1993; Fattovich et al., 1984; Figs. 1 and 2). The ACT was divided into different phases, among which the Butana (from 6000 BP) and the Gash (5000–3500 BP) were the two most important groups in the present study (Fattovich, 2010; Gautier & Van Neer, 2006). The Butana Group ceramics were linked to the introduction of domesticated sorghum (Beldados, 2015, 2019; Fattovich, 2010). Additionally, similarities between the pottery of the Gash group and that of the Danei Kawlos site in northern Ethiopia (3691–3490 BP) present evidence of contact (Negash & Marshall, 2021) and Mezber (D'Andrea et al., 2023). Another key culture situated in the lower Nubia (present-day Sudan) is the C-Group culture (~ 4400–3500 BP; Bianchi, 2004). According to Clark's (1962, 1967) model, the C-Group people may have introduced pastoralism (cattle and ovicaprids) into the NHE approximately 4000 years ago, migrating due to the desertification of the Sahara and Sahel (and consequent famine) at the end of the African Humid Period (AHP). During times of economic pressure, lowland pastoralists may have viewed agriculture in the highlands as a reliable safety net due to a more stable environment and lower population levels. The presence of faunal remains in Ethiopia, including cattle, sheep, and goats, can be traced back to approximately 3500–4100 BP. Domesticated animal remains were discovered at various archaeological sites, such as Lake Besaka (Brandt, 1982), Danei Kawlos (Negash & Marshall, 2021), Gobedra ~ 3000 BP (Phillipson, 1977), Mezber ~ 3500 BP (Woldekiros & D'Andrea, 2022), Kurub-07 ~ 3900–3600 BP (Khalidi et al., 2020), Laga Oda ~ 3500 BP (Clark & Prince, 1978), and Yabello, dated to approximately 4100 BP, and have been a subject of debate, as the reliability of the sample dating has been questioned by many researchers (Girma, 2001).

If the ACT people introduced cattle and ovicaprids into the NHE, they might have also introduced other African domesticated crops (i.e., sorghum and/or cowpea). Determining the origin of crops that arrived from west Ethiopia to the NHE is complicated by the uncertainty surrounding their domestication sites. The race *bicolor* of sorghum is considered to have been domesticated near the Atbara and Gash rivers (Eastern Sudan) by people of the Butana group, around 6000 BP, and subsequently introduced into South Asia around 4000 BP and to West Africa after 3000 BP (Fuller & Stevens, 2018; Winchell et al., 2018). However, some genetic studies have suggested the independent domestication of the *guinea* race in the tropical region of western Africa (Morris et al., 2013). On the other hand, the Niger Basin is

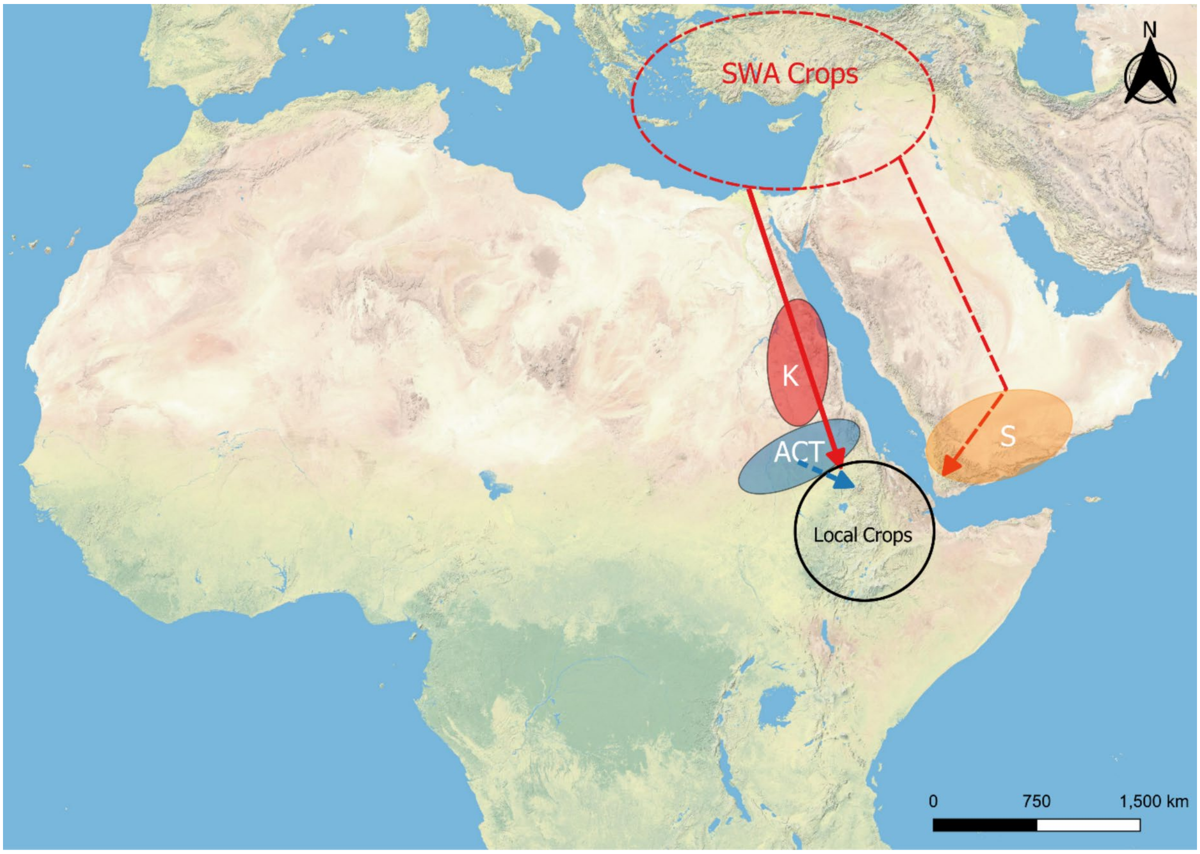


Fig. 1 Archaeological cultures around the NHE at the 4th and 3rd millennia BP and hypotheses for the origins of crops there: the blue stain represents the approximated area occupied by the people producing the Atbai Ceramic Tradition (ACT); the red stain represents the approximated area occupied by the kingdom of Kerma (K); the orange stain represents the approximated area occupied by the Sabeans (S); the red arrow represents an introduction of SWA crops from the North and the blue-dashed represent the introduction of African domesticated crops through the ACT(section "North-West of NHE"); the red-dashed arrow represents an East provenance of SWA crops (section "East of NHE"); the black circle represents the local domestication of crops (section "Locally"). Figure built using the Natural Earth (2023)

considered the likely center of cowpea domestication at approximately 4000 BP (D'Andrea et al., 2007; Herniter et al., 2020). However, the exact location of cowpea domestication remains uncertain, with both West and East Africa proposed as possible centers (Herniter et al., 2020; Huynh et al., 2013). The presence of African-origin crops such as cowpeas in the Indian subcontinent around 4000 years ago might suggest the possibility that these crops were potentially transported across the Red Sea to the Arabian Peninsula (Beldados, 2015, 2019; Herniter et al., 2020; Winchell et al., 2018).

A recent study carried out at the Mezber site in Tigrai suggested that early agro-pastoralist societies resided in the highlands during the Initial Phase (3500 BP; D'Andrea et al., 2023). Paleobotanical studies have revealed the presence of SWA crops. Barley was present in the earliest Initial Phase deposits at 3100 BP, with a caryopsis directly dated to the Initial Phase, at 2780 BP (the earliest direct date for barley in the Horn of Africa), and lentil to 2810 BP (Beldados et al., 2023; D'Andrea et al., 2023; Ruiz-Giralt et al., 2023). The consumption of sorghum as well as locally domesticated plants, including t'ef, noog, and finger millet, was identified from the micro-botanical analysis, which dates to approximately 3100 BP (Beldados et al., 2023; D'Andrea et al. 2023; Ruiz-Giralt et al., 2023).

Thus, African domesticates were already present in the early agricultural systems of the NHE. However, the question remains: Why did it take so long

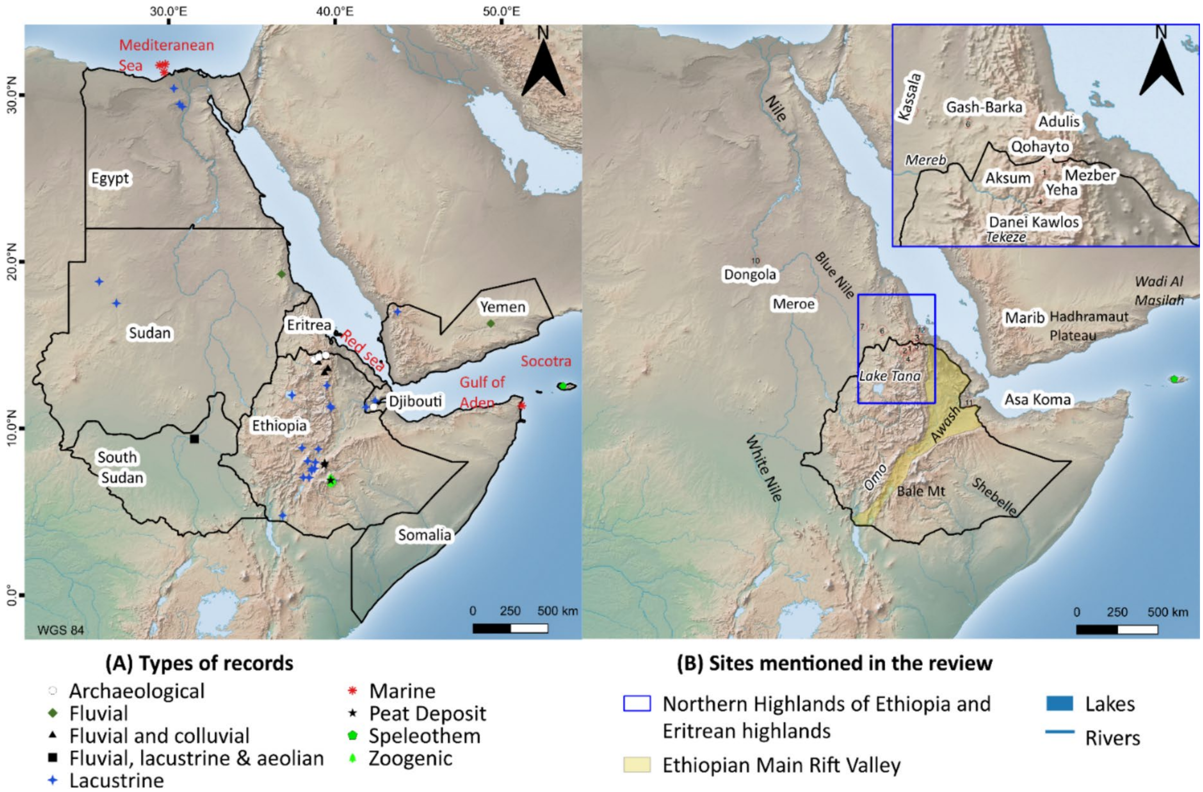


Fig. 2 Study area location: **A** map with the location and types of records analyzed in the reviewed paleoenvironmental studies; **B** location of sites mentioned in the review. Figure built using the Natural Earth (2023)

for these crops to be cultivated in the NHE when they were known in the surrounding lowlands? Did local hunter-gatherers resist the adoption of farming? Did the crops require a long period of adaptation? Was the climate in the NHE unsuitable for cultivation of these crops? Alternatively, is it simply a case of insufficient archaeological exploration, with evidence of early agriculture yet to be uncovered? Alternatively, could it be an issue of preservation?

Northern from the previously mentioned groups, in present-day Sudan (i.e., Upper Nubia), there was the Kerma kingdom. They were the earliest sub-Saharan African polity, between 4500 and 3500 BP (Figs. 1 and 2; Edwards, 2004; Hafsaas, 2006). There were interactions with Egypt and the presence of taurine cattle skulls in cemeteries indicates that this kingdom had a subsistence economy based on pastoralism (Edwards, 2004; Vincentelli, 2006). At the same time, Kerma was supported by a fertile hinterland with irrigation-based agriculture (Welsby et al., 2002). In this scenario, SWA crops (i.e., emmer wheat, barley, lentils, fava beans, flax, and chickpeas) along with pastoralism could have been introduced in the NHE through contact with the people of Kerma or by the latter moving into the NHE. Egyptian texts refer to the land of Punt, which is thought to partially correspond to the Pre-Aksumite territory, according to Hafsaas's (2006) and Fattovich's (2018) descriptions (Fig. 2). The tempo and reasons for a putative movement of Kerma people into the NHE require explanation. Again, why did it not happen before?

East of NHE

On the other side of the Red Sea, sedentary farming communities appeared in present-day Yemen (Fig. 2), cultivating SWA crops and probably some African domesticates as early as 5358–4205 BP (Edens & Wilkinson, 1998; Harrower et al., 2010). At this time, trade along and across the Red Sea was already evidenced in the archaeological record (Edens & Wilkinson, 1998). At about 3800 BP, the precedent of the

Sabean culture was identified on the fringes of the Arabian desert (Edens & Wilkinson, 1998) (Fig. 1). The Sabean were an urban society that depended on agriculture (terracing receiving rainfall and runoff in the highlands and flood irrigation in the lowlands) that gained notoriety at 3000 BP with increasing trade activity (Edens & Wilkinson, 1998; Ghaleb, 1990; Harrower et al., 2010; Wilkinson, 1999, 2006). The movement of Sabeans to the NHE is suggested to have occurred around 3000 BP (Harrower et al., 2010; Sergew, 1972). Until recently, there has been a debate regarding the introduction of SWA crops and farming technologies in the NHE through a Sabean migration or cultural diffusion. It was suggested that local domesticated crops emerged alongside the SWA assemblage to complement the latter. However, recent studies conducted by D'Andrea et al. (2023) at the Mezber site challenged this argument by pushing agricultural practices further back in time to 3500 BP.

Considering that the crop package used in Egypt was not significantly different from that found in the Arabian Peninsula, both based on SWA cultivars, it is difficult to distinguish whether these crops were introduced in the NHE from the north or from the east. The exception is the presence of naked wheat (durum and bread wheat). It is known that emmer was the only wheat species cultivated in Ancient Egypt until the Hellenistic period, when naked wheats (durum and bread) were introduced (Scott et al., 2019), whereas naked wheats were grown in the Arabian Peninsula at least since the Bronze Age (Dabrowski et al., 2024). Therefore, the presence of naked wheats prior to 2400 BP in the NHE could be seen as an indication of an eastern route for the introduction of these crops. Thus far, naked wheats only appear in the transition from the Pre to Aksumite period (Ruiz-Giralt & Beldados, 2024) and from Eritrea, Sembel 2800–2600 BP (D'Andrea et al., 2008). The absence of free-threshing wheats in the NHE when they were grown in the Arabian Peninsula vows against an East route for the earliest introduction of these crops, although this route was certainly predominant in historical periods (*p.ex.* for the introduction of zebu cattle).

The NHE has long been recognized as a center of crop diversity, with plenty of genetic studies conducted on local heirloom varieties. By comparing genomes of varieties of SWA crops with those of varieties from neighboring regions, it should be possible to infer their routes of spread. However, multi-regional studies are rare, and the dating of arrival based on genetic data is seldom possible. For barley, most Ethiopian/Eritrean landraces are genetically closer to those of the Arabian Peninsula than to Egyptian/Sudanese ones (Milner et al., 2019; Poets et al., 2015) with a few varieties being closer to North African/Near East ones (Pasam et al., 2014). The same scenario is observed for emmer wheat and lentils, with most Ethiopian accessions being part of the same gene pool of varieties from Yemen, Saudi Arabia, and Oman, although a few clustered with Near East and Egyptian landraces (Fadida-Myers et al., 2022; Iob & Botigué, 2023; Liber et al., 2021; Pavan et al., 2019). This pattern can be explained by different introductions in different time periods. The application of coalescence or time-of-divergence methods to those data may be informative as to which of these routes to the NHE was first taken by people bringing these crops.

Locally

Ehret (1979 and references therein) suggested that local plants (mainly t'ef) were the first to be cultivated in the NHE for geographic reasons. This hypothesis was based on the idea that local people would already have agricultural knowledge, gained by movements of communities or commercial interactions, and it is linked with the evolution of the Afro-Asiatic languages long before the rise of the Pre-Aksumite. In fact, recent evidence strengthens the idea that the cultivation of African domesticates and SWA crops coexisted with local domesticates during the Initial Pre-Aksumite Period (Beldados et al., 2023; D'Andrea et al., 2023; Meresa et al., 2024; Ruiz-Giralt et al., 2023).

Another scenario supporting this hypothesis is the one proposed by Finneran (1999). In this model, he suggested that the local environment initially dictated primary economic needs, giving rise to well-adapted hunting and gathering systems. During periods of climatic shifts, these systems transitioned to plant cultivation, likely based on two or three local species. Only later were SWA and African domesticated crops integrated. Low human population density and the reduced environmental extremes experienced in the NHE contributed to the stability of its agricultural complex, which ultimately served as the foundation for the emergence of complex societies (Finneran, 1999).

However, local domesticates, such as t'ef, only became prominent during the Aksumite period (Ruiz-Giralt & Beldados, 2024). This suggests that the early presence of local species may not necessarily indicate cultivation but rather the gathering of wild resources to complement food produced through agriculture in a mixed economic system. Ethnoarchaeological investigations by Lyons and D'Andrea (2003), which compare the function of ovens and griddles and analyze the presence of gluten components in bread, offer additional insights. Their study examines the prevalence of griddle usage in the highland regions of Ethiopia and its potential association with indigenous African plants. The findings suggest that griddles could indirectly signify the presence of these plants in archaeological contexts. Consequently, the use of griddles likely predates the introduction of Near Eastern cereals, indicating an early reliance on indigenous African species. The choice between ovens and griddles for bread baking appears to have been influenced by the functional properties of the ingredients, such as the gluten, starch, or pentosans present in cereals. Lyons and D'Andrea (2003) concluded that, despite the introduction of wheat and barley from South Arabia, there was minimal influence on Ethiopian food technology and culinary practices. This emphasizes the enduring significance of indigenous African crops and food preparation techniques in the region's agricultural and cultural history. Similarly, D'Andrea and Wadge (2011) conducted an ethnoarchaeological investigation into t'ef processing in northern Ethiopia. They hypothesized that the domestication of t'ef was initiated by early pastoralist societies. These groups were engaged in the collection and utilization of wild grasses, including the wild progenitor of t'ef. This sustained interaction with wild grasses likely facilitated the eventual domestication of t'ef as a cultivated crop.

Study Area

We reviewed paleoenvironmental data for the region spanning northeastern Africa and the southwestern Arabian Peninsula. This region encompasses the territory once occupied by the Pre-Aksumite and Aksumite kingdoms, covering parts of present-day Ethiopia, Eritrea, and Yemen, as well as neighboring regions with which these civilizations maintained cultural and commercial relations, including the geographically proximate areas of modern-day Djibouti, Somalia, Egypt, Sudan, and South Sudan (Fig. 2).

According to Köppen–Geiger's climate classification, northeastern Africa and the southwestern Arabian Peninsula currently exhibit temperate, arid, and tropical climates (Beck et al., 2018). Arid regions are influenced by subtropical anticyclones year-round, whereas tropical areas are affected by the migration of the Intertropical Convergence Zone (ITCZ), which shifts in response to changes in maximum solar heating (Gasse, 2000). The movement of the ITCZ creates a northern belt characterized by monsoonal climates with summer rains and winter droughts, delineating a humid equatorial zone with two rainfall peaks (Gasse, 2000).

The spatial and seasonal climatic variability in the study area is further influenced by interactions between atmospheric and oceanic circulation systems as well as by the region's topography and landscape features (Gasse, 2000). The highlands experience cooler temperatures and higher precipitation levels than the lowlands because of their elevated topography (Fig. 3b) (Hildebrand et al., 2019). The orientation of the highlands, whether facing west or east, also affects the climate, as hilly terrains create varying climatic conditions. Additionally, permanent water bodies, such as East African rift lakes, play a role in shaping regional and local climates (Hildebrand et al., 2019).

The main focus of the review, the NHE, is located in the northern part of the Horn of Africa and includes the Tigrai Highlands (Fig. 2B). The elevation ranges from approximately 500 m above the mean sea level (amsl) in the northeast to approximately 4000 m amsl in the southwest (Machado et al., 1998). Approximately 53% of the highland area is below 1500 m amsl, which corresponds to the agro-climatic *Kolla* zone. The *Woina Dega* zone, another agro-climatic region, constitutes 39% of the highlands and lies between 1500 and 2300 m amsl. The *Dega* zone, ranging from 2300 to 4000 m amsl, accounts for 8% of the highlands (Amare, 1996). Lake Ashenge is the only lake in the Tigrai highlands (Marshall et al., 2009). Rainfall patterns generally followed a southwesterly trajectory, increasing with altitude from east to west and decreasing from south to north (Fig. 3b) (Finneran, 2007). Two distinct rainy seasons occur in this region: the main season, known as *Keremt*, from June to October, and a shorter season, *Belg*, occurring

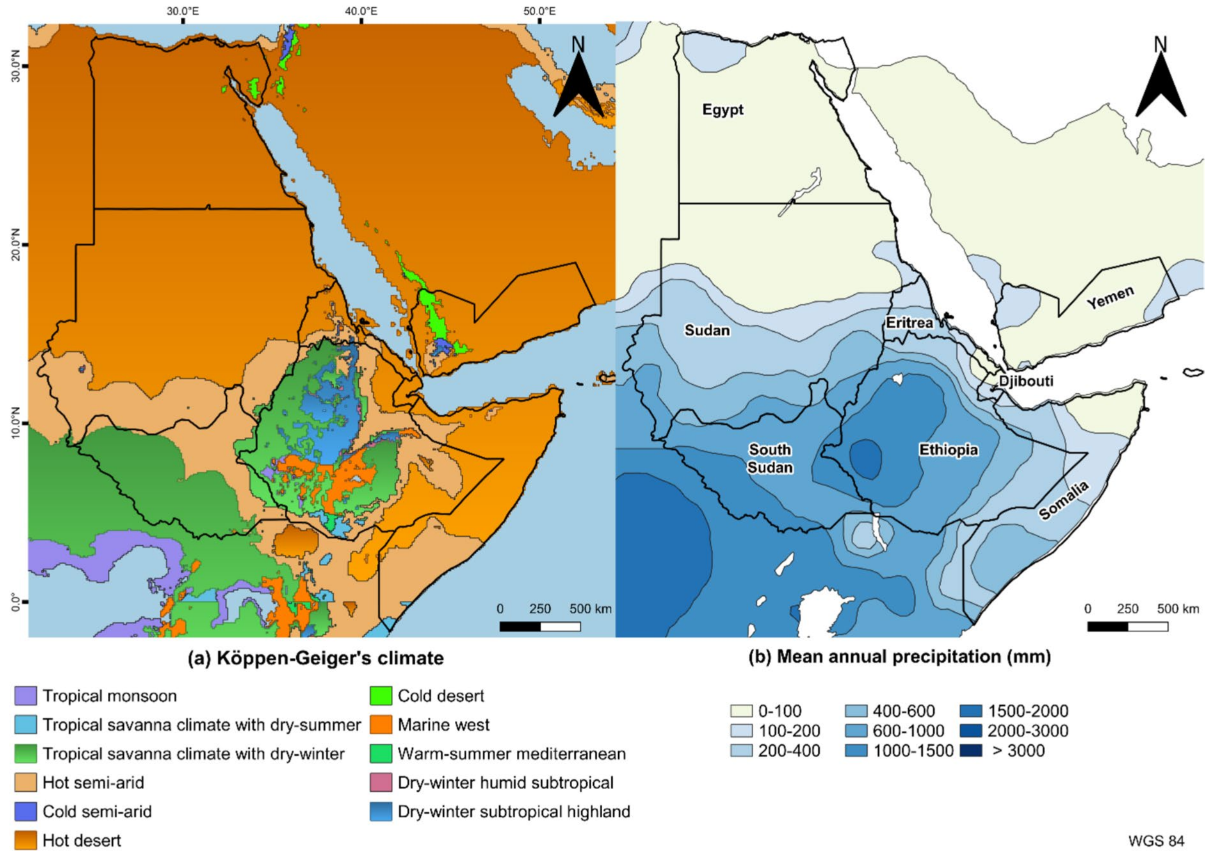


Fig. 3 Present-day climate in the study area: **a** Köppen-Geiger's climate classification; and **b** mean annual precipitation (mm). Figure created using the raster file from Kottek et al. (2006) and Deichmann and Lars (1991)

between February and March. The average temperature in the area is 18 °C, but varies significantly with elevation (Finneran, 2007; Hildebrand et al., 2019).

Environmental Data

This study examines the role of climate change in the emergence of agriculture and complex societies in the NHE by synthesizing paleoenvironmental data spanning 6000 to 1000 BP. The research encompasses Ethiopia, Eritrea, Djibouti, Somalia, Sudan, South Sudan, Egypt, and Yemen. Through a comparative analysis of environmental changes in the NHE and adjacent regions, the study aims to elucidate the processes that shaped agricultural development and the rise of complex societies.

To identify relevant academic literature, a systematic search was conducted using Google Scholar, Scopus, and the software "Publish or Perish" (Harzing, 2024). The review was limited to published, peer-reviewed articles. A Boolean search query was designed to target publications related to the research area and thematic topics in archaeology, geoarchaeology, and paleoenvironmental studies. Key terms such as "archaeology," "Aksumite," "geoarchaeology," "Holocene," "palaeoenvironment," and "palaeoclimate" were combined using logical operators (AND, OR) to ensure comprehensive retrieval of relevant results. Additional keywords, including "sediment," "geochemistry," "diatom," "ostracod," "pollen," and "isotope," were incorporated to reflect common proxies used in paleoenvironmental research. Specific words were enclosed in quotation marks to match exact terms, and the search process retrieved results across multiple pages. Metadata collected included publication titles, authors, and years of publication (SM2 for details).

Publications were excluded if they fell outside the defined scope of the study, which included the following criteria: (1) studies not focused on the geographical regions of interest (Ethiopia, Eritrea, Djibouti, Somalia, Yemen, Egypt, Sudan, and South Sudan); (2) studies addressing time periods outside the chronological range of 6000–1000 BP; (3) studies lacking relevant paleoenvironmental or climatic data; and (4) duplicate publications. The retrieved data were systematically organized and stored in a structured format using spreadsheet software (e.g., Microsoft Excel) to facilitate analysis and documentation (SM2).

From an initial pool of 132 articles identified, 50 were deemed relevant and included in the review for Ethiopia and Eritrea. For Djibouti, Somalia, and Yemen, a total of 66 articles were identified, of which 13 were ultimately selected for review following screening: Djibouti (5), Somalia (1), and Yemen (7). For Egypt, Sudan, and South Sudan, a total of 277 articles were retrieved, with 24 articles on Egypt and nine articles on Sudan and South Sudan meeting the inclusion criteria. In total, 95 articles were reviewed (see SM2 for a detailed breakdown).

Paleoenvironmental Records and Proxies Analyzed

Twenty-three paleoenvironmental studies were conducted in the NHE, specifically on the Tigray Plateau ($N=16$). Further south within the NHE, seven studies focused on the Amhara region, covering both the eastern margin and western areas of the highlands. In the central and southeastern Ethiopian highlands, two studies were conducted northwest of the Rift Valley (Mount Dendi), while 14 were located southeast of the Rift Valley in the Arsi and Bale Mountains (Fig. 2).

The number of studies conducted in the lowlands is significantly lower compared to the highlands ($N=16$, SM1). This discrepancy is largely attributed to the fact that most lowland studies focus on earlier periods that fall outside the temporal scope of this research (6000–1000 BP). Lowland studies are primarily concentrated along the Rift Valley, with only one study conducted offshore in Somalia (Fig. 2). Unlike the localized continental histories documented by the Rift Valley records, the offshore Somali study provides insights into the broader northeastern African climate. Nevertheless, the reliance on a single offshore study limits the ability to draw robust conclusions about regional climatic patterns, highlighting the need for additional research in this area. Within the Rift Valley, studies are clustered in three main areas (Fig. 4): the northeast (Afar Basin, including Lake Abhé and the Chew Bahir Basin, $N=5$), the central Rift Valley (Ziway-Shala Basin and Lake Tilo, $N=8$), and the southwest ($N=2$) (SM1).

Neighboring regions show a higher number of studies ($N=40$). Egypt has the highest number of research studies ($N=23$), with a significant focus on the Nile Delta and Faiyum Depression (SM1, Fig. 2). This emphasis on Egypt may reflect its long history of archaeological and paleoenvironmental research, as well as the availability of funding and infrastructure. Sudan has ($N=9$) studies primarily concentrated in Northern Sudan and Northwestern regions (e.g., Nubian Palaeolake Basin, Wadi Howar) (SM1, Fig. 2). Yemen has the lowest

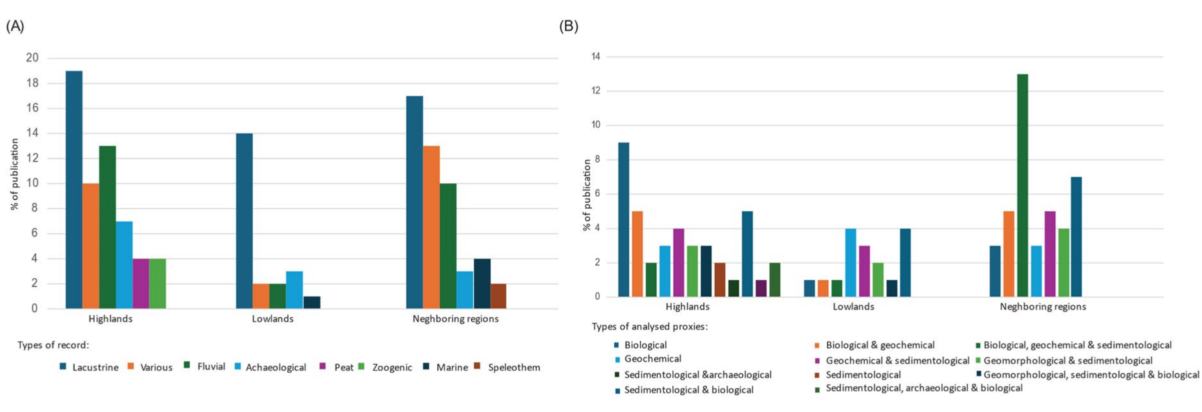


Fig. 4 Types of records (**A**) and proxies (**B**) used in the reviewed paleoenvironmental publications (SM1)

number of studies ($N=6$), with research distributed across highlands, lowlands, and Socotra Island (SM1, Fig. 2). The limited number of studies in Yemen may be due to political instability, limited infrastructure, or a lack of international collaboration. Another factor that may explain this is the probable low availability of continuous and undisturbed sedimentological records containing fossil organisms sensitive to environmental changes, which could hinder a comprehensive understanding of the region's paleoenvironmental history.

Highland research exhibits a balanced use of lacustrine (48.7%) and fluvial (33.3%) records, followed by various other records (25.6%). Archaeological records (18.0%) and peat and zoogenic deposits (each at 10.3%) are less commonly used. In the lowlands, lacustrine records dominate (87.5%). Among the remaining records, archaeological ones are the most frequently used (18.8%) (Fig. 4A). Neighboring regions, similar to the highlands, display a more heterogeneous distribution of records used in paleoenvironmental studies. In total, 42.5% of studies were conducted using lacustrine records, 32.5% with various records (including deltaic, palustrine, and aeolian deposits), 25.0% with fluvial records, 10.0% with marine records, 7.5% with archaeological records, and 5.0% with speleothem records (Fig. 4A).

The proxies used to reconstruct paleoenvironmental changes in the abovementioned sites were diverse, as were the combinations of different proxy typologies (Fig. 4), providing more complete histories of the paleoenvironmental changes (Huntley, 2012 and references therein). However, it is important to remember that, for example, distinct biological proxies are sensitive to different ecological factors at a range of spatial scales (Birks & Birks, 2006). Additionally, organisms also respond at the same time to many variables with interacting effects, so their isolation for reconstruction can result in inaccurate reconstructions (Huntley, 2012). Thus, this complicates comparisons among studies. Another factor complicating the comparisons is the different sampling resolutions used among the studies to reply to their distinct questions (Birks & Birks, 2006). All of this, combined with local depositional factors and the complexity of the study area atmospheric circulation (Bittner et al., 2021), will be responsible for the occurrence of asynchronies between climate changes identified in the records.

In the highlands, there was a strong emphasis on biological research (23%). The majority of these studies focused on pollen (an indicator of vegetation changes) and diatom or ostracod analysis (indicators of hydrological changes). While these proxies are widely used, their reliance on taphonomical processes may introduce biases, as certain environments may not preserve such material effectively. Some studies also combined these biological proxies with charcoal analysis (an indicator of fire dynamics). Biological and geochemical studies accounted for 12.8% of the research in the highlands. This relatively low percentage suggests that integrated approaches combining biological and geochemical proxies are underutilized, potentially limiting the depth of paleoenvironmental reconstructions.

In contrast, the lowlands focused more on geochemical proxies (25%) and combinations of geochemical and sedimentological studies (18%). This emphasis on geochemical proxies (e.g., $\delta 18O$, $\delta 13C$, $\delta 15N$, $\delta Dwax$, total organic carbon, carbonate content, and total nitrogen) may reflect the availability of suitable sedimentary archives in lowland environments. However, the interpretation of geochemical data can be complex and context-dependent, requiring careful consideration of local factors such as diagenesis and source variability. Sedimentological proxies (e.g., sediment texture and sorting) were often used in conjunction with geochemical analyses, providing additional insights into depositional processes (Friedman, 1979).

In neighboring regions, the most common types of proxies analyzed were biological, geochemical, and sedimentological (32.5%, Fig. 4). Studies combining geomorphological, sedimentological, and biological research were also conducted, though less frequently. Geochemical proxies included elemental composition of sediments and isotopic ratios such as 87Sr/86Sr and 143Nd/144Nd, which are indicative of sediment sources and transportation mechanisms. Radiocarbon dating is the most common methodology used to establish timeframes followed by OSL dating (SM1).

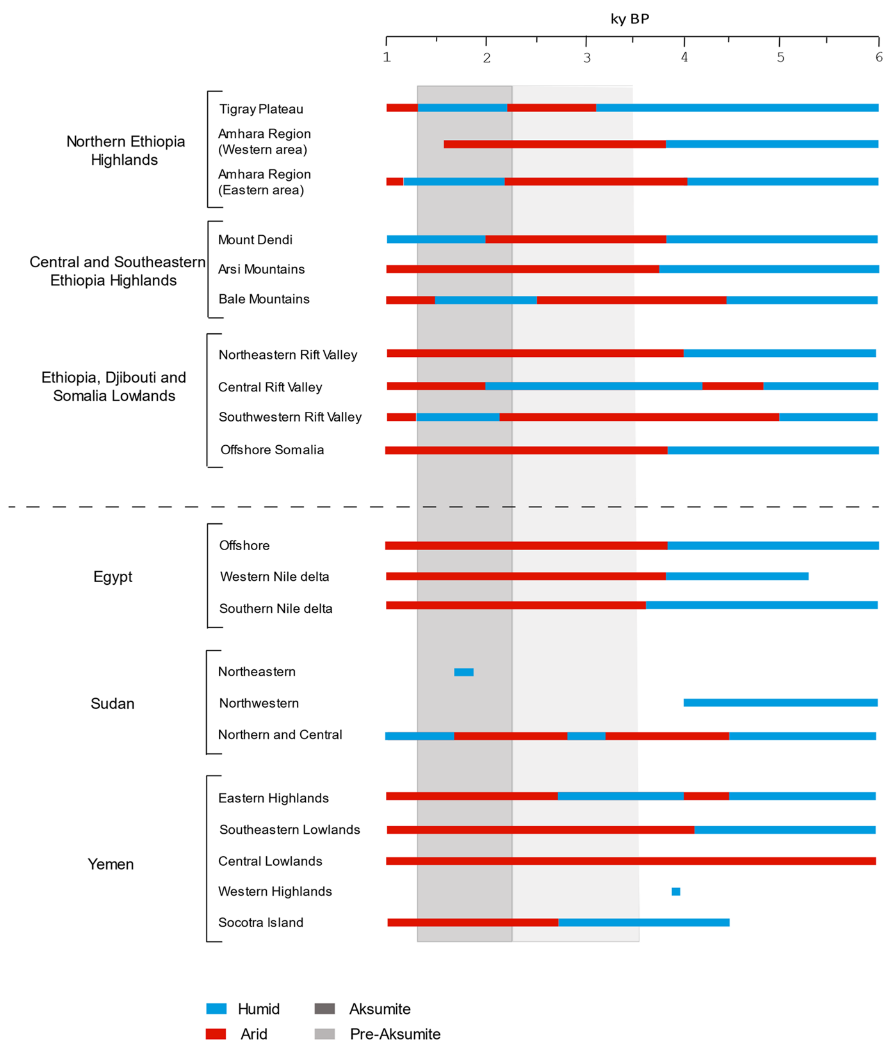
Paleoenvironmental Evolution (6000–End of AHP)

In the Ethiopian highlands, a pronounced humid phase, i.e., AHP, persisted from approximately 6000 to 3100 BP (Fig. 5). However, its termination was not abrupt or uniform across different parts of the highlands, reflecting the interplay of regional climate drivers and localized environmental factors (Tierney & deMenocal, 2013). For instance, in the northern highlands, particularly on the Tigray Plateau, the aridification trend that marked the end of the AHP was experienced between approximately 5160 and 3100 BP (Fig. 5; Berakhi et al., 1998; Brancaccio et al., 1997; Butzer, 1981; Dramis et al., 2003; Dramis & Fubelli, 2015; Gebru et al., 2009; Machado et al., 1998; Marshall et al., 2009). This area was among the last regions in the highlands to retain the conditions of the AHP. In contrast, in the western Amhara region, the end of the AHP occurred earlier, between 6000 and 3800 BP (Fig. 5; Costa et al., 2014; Marshall et al., 2011), while the eastern Amhara region experienced this transition between 4500 and 4000 BP (Fig. 5; Loakes et al., 2018).

In the central and southeastern highlands, the termination of the AHP also varied. Around Lake Dendi, the AHP ended gradually between 6000 and 3800 BP (Fig. 5; Wagner et al., 2018), while in the Arsi Mountains, the transition occurred around 3700 BP (Bonnefille & Hamilton, 1986; Hamilton, 1982; Umer & Bonnefille, 1998). In the Bale Mountains, the AHP ended earlier, between 5000 and 4000 BP, with a continuous trend towards drier conditions beginning around 6000 BP (Fig. 5; Bittner et al., 2020, 2021, 2022; Kuzmicheva et al., 2013, 2014, 2017, 2018; Tiercelin et al., 2008; Umer et al., 2007).

While the Ethiopian highlands exhibited a gradual and regionally variable transition to aridity,

Fig. 5 Synthesis of the spatial and temporal variations of the humid and arid environmental phases based on the publications presented in the SM1



lake records from the Rift Valley reveal additional insights into hydroclimatic shifts. In the northeastern Rift Valley, lake levels decreased between 6000 and 4000 BP, marking the end of the AHP (Fig. 5; Gasse, 1977; Gasse & Fontes, 1989; Gasse & Street, 1978; Mologni et al., 2021). In the central Rift Valley, the AHP ended slightly earlier, between 5000 and 4500 BP (Fig. 5; Benvenuti et al., 2002; Chalié & Gasse, 2002; Gillespie et al., 1983; Lamb et al., 2002; Telford & Lamb, 1999), and in the southwestern Rift, it ended around 5000 BP (Foerster et al., 2012, 2015). These fluctuations in lake levels reflect the significant role of localized hydrological processes and tectonic activity in shaping the region's climate and environment (Fig. 5; Grove et al., 1975; Lamb et al., 2002).

Further afield, in Egypt and Sudan, the end of the AHP aligns with a progressive climatic transition exhibited in the NHE. In Egypt, the AHP ended around 3700–3600 BP, as evidenced by variations in the Nile River's flow, which were influenced by conditions in the Ethiopian Highlands (Fig. 5; Baioumy et al., 2010; Blanchet et al., 2013; Revel et al., 2015; Zaky et al., 2020). Geochemical studies indicate that this gradual shift to aridity began around ~5000 BP, marked by decreasing freshwater input and more saline conditions in the Nile Delta (Dominik & Stanley, 1993; Hamdan et al., 2020a, b; Hassan et al., 2012, 2017; Revel et al., 2014), supported by a gradual increase in strontium isotope ratios (87Sr/86Sr) around 5500 BP (Flaux et al., 2013). Lake Faiyum also shows evidence of shrinking lake levels, high fluctuations, and a transition to brackish conditions (Hamdan et al., 2020a, b; Marks et al., 2018, 2022). The gradual decline in Nile flow had profound implications for agriculture and settlement patterns, potentially contributing to sociopolitical changes, such as the collapse of Egypt's Old Kingdom (Cullen et al., 2000; Hamdan et al., 2019, 2020a, b, 2024; Hassan et al., 2017; Marks et al., 2018, 2022; Revel et al., 2014; Stanley et al., 2003).

In Sudan, records linked to the Nile and White Nile rivers indicate the AHP lasted from 6000 to 4000 BP (Fig. 5; Dawelbeit et al., 2019; Florenzano et al., 2019; Hoelzmann et al., 2000; Kröpelin & Soulié-Märsche, 1991; Macklin et al., 2013; Marks, 1993; Williams & Adamson, 1980; Williams et al., 2010; Woodward et al., 2015a). In northern Sudan, lake levels gradually decreased between ~6300 and 4000 BP, with a transition to more arid conditions by 4000 BP, as evidenced by geochemical analysis (Hoelzmann et al., 2001).

In Yemen, the Arabian Humid Period, equivalent to the AHP, ended in the eastern highlands around 4500 BP, as indicated by fluvial, lacustrine, and speleothem records (Fig. 5; Anderson, 2007; Berger et al., 2012; Davies, 2006; Van Rampelbergh et al., 2013). Similarly, in Somalia, the AHP ended around 3800 BP, consistent with broader aridification trends in North Africa, as supported by Sr–Nd isotope analysis from marine cores (Fig. 5; Jung et al., 2004). The earlier end of the AHP in Yemen, compared to Ethiopia's highlands, may be attributed to shifts in the ITCZ, which modulated rainfall in these regions (Fig. 5; Fleitmann et al., 2007).

Paleoenvironmental Evolution (End of AHP–1000 BP)

As the AHP came to an end, the Ethiopian highlands entered a new climatic phase characterized by progressively arid conditions. However, the timing, duration, and severity of this aridification varied across different regions, reflecting the complex interplay of local topography, hydrology, and atmospheric circulation patterns. In the Tigray Plateau, the arid phase was relatively brief, lasting from approximately 3100 to 2500/2200 BP, coinciding with the end of the Pre-Aksumite culture and the rise of the Aksumite civilization (Fig. 5; Diblasi, 1997; Dramis et al., 2003; Gebru et al., 2009; Hardt et al., 2023; Lanckriet et al., 2015a, b; Machado et al., 1998). Similarly, in the eastern Amhara region, Mount Dendi, and the Bale Mountains, this drier phase ended around 2200 BP, 2000 BP, and 2500–2000 BP, respectively (Fig. 5; Bittner et al., 2020; Jaeschke et al., 2020; Kuzmicheva et al., 2017; Loakes et al., 2018; Umer & Bonnefille, 1998; Wagner et al., 2018). In contrast, the western Amhara region and the Arsi Mountains experienced a longer and earlier onset of aridity, beginning around 3800–3700 BP and persisting until approximately 1000 BP (Fig. 5; Bonnefille & Hamilton, 1986; Bonnefille & Mohammed, 1994; Hamilton, 1982; Marshall et al., 2011).

Paleoclimate studies indicate a dry phase during the Early Pre-Aksumite period, followed by wetter conditions during the rise of the Aksumite civilization, possibly linked to monsoonal variability (Butzer, 1981; Hassan, 1997; Terwilliger et al., 2013).

According to Marshall et al. (2009), this climatic shift may have spurred the development of the Aksumite Empire. Conversely, Terwilliger et al. (2011) proposed that increasing aridity, interspersed by wetter intervals, was the norm until 1300 BP, with no significant long-term climate change discernible.

During the Aksumite period, some parts of the Ethiopian highlands experienced localized wet phases, likely influenced by regional monsoonal shifts and hydrological changes rather than a return to AHP-scale humidity (Butzer, 1981; Marshall et al., 2009). This wet phase, characterized by strong periodic floods, wet slope soils, and high seasonal rainfall, persisted until approximately 1500–1300 BP in the Tigray Plateau, coinciding with the decline of the Aksumite civilization (Butzer, 1981; Dramis et al., 2003; Gebru et al., 2009; Lanckriet et al., 2015a, b; Machado et al., 1998; Terwilliger et al., 2013).

In the eastern Amhara region and southeastern and central highlands (Mount Dendi), this wet phase lasted until about 1300–1100 BP and 1000 BP, respectively (Fig. 5; Jaeschke et al., 2020; Loakes et al., 2018; Wagner et al., 2018). The Bale Mountains experienced a relatively brief wet pulse that concluded around 1500 BP (Bittner et al., 2020, 2021). Following this period, arid conditions re-emerged and persisted until approximately 1000 BP across the Tigray Plateau, the eastern Amhara region, and the Bale Mountains (Fig. 5; Bittner et al., 2020, 2021).

During this period, human activities significantly altered the landscape, as evidenced by paleorecords. In the Tigray Plateau, deforestation and agricultural expansion around 1600 BP coincided with increased erosion (Marshall et al., 2009, 2011). Similarly, in the eastern Amhara region, intensified land use around 2300 BP led to visible soil degradation and changes in pollen composition (Darbyshire et al., 2003). In the Wollo area, Coltorti et al. (2009) reported that climatic aridification and human activities became visible in increased erosion and sediment deposition in colluvial/alluvial records between 4000 and 2500 BP. Furthermore, pollen records from the Arsi and Bale Mountains in the southeastern highlands indicate human-altered vegetation between 2000 and 1000 BP (Fig. 5; Bonnefille & Hamilton, 1986; Hamilton, 1982; Kuzmicheva et al., 2017, 2018; Mologni et al., 2022; Umer et al., 2007).

In the northeastern Rift Valley, while the climate remained generally arid, minor lake transgressions occurred at Lakes Asal and Abhé between 2700 and 2300 BP and 1500 and 1000 BP (Fig. 5; Gasse, 1977; Gasse & Fontes, 1989; Gasse & Street, 1978; Mologni et al., 2021; Street & Grove, 1976, 1979). These transgressions likely resulted from surface runoff originating on the Ethiopian Plateau via the Awash River and/or groundwater interconnections between the lakes' basins (Fig. 5; Gasse, 1977; Gasse & Fontes, 1989; Gasse & Street, 1978; Mologni et al., 2021; Street & Grove, 1976, 1979).

In the central Rift Valley, records indicate a wet phase that contrasts with the broader climatic trends in the highlands and lowlands following the AHP. These wet phases, occurring between 4200 and 2500 BP and 2800 and 2000 BP, were likely influenced by a combination of climate, volcanic activity, and geothermal groundwater inflows into the lakes (Fig. 5; Benvenuti et al., 2002; Chalié & Gasse, 2002; Gillespie et al., 1983; Lamb et al., 2002; Telford & Lamb, 1999). Similarly, in the southwestern Rift Valley, a wet phase persisted between 2000 and 1300 BP, aligning with both the Aksumite period and a corresponding wet phase in the highlands (Fig. 5; Foerster et al., 2012, 2015).

After 4200 BP, the Nile River system underwent significant hydrological shifts, marked by declining flood levels, prolonged droughts, and reduced sediment deposition. These changes resulted in widespread land degradation, including floodplain shrinkage and declining soil fertility, which contributed to agricultural instability (Hamdan et al., 2019, 2020a, 2024; Hassan et al., 2012). This aligns with periodic aridity episodes identified at ~ 5000, 4200, 3200, and 2300 BP in the Sebennitic Distributary and Burullus Lagoon, leading to decreased Nile flow and reduced human activity. These events correlate with major paleoclimatic shifts recorded in the Nile Delta, Levantine Basin, and Faiyum Depression (Stanley et al., 2021). Furthermore, Lake Fayum (Lake Qarun) decline, bioturbation, pot sherds, and broken mollusk shells dominate the deposits, evidencing increased human activity and sediment reworking. From 2400 BP onward, the lake shows a drastic reduction in size (Hamdan et al., 2020a, 2024; Hassan et al., 2012).

In Sudan, episodic wet pulses occurred between 3200 - 2800 BP and 1900 - 1000 BP, reflecting temporary shifts in regional hydroclimate (Fig. 5; Mawson & Williams, 1984; Williams & Adamson, 1980; Williams et al., 2010). In the southeastern lowlands, the end of the AHP was recorded at 4100 BP, with the central lowlands remaining desert or semi-desert throughout the period (Fig. 5; Hoelzmann et al., 2001; Lézine et al., 2010; Parker et al., 2006). In the Kordofan region of central Sudan, between 3300 and 1100 BP, massive wind erosion (deflation surfaces) removed sediments, resulting in a hiatus in the sedimentary record. However, pollen data indicate extreme aridity, characterized by desert-like vegetation (Dawelbeit et al., 2019). Holocene fluvial sedimentary records in the Nile catchment also support this aridity period, during which tributary wadis became strongly ephemeral, and windblown dust became a major factor in sedimentation (Macklin et al., 2013; Woodward et al., 2015a, 2015b).

Contrary to these regional trends, Socotra Island records indicate a long-term increase in precipitation from approximately 4400 BP, illustrating localized deviations from the broader aridification observed elsewhere (Fig. 5; Fleitmann et al., 2007). The period between 2500 and 1000 BP shows high $\delta^{18}O$ values, suggesting drier conditions followed by a wetter phase (Van Rampelbergh et al., 2013).

Factors Behind Environmental Variability

The variability in the timing and nature of the environmental changes across the study area can be attributed to differences in the types of records, proxies used, their inherent sensitivities, and localized environmental conditions. Each proxy offers a unique lens for past environmental conditions, but the interpretation of their records often depends on their resolution, spatial coverage, and the interplay of natural and anthropogenic factors. Isotopic, sedimentological, and palynological records each not only provide distinct insights into the environmental conditions but also carry inherent biases that shape interpretations. For example, in opposition to other studies in the Tigray Plateau, the $\delta^{18}O$ data from Lake Ashenge (~5600 BP) reveal abrupt aridification linked to monsoon weakening, yet such signals may conflate regional precipitation shifts with localized hydrological processes, such as groundwater inputs or evaporation dynamics (Marshall et al., 2009). In contrast, Lake Tana's gradual sediment decline (~6800–4200 BP) reflects the buffering capacity of its large catchment, illustrating how sedimentological proxies integrate long-term trends but often obscure rapid climatic events (Costa et al., 2014; Marshall et al., 2011). Similarly, pollen records from the Bale Mountains highlight microclimatic refugia where elevated terrain retained moisture until ~4000 BP, though preservation biases likely underrepresent arid-adapted species, complicating ecological reconstructions (Bonnefille & Hamilton, 1986).

Human activities further complicate proxy interpretations. In the Tigray Plateau, deforestation and agricultural expansion (~1600 BP) amplified erosion signals, blurring the line between climatic and anthropogenic drivers in colluvial records (Marshall et al., 2009, 2011). Likewise, Sr–Nd isotopes in Nile Delta sediments trace declining Ethiopian Highland rainfall (~5000 BP), but downstream impacts, such as Old Kingdom collapse, remain debated due to overlapping sociopolitical stressors (Woodward et al., 2015a, 2015b). Regional connectivity is evident in synchronicity between Sudanese wet phases (~3200–2800 BP) and Ethiopian Rift Valley humid intervals, likely tied to ITCZ coherence, while anomalies like Socotra Island's precipitation spike (~4400 BP) underscore oceanic moisture influences distinct from continental monsoons (Jung et al., 2004; Williams et al., 2010).

In the Central Rift Valley, volcanic activity and geothermal groundwater inflow likely played a critical role in sustaining localized wet conditions despite broader regional aridification. Geothermal-fed lakes and springs provided a continuous water source, buffering against declining precipitation and slowing evaporation. This process, combined with hydrothermal discharge and groundwater-driven vegetation refugia, may explain the prolonged wet phases recorded between ~4200 and 2500 BP and ~2800 and 2000 BP, contrasting with the widespread drying observed elsewhere (Benvenuti et al., 2002).

Topography plays a crucial role in shaping regional climatic responses, particularly in delaying the onset of aridification in high-altitude environments. The southeastern highlands, with their higher elevation and cooler temperatures, facilitated prolonged moisture retention by reducing evaporation and enhancing orographic precipitation (Bittner et al., 2020; Kuzmicheva et al., 2017). Palynological records from the Bale Mountains indicate that these conditions allowed localized wet phases to persist until ~4000 BP, even as surrounding lowland regions underwent more rapid drying (Bittner et al., 2020; Kuzmicheva et al., 2017).

Discussion

An analysis of past environmental changes in the NHE, compared to neighboring regions, provides valuable insights into the emergence of agriculture in the area. However, as Finneran (1999) and Harrower et al. (2010) have emphasized, this process cannot be attributed to a single factor. Instead, it reflects a complex interplay of environmental, social, and cultural influences that are deeply interconnected and cannot be fully disentangled.

This study reviews environmental changes in the NHE and its neighboring regions over the period from 6000 to 1000 BP, a time frame that coincides with the development of agriculture and the rise of one of the most influential kingdoms in ancient history. Assessing the extent to which environmental changes influenced cultural processes—such as agriculture, urbanization, and long-distance trade—remains challenging due to several factors: research limitations, and the inherently complex interactions between human-environmental dynamics and socio-cultural developments.

Climate and Development of the Agricultural Pre-Aksumite and Aksumite Culture

One hypothesis suggests that the aridification of the lowlands at the end of the AHP drove pastoralists and incipient agriculturalists from eastern Sudan to the plateaus and high pastures of the NHE, where conditions were still amenable. This puts a strong emphasis on climate as an explanation for social and cultural changes (*i.e.* transition to agriculture). Eastern Sudanese agropastoral communities play a significant role in influencing NHE to adopt complex societies and agropastoral practices (D'Andrea et al., 2023). Although detailed research and comprehensive data are still lacking, it is suggested that the agropastoralism and early social complexity observed in the Pre-Aksumite period may have been influenced by the Agordat or Gash Groups (Brandt et al., 2008; Finneran, 2007). The ceramics' resemblance to those from Sudanese cultures, including the Jebel Mokram, Early Kerma period, Pan-grave, and C-Group cultures, indicates potential interactions and cultural exchanges between these regions (Beldados, 2007; Sadr, 1991). The movement of pastoralist populations in a wider region may be associated with a period of aridity of 3700 BP (Bard, 2021; Lesur et al., 2014). At the same time, the archaeological record suggests the earliest agro-pastoralist communities in the lowlands lived in the Nile Valley, where water stress would not have been felt as the humid conditions at the NHE would have fed the river. This is not to say that pastoralism and early agriculture were not introduced in the NHE by ACT groups in possession of SWA and African crops, only that climate-driven migrations are an unsatisfactory explanation.

The paleoenvironmental data indicate the occurrence of a distinct wet pulses between 2500 and 2000 BP and 1500 and 1000 BP in the NHE (and part of the Ethiopian lowlands, i.e., southwestern Rift Valley). This climatic phase coincides with the critical transition from the Pre-Aksumite to the Aksumite period (Fig. 5), which might suggest a link between environmental changes and socio-political developments in the region. The increased rainfall during this period likely contributed to more favorable conditions for agriculture in the Ethiopian highlands. As a result, agricultural productivity may have surged, leading to a surplus of resources, which in turn could have supported the rise of urban centers and the emergence of organized polities, hallmark characteristics of the Aksumite civilization. Such arguments align with environmental determinism theories, where climatic changes act as catalysts for socio-political and economic transformations. This, in turn, facilitated the emergence of urban centers and the political centralization seen in the Aksumite period.

In the highlands of the neighboring Yemen region, there was a wet phase between 4000 and 2700 BP that is temporally coincident with the appearance of the agricultural-based Sabean culture (3800 to 3000 BP). This fact might suggest that environmental conditions might have favored the development of agriculture in Yemen. The end of this wet phase in the eastern part of the Red Sea is contemporary with a move towards settled agro-pastoral communities in the NHE, engaged in monumental construction, as evidenced by the Early and Middle Phases at Mezber (D'Andrea et al., 2023) or the Yeha II phase of the homonymous site (Fattovich, 2009). It is also during this time that a change in the abundance and type of crops occurs in the NHE, with a stronger emphasis on SWA crops (Ruiz-Giralt & Beldados, 2024), and a South Arabian influence in elite material culture becomes clear (Phillipson, 2012). These changes in the archaeological record have been explained by a movement of Sabean people from the Arabian Peninsula into the NHE, or at the least the establishment of Sabean enclaves (Fattovich, 2010; Japp et al., 2011; Köster, 2021). The climatic data reviewed here gives credence to the movement hypothesis. The end of the humid phase in the Yemen area *ca.* 2700 BP could have led to a movement of migrant towards the NHE. The greater water availability and environmental stability in the highlands compared to the lowlands would have led to the establishment of Sabean enclaves there (Harrower et al., 2010; Sergew, 1972). They would have brought with them their crops (*p.ex.* emmer, lentils, flax), agricultural innovations, and some aspects of their material culture (monumental construction, writing) (Bard et al., 2000; Butzer, 1981; Curtis, 2007 and references therein; D'Andrea et al. 2008; Kobishchanov, 1979; Michels, 1988, 1994, 2005; Stiehler, 1948; Sulas, 2014; Sulas et al., 2009). Caution is advised as the occurrence of climate shifts in the Arabian Peninsula does not exclude that the cultural exchanges between Sabeans and NHE populations that are visible in the archaeological record may have occurred within the context of trade, and not due to migrations. The Red Sea region and NHE have a well-documented history of long-standing trade relations as early as the sixth millennium (Khalid et al. 2010; Zazzaro, 2013), extending far beyond the arrival of the Sabeans. This raises the question: Did the introduction of domesticated crops and agricultural practices in the NHE require the migration of an entire Sabean community, or could it have been facilitated by a smaller, more mobile group of people? This discussion invites us to consider the role of trade and cultural exchanges in the spread of agricultural knowledge. The transfer of agricultural practices and domesticated crops might not have necessitated large-scale migration but could have been achieved through the interactions of trade networks. A group of people who frequently travelled between the Red Sea region and the NHE could have served as key agents in transmitting new crops and farming techniques. Could a small group of traders or people significantly influence agricultural development? Is larger community migration necessary for such cultural and technological transfer?

Based on the available information, the scenario presented in the section "East of NHE" does not appear to have played a significant role in the early stages of agriculture in NHE. The situation outlined in the section "North-West of NHE" deserves consideration as there are archaeobotanical findings of African domesticated crops in the NHE record already at around 3500 BP (Ruiz-Giralt et al., 2023). Those same groups could have introduced some SWA crops, such as barley (Beldados et al., 2023; D'Andrea et al., 2023; Meresa et al., 2024; Ruiz-Giralt et al., 2023). This is further supported by evidence of flax/linseed appearing earlier in the Horn of Africa than in South Arabia (Beldados et al., 2023; Ruiz-Giralt et al., 2023). Beldados et al. (2023) propose that the introduction of SWA crops may have come from Eastern Sudan or South Arabia, or possibly a combination of the two. Indeed, this could have happened, albeit at different stages.

We propose that an early agricultural stage occurred from 3500 to 2700 BP, led by a movement of mostly pastoralist ACT groups with a subsistence based on cattle and ovicaprids as well as cultivation of a variety of African and SWA crops, possibly complemented by the harvest of local wild plants. This movement was not driven by climate change but by a dynamic exploration of new territories. During this stage, some varieties of barley, flax, and lentil adapted to highland environments. At around 2700 BP, the aridification of South Arabia would have led to a second stage, characterized by the introduction of new SWA crops (*p.ex.* naked wheat) and new varieties of existing SWA cultigens (*p.ex.* barley and lentils). This occurred via contacts (or migrations) between the NHE and Sabean groups. This mixture of different varieties could explain the extraordinary genetic diversity of these crops in Ethiopia: a localized mixture of plants with different origins, old, locally adapted and geographically isolated enough to have escaped more recent introductions. The arrival of novel farming methods, relatively humid conditions, and intensification of the cultivation of local crops (such as t'ef or finger millet) would have permitted a food surplus at the NHE. This surplus would in turn serve to intensify external trade, the emergence of local elites, and, in due time, the establishment of the Aksumite kingdom.

Conclusion

Synthesizing paleoenvironmental data from published studies is challenging due to several factors, including the limited number of studies conducted in relevant areas and time periods, their uneven geographical distribution, low diversity in record types, and varying sampling resolutions. These issues are compounded by political and socio-economic instability in the region, as well as a predominant research focus on human evolution rather than more recent periods. Additionally, the natural distribution of sites capable of preserving continuous sediment records, such as lacustrine deposits, further limits available data. To address these challenges, it is necessary to increase sampling diversity by incorporating sediments from archaeological sites, despite potential methodological issues. Furthermore, inconsistencies in climatic phase synchronization across different regions underline the need for more high-resolution, multi-proxy studies to improve chronological accuracy in reconstructing past environmental changes.

In conclusion, an integrated view of the paleoenvironmental changes that occurred in the Northern highlands of Ethiopia, the Horn of Africa, and surrounding regions between 6000 and 1000 BP provides the context for which to explain the emergence of agriculture and urban societies in this region. Based on this, we concluded that:

1. Paleoenvironmental conditions in the broad region at large during this transition stage were not uniform but rather presented huge variation and different tempos for the occurrence of significant changes.
2. Early agriculture and the rise of Pre-Aksumite societies in the NHE were not directly linked to the environmental changes that occurred in the region around 3500 BP. Social phenomena and dynamics between local human groups in the region provide more satisfactory explanations.
3. The NHE highlands experienced a shift towards higher humidity during the Proto-Aksumite transition phase and Aksumite period, specifically between 2500 and 2000 BP and 1500 and 1000 BP. This transition might lead to higher agricultural productivity and the food surplus that were the basis of the Aksumite kingdom. Hence, it can be concluded that changes in the paleoenvironment had significant implications for the development of this state society.

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Author Contribution Degsew Z. Mekonnen: conceptualization, methodology, investigation, formal analysis, writing — original draft, visualization, funding acquisition.

Ana Gomes and Hugo R. Oliveira: conceptualization, writing — review and editing, supervision, funding acquisition.

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Data Availability All data is included in the text and supplementary files.

Declarations

Competing Interests The authors declare no competing interests.

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