African Journal of Advanced Studies in Humanities and Social Sciences (AJASHSS)
المجلة الإفريقية للدراسات المتقدمة في العلوم الإنسانية والاجتماعية
Online-ISSN: 2957-5907
Volume 5, Issue 1, 2026
Page No: 648-666
Website: https://aaasjournals.com/index.php/ajashss/index
Arab Impact factor 2024: 0.81 **SJIFactor 2024: 6.856** **ISI 2025: 1.191**

Phenological Factors and Subsistence Strategies in Changing Environments: A Case Study of Late Pre-Pastoral/Late Acacus Sites in the Libyan Sahara during the Early–Mid Holocene

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العوامل الفينولوجية واستراتيجيات الاعاشة في البيئات المتغيرة: دراسة حالة للمواقع ما قبل الرعاوية/الأكاكوس المتأخر في الصحراء الليبية خلال الهولوسين المبكر والأوسط

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Received: December 14, 2025	Accepted: March 02, 2026	Published: March 16, 2026

Abstract:
This study evaluates the phenological mechanisms and factors that drove changes in spatial organization and economic strategies at Pre-Pastoral/Late Acacus habitation sites occupied by pottery-using hunter-gatherers in the Libyan Desert. These sites provide crucial chronological and economic evidence for understanding paleoclimate dynamics in the region. An integrative methodology was employed, combining palynological analysis with historical, archaeological, and paleoecological approaches. A comparative framework across both temporal and spatial scales was applied to examine the interactive relationship between climatic fluctuations and human adaptive strategies, linking these patterns to ecological, stratigraphic, and typological changes observed in both neighboring and more distant areas within the same chronological context. The results indicate that declining humidity during the Early–Middle Holocene disrupted seasonal vegetation cycles, affecting the availability of natural resources. In response, hunter-gatherer groups adopted a semi-sedentary spatial organization in a strictly mountainous environment, characterized by more complex architectural structures and a specialized subsistence economy. This economy relied on a wide range of plant and animal resources, the production of large sandstone flakes, the use of microlithic toolkits, and various manufactured items such as baskets and bone tools. Pottery was widespread and decorated Dotted Wavy Line pottery, and in some cases, dotted-line patterns. The study concludes that phenological changes were a major driver in reshaping the economic and social structures of Late Acacus communities, shaping human adaptive strategies and resource management in an increasingly arid desert environment.

Keywords: Phenological Factors; Late Acacus; Spatial Organization; Libyan Sahara; Economic Strategies; Early–Mid Holocene.

الملخص
تقيم هذه الدراسة الميكانيزمات/العوامل الفينولوجية التي أدت إلى حدوث تغيرات في التنظيم المكاني والاستراتيجيات الاقتصادية لمواقع الإقامة ما قبل الرعاوية/الأكاكوس المتأخر والتي شغلها الصيادين الجامعين المستخدمين للفخار في الصحراء الليبية. حيث توفر هذه المواقع بينات هامة، وتواترات كرونولوجية واقتصادية لدراسة المناخ القديم في المنطقة. تم اعتماد منهجية تكاملية تجمع بين التحليل البالينولوجي والمقاربات التاريخية والأثرية والإيكولوجية القديمة، مع توظيف مبدأ المقارنة وفق نمطين زماني، ومكاني في محاولة لفهم العلاقة التفاعلية بين التحولات المناخية وأنماط التكيف الإنساني في المنطقة، مع ربطها بالتغيرات الايكولوجية والاستراتيغرافية، والتيبولوجية التي حصلت في المناطق المجاورة من منطقة الدراسة أو حتى تلك البعيدة عنها، والتي تنتمي للعمق الكرونولوجي نفسه. تشير النتائج إلى أن انخفاض معدلات الرطوبة خلال الهولوسين المبكر/الأوسط قد تسبب في حدوث اضطرابات في الدورات الموسمية للنباتات، مما أثر على توفر الموارد الطبيعية، ودفعت بمجموعات الصيادين-الجامعين إلى تبني تنظيم مكاني شبه مستقر في بيئة جبلية خالصة، وسط مبان أكثر

تعقيداً، واقتصاد متخصص مبني على استغلال طيف واسع من الموارد النباتية والحيوانية، وصناعة رقائق كبيرة على حجر رملي، مع استخدام أطقم أدوات ميكروليتية، وقائمة مواد صنعية مثل السلال والأدوات العظمية، في حين كان الفخار شائع الاستخدام، ومزخرف وفق تقنية الضغط بالمهزة، وفي حالات أخرى بخطوط منقطة. وتخلص الدراسة إلى أن التغيرات الفينولوجية شكلت عاملاً رئيساً في إعادة تشكيل البنية الاقتصادية والاجتماعية لمجتمعات الأكاكوس المتأخر، وأسهمت في توجيه استراتيجيات التكيف البشري وإدارة موارده مع بيئة صحراوية أخذة في الجفاف

الكلمات المفتاحية: العوامل الفينولوجية، الأكاكوس المتأخر، التنظيم المكاني، الصحراء الليبية، الاستراتيجيات الاقتصادية، الهولوسين المبكر-الأوسط.

Introduction:

Late Acacus sites belong to the Holocene Saharan–Coastal technical complex, which has been described in the literature under various historical, archaeological, ecological, and technical designations, including the Early Khartoum horizon, the Pre-Pastoral horizon in the Tadrart Acacus and surrounding regions, and the Niger–Air–Ténéré complex. These cultural traditions spread their artefacts and pottery across a vast geographical area. The reasons behind this rapid expansion remain insufficiently clarified, particularly given that the Dotted Wavy Line pottery complex represents the earliest cultural manifestation following the demographic hiatus of the Late Pleistocene .With climatic improvement and the onset of humid conditions during the Early Holocene, human groups reoccupied territories previously abandoned due to aridity. One prevailing theory suggests that pottery spread among diverse human groups across the Sahara and Sahel, the Middle Sahara, the Eastern Egyptian Desert, Eastern Sudan, the Atlantic regions, the Mediterranean coast, and the Western Libyan Desert, with minimal variation in decorative style—specifically the Dotted Wavy Line motif—throughout this extensive area.

As Barry Sutton argued in two articles published in the 1970s, based on analyses of physical anthropology and linguistic evidence, this unique cultural phenomenon—the diffusion of the Dotted Wavy Line pottery complex—resulted from the early migration of Zanzibar populations speaking ancestral forms of modern Nilo-Saharan languages from Central Africa. These groups relied heavily on aquatic resources such as rivers and lakes for subsistence, hence the designation “Aquatic Stone Cultures” (Sutton 1974; 1977). Accordingly, the centre–periphery hypothesis appears theoretically and empirically inadequate for explaining the invention and spread of pottery in Africa and should therefore be reconsidered. Early radiocarbon dates for Saharan pottery instead suggest a local and independent technological innovation.

In Libyan Saharan prehistory, the term “Late Acacus” is generally associated with hunter-gatherers and fisher communities equipped with Mesolithic lithic industries who settled in the Tadrart Acacus range and surrounding areas during the Early Holocene, exploiting a broad spectrum of plant and animal resources. It should be noted that the adoption of the term “Pre-Pastoral” as a recognized technical designation emerged only after prolonged scholarly debate among Africanist archaeologists. This debate challenged the uncritical application of European chronological terms—such as Paleolithic, Mesolithic, and Neolithic—to the Early and Middle Holocene cultural sequences of North Africa (Di Lernia and Garcea 1997; Garcea 2004). These imported classifications often failed to provide comprehensive interpretative models for Saharan Holocene cultures. For example, pottery and polished artefacts have traditionally been considered diagnostic indicators of the Neolithic. Consequently, any site containing such materials was classified as Neolithic, whereas sites lacking pottery were assigned to the Epipaleolithic or Mesolithic. However, the presence of pottery within Late Paleolithic stratigraphic sequences challenges this conventional framework. In reality, these communities continued to maintain hunter-gatherer subsistence systems despite possessing pottery technology.

The study area comprises the Tadrart Acacus mountain range in the central Sahara, located in the Fezzan region of southwestern Libya (24°00′–26°00′ N; 10°20′–11°20′ E). This sandstone massif is intersected by numerous west–east valleys and bordered by a steep western escarpment. It contains abundant caves and rock shelters that served as recurrent human occupation sites from the Late Paleolithic onward, preserving dense accumulations of organic plant and animal remains alongside artefacts.

Hydrologically, Wadi Teshuinat represents one of the most significant valleys in the range. Characterized by localized microclimates with relatively higher humidity and rainfall, it supported abundant groundwater and dense vegetation. These environmental conditions made it a favourable habitat repeatedly occupied by hunter-gatherer groups practicing short- and long-term settlement strategies. Archaeological remains include microlithic and polished stone tools, hearths, plant- and bone-based artefacts, grinding stones, thin habitation layers, and extensive rock art. Notably, this valley served as the principal base for the Libyan–Italian archaeological mission led by Fabrizio Mori.

The significance of this study lies in its focus on Late Acacus sites that provide comprehensive datasets for reconstructing paleoclimatic fluctuations and their ecological consequences. Archaeological surveys have yielded radiocarbon dates, stratigraphic sequences, and typological data illuminating environmental conditions and their influence on human settlement, subsistence systems, and technologies. Since settlement patterns were closely tied to environmental factors, it is essential to emphasize how fluctuations in natural resources expanded,

diversified, or constrained subsistence systems. Such processes are closely associated with phenological events linked to alternating wet and dry climatic phases and their effects on plant and animal life cycles. These dynamics are traceable in stratigraphic deposits and post-depositional processes at sites such as Ti-n-Torha, Uan Afuda, and Uan Tabu. Consequently, Middle Saharan mountain regions followed distinct cultural trajectories, particularly regarding the transition toward food production (Rotunno and Crema, 2025).

Within this framework, the present paper seeks to investigate the mechanisms that led to changes in settlement patterns during the Late Acacus period. Specifically, it examines the phenological processes that influenced transformations in spatial organization and economic strategies. The study analyses stratigraphic, typological, ecological, and technological data from Mesolithic hunter-gatherer sites that utilized pottery between 8800 and 7400 BP. It incorporates socio-economic indicators, artefact assemblages, rock art, and chronological evidence.

Methodologically, the study is grounded in a theoretical model structured around three principal variables: climate and associated phenological events as independent variables; spatial organization and economic strategies as dependent variables; and material culture as behavioural indicators. The research employs an integrative methodology combining palaeoenvironmental analysis with archaeological and historical approaches. It applies the principle of comparison across both temporal and spatial dimensions to elucidate the interactive relationship between climatic change and human adaptation, situating the Acacus evidence within broader regional contexts.

The study further critically evaluates the hypothesis that Late Acacus hunter-gatherers at sites such as Uan Afuda, Uan Tabu, and Ti-n-Torha engaged in incipient domestication practices. This evaluation rigorously investigates the interrelationship between climatic fluctuations, phenological dynamics, and adaptive strategies. The theoretical framework adopted herein seeks to elucidate the dynamic and reciprocal interplay between human observers and their environment, highlighting the variability of natural resources as a determining factor in the expansion or contraction of subsistence regimes, the stimulation of technological innovation, and the configuration of predatory economic strategies.

1- Chronological Framework and Cultural Frequency:

Field studies and archaeological investigations of prehistoric sites in the Libyan Desert began in the 1950s. The first systematic archaeological documentation of pre-pastoral cultures in the Acacus Mountains originated from Passa's excavations at the Fozzigiaren site, where he identified two radiocarbon dates: one at 8100 ± 100 years ago and another at approximately 7900 years ago. This coincided with Mori's expedition to the Acacus Mountains, particularly in the Wadi Teshuinat, where he documented, classified, and interpreted the rock art complex. Mori demonstrated exceptional skill not only in interpreting the cultural content of rock art, its cosmological vision, and underlying concepts (Mori, Fabrizio, 1998, 31–38) but also in developing a detailed five-phase chronological framework. This framework was based on variations in style, techniques, subject matter, and the relationship between rock art, the environment, and archaeological evidence (Mori, 1998, 43–51). It later served as the basis for establishing chronological sequences in the region.

While Mori significantly advanced the understanding of rock art and its conceptual dimensions, a knowledge gap persisted regarding the frequency and continuity of human habitation and its relationship to rock art. To address this, in the early 1970s, the Institute of Palaeoanthropology at the University of Rome launched a research project with a strong anthropological focus, aimed at reconstructing the stratigraphic and cultural record of the early Holocene in the Acacus series and surrounding areas.

A central objective of this research was to establish a clear methodology for survey work, chronological verification, and the cultural orientation of the hypotheses. By the early 1980s, studies in the Acacus region shifted towards an integrative approach, combining archaeological investigations with various natural sciences. Researchers re-examined cultural dynamics and human behavior in relation to climatic and environmental conditions, local fauna and flora, and sedimentation processes. This interdisciplinary approach enabled reconstruction and synthesis of subsistence strategies, subsequently analyzed using ethno-anthropological models.

Significant contributions were made in the detailed description of archaeological layers, linking typological and stratigraphic evidence with absolute chronological data obtained through multiple techniques, including radiocarbon (C14) dating, thermoluminescence (TL) dating, and optically stimulated luminescence (OSL) dating (Martini, M. et al., 1999, 67–72). It is important to note that absolute dates represent statistical ranges, expressed in ± years. The integration of typological data, stratigraphy, artefacts, and cultural processes has allowed for a refined absolute chronology.

Based on findings from the joint Italian-Libyan mission of the University of Rome "La Sapienza," the Acacus cultural horizon has been divided into three distinct blocks: the Late Palaeolithic settlement characterized by stone tools, and the pre-pastoral horizon, comprising the Early Acacus and Late Acacus phases. Within the pastoral horizon, three phases—Early, Middle, and Late—can be identified.

The chronological range of pre-pastoral sites in the Acacus has been determined to span approximately 10,000 to 8,580 ± 80 years ago. A key question is whether the pre-pastoral archaeological record reflects

a continuous evolutionary sequence or whether temporal gaps exist between phases. Some researchers have identified a significant discontinuity—a sterile eolian sand layer approximately one meter deep—between Late Pleistocene hunter-gatherer and early Holocene/Epi-Paleolithic settlements (di Lernia, 1999c, 223–224). This discontinuity is thought to result from drought conditions during the late Pleistocene (di Lernia, 1999a, 7–8). Despite gaps in the record, the archaeological sequence should be viewed not as a series of disconnected possibilities but as a continuous thread linking successive cultural and evolutionary stages. For example, following climatic amelioration in the early Holocene, hunter-gatherers resumed settlement in the Acacus region and its environs.

From a laboratory perspective, radiocarbon dates for Early Acacus sites indicate a long period of occupation, suggesting continuity into the Late Acacus period and beyond to pastoral settlements. At Uan Afuda, the chronological range of the Early Acacus has been revised from 9800 ± 260 to 8900 ± 260 years ago (di Lernia, 1999b, 63), and the Late Acacus from 8765 ± 100 to 8000 years ago (di Lernia, 1999b, 82). At Uan Tabu, radiocarbon dates span from 9810 ± 75 to 8880 ± 100 years ago (Garcea, 2001a, 225), revealing economic, subsistence, and technological patterns distinct from those of the Late Acacus settlements, which appear partially eroded. The Late Acacus horizon extends from 8870 ± 100 to 8580 ± 80 years ago (Garcea, 2001a, 227.(

Excavations led by Barbara Barich in northern Acacus in 1978 further explored Late Acacus settlements and early pottery use, notably at the Ti-n-Torha site in Wadi Owais (Barich, 1984a, 399–400). Distinct radiocarbon dates were recorded at Ti-n-Torha/Two Caves: level R-1404 at 8400 ± 90 years ago and level R-1406 at 8620 ± 50 years ago; at Ti-n-Torha/East, level R-1160α yielded 8540 ± 140 years ago (Barich et al., 1984b, 412–413.(

Absolute chronologies for Late Pre-Pastoral settlements have also been recorded in surrounding regions. In the Air-Tenere region of Niger, Epi-Paleolithic settlements show dates comparable to Ti-n-Torha and Uan Afuda: 8938 ± 174 years ago at one site (Smith, 1993, 70), 8689 ± 285 at Tamaya Mellet, 8691 ± 234 at Tagalagel, and 8363 ± 79 at Adrar Bous (Jesse, 2003, 45). The Ongourou Valley in Mali preserves even older dates, with one radiocarbon date of 9800 ± 1000 years ago, and two additional dates at 9785 ± 70 and 9550 ± 100 years ago (Huysecom et al., 2009, 908). At Bir Kiseiba in Egypt, radiocarbon dates align with Ongourou, concentrating between 8430 ± 158 and 8255 ± 130 years ago (Jesse, 2003, 45.(

Taken together, these absolute dates provide sufficient resolution to assess whether they reflect continuous cultural processes—accumulating evolutionary changes in Early Acacus and its foraging economies—or a sequence culminating in Late Acacus settlements characterized by Mesolithic techniques. The chronological sequence integrates considerations of place, time, energy, and biomass.

Radiometric, C14, and OSL data from the Late Acacus indicate that residential sites were located across varied physical and geomorphological contexts, including mountain ranges, plains, and valleys, which were inhabited either periodically or continuously over extended periods. Artefacts and stone structures offer complementary evidence, and geomorphological surveys combined with stratigraphic and typological analyses have identified spatial organization and settlement patterns specific to different environments.

2- Spatial Organization and Associated Settlement Patterns:

The emergence of spatial organization within settlement sites became a distinguishing feature in the Late Acacus phase. At Uan Tabu, a wooden hut was discovered within the site, and analysis of the artifacts indicated that some activities were deliberately conducted inside the hut, while others took place outside (Garcea, 2004, 126). From a functional perspective, the spatial organization of hunter-gatherer groups in the Acacus sequence, and of the surrounding areas during the Early Holocene or the pre-pastoral cultural horizon, is usually expressed through a set of indicators: living areas, stone structures, hearths, rock art, and artifacts, among others. These all provide key insights into human culture and offer a remarkable record indicating numerous variations, similarities, and differences among prehistoric desert cultures in terms of both quantity and quality. From an economic-strategy perspective, the diversity observed suggests patterns of similar development or comparable regional adaptations.

From a geomorphological perspective, Late Acacus settlements were distributed across various environments: in the mountains, i.e., rock shelters, as well as surrounding areas including wadis, lakes, and dune regions, such as Erg Uan Kasa, Adhan Marzouk, Wadi Tanezzuft and the **Messak Settafet** Plateau (Garcea, 2001a, 224). Sites located in the mountains tended to be larger and richer in sedimentary and organic content compared to those in wadis, lakes, and dunes, which were characterized by being small, isolated, single-activity sites; these smaller sites typically formed clusters resembling camps with specialized functions (di Lernia, 1999b, 67–68).

In general, the indicators of spatial organization in the Late Acacus appear extensive, highly complex in form and stratigraphic content, and considerably larger compared to those of the Early Acacus (Table 1). They included numerous unshaped stone hearths—a characteristic feature of this phase—which were more complex, larger (Figure 1), and thicker, with some reaching 20–30 cm in diameter and thickness at Uan Tabu. These hearths appear to have been repeatedly used for the same activities over time, i.e., according to multi-phase arrangements and/or recurring functional cycles (Garcea, 2001a, 225).

Table 1 | Kye features of the two Pre-Pastoral groups: Early Acacus and Late Acacus in the Tadrart Acacus Mountains and surrounding areas.

Cultural Horizon (Pre-Pastoral Phase in the Acacus)		
Elements	**Early Acacus**	**Late Acacus**
Radiocarbon Dates (^{14}C)	ca. 9760–8800 BP	ca. 8800–7400 BP
Economy	Specialized acquisitive economy (narrow spectrum)	Diversified acquisitive economy (broad spectrum)
Settlement Type	Logistical organisation (mountains and lake basins)	Semi-stable spatial organisation (mountain environment)
Mobility	Logistical mobility	Dynamic with relative stability
Material Culture	Flint knapping on sandstone; microlithic toolkit of quartz and quartzite	Basketry, grinding stones, and large-flake limestone industries
Pottery	Extremely rare	Dotted Wavy Line pottery
Climate	Transition from wet to drier conditions	Increasing aridity

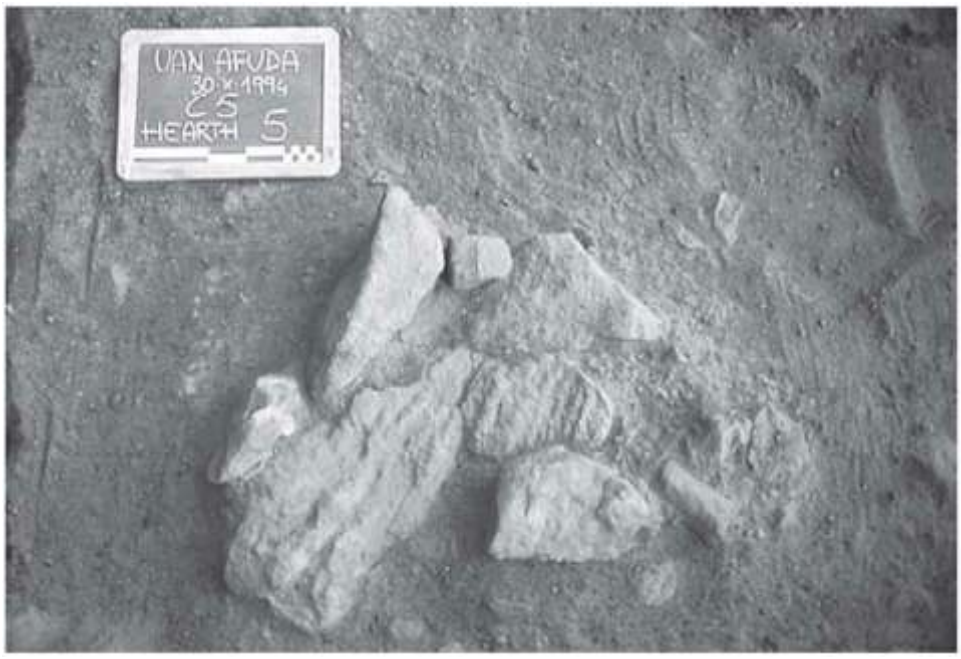

Figure 1| Structured hearth 5 from the Uan Afuda rock shelter (square C5, Layer 1), uncovered during the 1994 excavations. Sandstone slabs were used to delineate the perimeter of the hearth. (After di Lernia, 1999b, 84)

The presence of charcoal and faunal remains clearly indicates that the hearths were primarily used for processing plant and animal materials to increase their productivity and digestibility, thereby maximizing nutritional content. However, the presence of stone tools suggests an additional functional interpretation: that the hearths were also used in lithic tool production. Historically, the use of the pressure-flaking technique coincided with the thermal treatment of stone, which improved the technical quality of tool-making by allowing humans greater control over the final shape of tools, especially hunting implements (Webb and Marian, 2009, 820–821; Mourre et al., 2010, 659–660).

Overall, the indicators of spatial organization provide keys to understanding site formation and the organization of material culture, pointing to a semi-sedentary spatial arrangement, particularly in mountainous environments. This, in turn, suggests a reduced mobility rate among Late Acacus groups. Indeed, residential sites were larger in size, as observed at Uan Afuda, where the residential area was estimated to be around 800 square meters. Stone buildings, hearths, and dense artifact-bearing layers all indicate long-term use by Late Acacus hunter-gatherers (di Lernia, 1999c, 231–232).

Moving to the Ti-n Torha /Two Caves site, similar to the case of Ti-n Torha /East, sediment thickness, post-depositional dynamics, and stone structures provided information on spatial organization, and even more so on the continuity of occupation within the two rock shelters, particularly from the lower levels (Rinf and R) up to levels (CI) and (CII) (di Lernia, 1999c, 233). Huts were identified within the residential space at Ti-n Torha /East, all located at the valley bottom. Their distribution coincided with decreased humidity levels during the Late Acacus phase (Barich et al., 1984b, 414), along with the production of decorated pottery, often using the incised-stamped technique.

While the accumulation of raw materials, techniques, deposition of faunal organic matter, and lithic debitage indicate a tendency toward continuity and stability within the Ti-n Torha cultural horizon across its three shelters, stone structures—based on their size—were used for various purposes: defensive barriers, windbreaks, protection from rain, and division of space among cave inhabitants. It is reasonable to assume that the inhabitants alternated use of the two shelters during different seasons (Barich, 1984a, 400). Large grinding stones and other heavy objects, which were practically difficult to transport, indicate reduced mobility or seasonal occupation within the site. Here, I believe Barbara Barich was correct in describing Ti-n Torha as a "small village," given that it contained rudimentary houses constructed from local stone blocks (Barich, 1984a, 401).

There are also stone places, i.e., clusters of worked pebbles and rock fragments showing traces of fire treatment, recorded in the Tadrart Acacus and surrounding area. Additionally, connected stone rows were probably used as windbreaks, and craft materials included stone tools made of sandstone (Barich et al., 1984b, 41). An increase in the size and number of grinding stones was also a key feature of the Late Acacus phase. For example, the absolute number of grinding stones in the upper layers of the Uan Afuda shelter reached four hundred, compared to the Early Acacus phase (di Lernia, 1999b, 83).

Connected stone rows, likely used as windbreaks, and craft materials included stone tools such as points, blades, crescent-shaped tools, and drills with few spalls, all made from locally sourced raw materials like quartzite and chert (di Lernia, 1999c, 226). These were transported along with fossilized wood, gypsum from Erg Uan Kasa and Messak Settafet (di Lernia and Cremaschi, 1995, 225–232).

Sandstone was the most commonly used material for tool production at Uan Afuda during the Late Acacus phase (Garcea, 2001b, 97) (Figure 2). Approximately 73% of the tools in the Uan Tabu techno-complex were made of sandstone (Garcea, 2001b, 98). The artifact assemblage also included small groups of wooden and polished bone tools (Figure 3) (di Lernia, 1999b, 65).

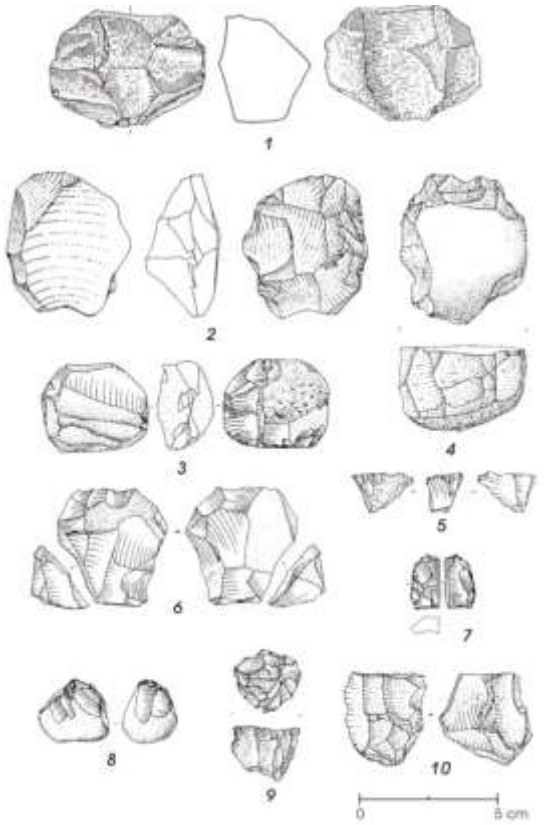

Figure 2| Stone cores from the Late Acacus layers: 1-3: multidirectional cores; 4: core on hand quern; 5, 9: pyramidal cores; 6: core on flake; 7: core on scaled piece; 8: ninety degree core, on quartz; 10: single platform core. After di Lernia, 1999b, 99).

Figure 3| Polished bone tools discovered at Uan Tabu (Garcea, 2004: 134).

Mesolithic settlement sites in southwestern Fezzan—at Erg Uan Kasa, Adhan Murzuq, Adhan Ubari, Wadi Tanezzuft and the **Messak Settafet** —were distributed across lake basins, ponds, and dune areas (di Lernia, 1999b, 63). These formed clusters resembling temporary and mobile camps, with specialized functional areas showing selective expertise. Various microlithic techniques were employed, producing blades, sharp points, and other tools (Cremaschi and Di Lernia, 1999, 253).

The inhabitants relied on a wide range of animal resources, including small and large mammals, fish, and birds. Radiocarbon dating places this activity between approximately 8,900 and 8,000 years ago (Cremaschi and Di Lernia, 1999, 281–282).

Perhaps among the most remarkable archaeological evidence was uncovered at **Messak Settafet**, where researchers found approximately 837 sandstone blocks of varying sizes and weights (Gallinaro and di Lernia, 2018, 4–6). Despite ongoing debate about their function—whether they were used for hunting purposes or as enclosures for holding animals—rock art provides conclusive evidence that these stone blocks were primarily used to capture and tame large wild animals, restricting the movement of giraffes, wild cattle, rhinoceroses, and ostriches (Gallinaro and di Lernia, 2018, 17–18).

The dense presence of grinding stones within the occupational layers at Uan Afuda and Ti-n Torha leads to the conclusion that there was a significant increase in the collection of wild plants and cereals. In many cases, the presence of baskets and pottery has been interpreted as an indicator of emerging production organization and an increasing tendency to control the environment and its fluctuations.

Since the Early Acacus/Epipaleolithic settlements were distributed across environments with different physical characteristics and followed varied settlement patterns, the intensification of arid conditions prompted Late Acacus groups to adopt new and diverse sedentary habits. Mobility decreased during this phase, allowing for the emergence of residential camps where occupation was repeated or continuous. This period was characterized by a settlement pattern based on the intensive exploitation of local resources, encompassing a wide range of plants and animals.

This raises the question of how hunter-gatherer groups organized their daily, seasonal, or periodic movements within the Acacus range and surrounding areas. Evidence collected through geoarchaeology, geomorphology, and geology suggests that some Early Acacus hunters and fishers moved intensively in the higher parts of the mountain range, likely because these areas offered the best conditions for occupation, while others preferred to move across the plains, wadis, and valleys. In this context, Garcea provides an ecologically based interpretation, arguing that mountain sites were often more habitable than wadi sites during dry seasons or periods, whereas wadi sites were more densely occupied under humid conditions (Garcea, 2004, 124).

Moreover, the results obtained from Marcolongo's geological and morphological study of the Acacus range provided us with valuable insights into this matter. The central part of the Acacus differed completely in its morphological characteristics from the northeastern area, where the elevation was relatively high (around 900 meters above sea level), and the valley system was more developed, intersecting within ecological networks that later became primary communication routes for human groups (Marcolongo, 1987, 76–77). Marcolongo also noted a wider spread of the valley system compared to the northern area, coupled with the absence of corridors across the drainage basin, meaning there were no connections with the western slope, whereas such corridors were somewhat developed in the northern region (Marcolongo, 1987, 78).

Furthermore, one cannot dismiss the hypothesis that the retention of groundwater resources in other belts—to the east and west of the range—may have encouraged the adoption of a particular strategy of movement within and beyond the mountain range. Human movements within a specific territory allowed for the development

of subsistence strategies, as groups became familiar with the region's geological characteristics and its diverse natural resources.

The question regarding the motivations behind the Late Acacus groups' preference for settling in the interior areas of the mountain range, while reducing or abandoning individual sites near shallow lakes and fast-drying ponds in the sand-dune fields of the lowlands, requires further study and investigation. I believe that the mechanism responsible for this—without a doubt—was the increasing climatic deterioration that affected the region during the 9th millennium BCE, and the hostile environments that resulted from it. Changes toward stability were linked, in one way or another, to the growth of cultural complexity, greater resource abundance, increasing population density, and, moreover, to the emergence of competition between groups.

Residential mobility in Uan Afuda manifested in the presence of extensive habitation areas, with diverse subsistence activities and specialized production (pottery, grinding tools, and baskets made from plant fibers) (di Lernia, 1999b, 82–83). On this basis, it is reasonable to suggest that the site was inhabited during most of the year. Conversely, the scarcity of evidence/artifacts scattered across the dune fields indicates, on the one hand, certain forms of resource exploitation, and on the other, the adoption of a more stable pattern of settlement, apparently associated with intensified environmental exploitation and internal socio-behavioral aspects of cultural complexity and growing population (di Lernia, 1999b, 85–86).

In addition to all of this, the stone tools, with their morphologies and diverse typological classifications, provide valuable information and indicators regarding spatial organization, settlement patterns, and functional diversity. It seems plausible here to propose the hypothesis that climatic fluctuations between wet and dry periods dynamically influenced economic strategies, prompting the development of new hunting techniques and leading humans to increasingly rely on storable resources, particularly wild cereals. As is well known, the formation and disappearance of archaeological sites depend heavily on the fluctuations of past environments, especially concerning the distribution of natural resources (water, plants, animals, and raw materials). Here, it is essential to emphasize the role of natural resource variability in either increasing and/or diversifying subsistence systems or even constraining them.

From an energy perspective, human survival was closely linked to the development of techniques to improve food quality and the search for suitable food sources. Nevertheless, the impact of the natural environment and climatic change was decisive. Indeed, climate has become a central factor in archaeological and prehistoric research, and it must be taken into account because of its profound influence on human life and cognitive perceptions—not only on material culture but also on economic choices. According to this principle, climate has always been (and remains) the prime suspect in any cultural transformation experienced by human groups. According to Adloff Kuper, the drought that struck the desert, along with the ecological mechanisms it triggered, acted as a driving force in Africa's history. Drought, in particular, stimulated the growth of urban centers along Africa's river systems (Kuper and Kropelin, 2006, 803–807).

Accordingly, the phenological factors resulting from climatic fluctuations between wet and dry periods forced humans/observers to continuously adapt their behavior to higher levels of efficiency, surrounding themselves with a "halo" of objects that functioned as an energetic field. This halo can be traced and measured through artifacts and through rock art in the Acacus, across its chronological phases and diverse thematic content. It seems plausible to hypothesize that the settlement strategy adopted by the Late Acacus groups—particularly during critical periods of environmental change characteristic of the pre-pastoral phase, especially the Late Acacus phase—represented a pattern of stability that minimized the efforts and caloric expenditure of Libyan Desert communities in accessing scattered food resources distributed in small patches.

At this point, we can also discuss the role of women in production activities, particularly regarding plant exploitation. Work appears to have been divided—albeit partially—along gender lines within hunter-gatherer groups, potentially involving some or all women and men, and very likely even children. Consequently, the gathering of wild plants introduced a new function for women—and for children as well—by relying on them for this task. Interestingly, this hypothesis finds support in the archaeological record: it is no coincidence that the proportion of female depictions is high in the art of the Round Head phase across the Acacus rock art repertoire and the Central Sahara mountain ranges. Kinship relations, social organization, and cultural complexity connected to the Uan Afuda groups in the Late Acacus phase can be inferred from changes in the technical complex, the material culture, and differential behaviors in natural resource management. Here, we should also highlight the significant contribution of gender archaeology, which is emerging as a promising branch in broader studies of prehistoric Africa (Barich, 2018, 219–229).

From a structural perspective, the development of the capacity to manage resources and store food inevitably necessitated the emergence of complex social units living in shared communal environments, functionally dependent on one another. The question of the relationships between Late Acacus groups, and how resources were shared among them, is extremely complex and remains, even under the best conditions, largely obscured. Indeed, reconstructing the socio-economic content of the Acacus groups in those ancient times resembles detective work due to the absence of decisive evidence. Inferences must rely on scattered data from bones, assemblages of stone tools, and various organic deposits—all of which remain insufficient. Understanding

social content cannot be achieved solely through material remains, as it also depends on demographic and environmental factors, as well as the metaphysical and other contextual dimensions.

Unfortunately, data indicative of funerary evidence belonging to the Acacus culture are extremely scarce. In general, information regarding the relationship between the early and late Acacus occupations and human species remains very limited. Despite the richness of the archaeological material, which has provided keys to interpreting the technical, environmental, and economic content of the early Acacus hunter-gatherer groups, aspects related to social content—such as demography, division of labor, activities, and social relations—remain elusive. I fully acknowledge that understanding social content solely through material remains is challenging, as it is also closely linked to demographic and environmental factors, as well as the metaphysical context, among others. Even manufactured tools and their varieties cannot be fully understood unless they are connected to their social and cultural context. In such cases, it becomes possible to translate these tools into cultural terms and assign them different labels, such as Epipaleolithic, Mesolithic, and so on.

Overall, the stratigraphic sequence of Uan Tabu Cave, measuring 255 cm in thickness, provides additional evidence indicating cultural and economic differentiation, spatial organization, mobility, and movement that characterized the early ninth millennium. Three separate units were identified based on their sedimentary and organic characteristics. The first and second units, each measuring 120 cm thick, contain ash, charcoal remains, plant fibers, and absolute radiocarbon dates ranging from 8720 ± 110 to 8600 ± 90 years ago for the first unit, and 8870 ± 100 to 8800 ± 100 years ago for the second unit (Garcea, 2001a, 227). The third unit, with a thickness of 80 cm, contains the earliest range of dates. Four burnt structures are present in both the first and second units, while the third unit contains only two structures (Garcea, 2001a, 229–230).

These units highlight two cultural entities. In the first and second units, there is clear specialization in hunting Barbary sheep, specifically *Ammotragus lervia* and *Hemitragus cristata*. In the third unit, evidence indicates a broader exploitation of resources, including diversified hunting, plant processing, and the use of pottery containers (di Lernia, 1999c, 227).

At Uan Muhuggiag, a stratigraphic deposit measuring 200 cm in thickness has come to light. Radiometric indicators containing Late Acacus artifacts were derived from the lower sequence, where assemblages of microlithic tools, manufactured items, dense plant remains, a wide range of animal resources, and a chronological range between 7800 and 7400 years ago were recorded (Barich, 1992, 109–122). Importantly, evidence of the care and domestication of Barbary sheep in enclosures within shelters was observed. A similar pattern in material culture, site formation processes, chronological sequence, and faunal assemblages is also observed at Fozigarn (di Lernia, 1999c, 228).

From an archaeological and historical perspective, we owe a great deal to Barbara Barich for her thorough research in the region, conducted using the most advanced methodological approaches of the time. She provided an analytical framework for interpreting the dynamics of cultural evolution and adaptive strategies of human groups in the Acacus. Barich interprets her data from a palaeoecological standpoint, particularly focusing on datasets related to some paleoclimatic sequences, such as the Chad–Tibesti system. Geologically, it is known that during the Last Glacial Maximum, Lake Chad expanded to the extent of forming an inland sea comparable to the Caspian Sea (MacDonald et al., 2012, 4), covering a vast area from the Central Sahara Highlands to parts of the adjacent plain, mountain ranges, savannas, and tropical forests. Consequently, its varying climatic sequences, characterized by periods of expansion and contraction, contributed to the palaeomorphological formation of the Central Sahara, Tibesti, Ajjer, and Acacus ranges. More specifically, Barich argues that there is a link between climatic change in Tibesti, climatic and cultural events, which can be observed through palaeomorphological evidence such as faunal remains and plant deposits (Barich et al., 1984b, 415–416).

As the rock art depicting large wild animals indicates a connection with the early Acacus occupation, it is also likely associated with the Late Pleistocene occupation, whereas the round-headed phase probably belongs to the Late Acacus occupation, assuming it also pertains to the Early Pastoral occupation. These rock paintings, with their diverse subjects, suggest a symbolic function and considerable importance for hunter-gatherers. In this regard, Graham Barker notes that engraved rock slabs primarily served as boundary markers for specific groups of hunter-gatherers and nomads. These groups exhibited a tendency to clearly delineate their seasonal territories while retaining the right to use certain highly regulated shared resources (Barker, 1993, 17; Adaba, 2020, 300).

From a broader regional cultural perspective, research results based on advanced approaches integrating multiple sciences, computational analogies, and ethnographic data provide a wide spectrum of information on spatial organizations, either similar or differing in content from those of the Late Acacus. Evidence from the pre-Tibolitian desert region allows the reconstruction of the lifeways of hunter-gatherers during the Early Holocene. Hunter-gatherers and fishers, equipped with Epipaleolithic and Mesolithic techniques (Barker, 1993, 18; Adaba, 2020, 300), returned to exploit the elevated plains, taking advantage of Early Holocene climatic improvement, which brought new moisture-rich carrying capacity. The increase in rainfall during this period can be linked to the northward shift of the monsoon cycle, as confirmed by Wickens' study of climate and vegetation changes in Sudan over the past 20,000 years (Wickens, 1982, 23–51).

Evidence indicating spatial organization and human settlement in the region during this period consists of a series of sites containing rock art—for example, depictions of cattle at the Maya Deep site, and a cow, gazelle, giraffe, and human forms at the Ṭabaqa site. The combination of cattle depictions and hunting animals at these sites indicates that the pre-desert region was inhabited by populations who combined a nomadic lifestyle with hunting activities (Barker, 1993, 18).

On the other hand, similarities have been observed between the frequencies of Mesolithic occupations in the Aïr–Tenere region of Niger, such as Tagalagal, Temet, Tamaya Mellet, and Adrar Bous (Jesse, 2003, 36–38; Smith, 1993, 73), and those at Uan Afuda. These similarities extend to economic strategies, spatial organization, as well as shared lithic toolkits, including blades, scrapers, and pointed implements. Moreover, an almost complete similarity has been documented between lithic typologies and economic activities at Ti-n Torha and Early Holocene occupation sites in Niger (Barich, 1984a, 405–408). Consequently, the Early Acacus and Aïr–Tenere cultural complexes in Niger can be considered environmental equivalents, inhabiting the same ecological and cultural context.

For comparison, archaeological evidence from the Sudanese Nile Valley, such as Abu Darbin and Botana, and from the Western Desert of Egypt, including the Fayum Depression, Bir Kiseiba, and Nabta Playa, exhibits greater diversity and complexity in both their forms and material culture than those of the Acacus (Abbas et al., 1989, 474–478). In the Sudanese Nile Valley, hunter-gatherers settled in riverine environments and engaged in fishing activities using wooden fish traps (Abbas et al., 1989, 480). In contrast, in the Western Desert of Egypt, a number of primary hunting and plant-gathering camps have been recorded, with spatial organization featuring large clusters of grinding stones (Wenke and Casini, 1989, 150–151).

Although Adham-type lithic technologies, dated to the end of the 9th millennium BCE, appear partially contemporary with the Late Acacus phase at Wān Afuda, there is no evidence of a direct connection or similarity between them (di Lernia, 1999c, p. 226). Another lithic technology, called the “Ghorab” type, was identified at Bir Kiseiba and Nabta Playa and seems to be contemporary with the Late Acacus phase. Epipaleolithic lithic assemblages, including blades and sharp flakes discovered at site 8/42 Dora in Jabal al-Haruj in central Libya, indicate a considerable similarity with Ghorab-type stone industries from the Eastern Desert (Kuper, 2015, 344–345).

Based on the above, it can be concluded that the morphological features of the Acacus range and its surrounding areas during the pre-pastoral phase made it, in prehistoric times, a natural hub repeatedly occupied by hunter-gatherer and fisher groups. These groups followed both short-term and long-term settlement patterns and left behind evidence reflecting complex human activity: semi-permanent spatial organization, particularly in mountainous terrains; logistical mobility between mountains, lake basins, and valleys; the use of sophisticated technologies; and an economic strategy based on the diversified exploitation of natural resources.

3- Ecological Context and Subsistence Strategies:

All sedimentary, micromorphological, palynological, palaeontological, geoarchaeological, and archaeological evidence from the caves of Uan Afuda and Uan Tabu (Cremaschi & di Lernia, 1999, 9–26; Cremaschi & Trombino, 1999, 27–38; Mercuri, 1999, 149–182) indicates a clear trend toward aridity during the Late Acacus period, in contrast to the wetter conditions of the Early Acacus period. The latter facilitated the formation of open local environments with high humidity and abundant water, which concentrated plant and animal resources at specific locations, creating attractive sites suitable for human habitation.

A geological indicator of a brief drought was identified in the stratigraphy of **Uan Afuda**, dated to approximately 8,900 years ago, represented by a sandy layer at the base of the Late Acacus. Pollen analyses from this layer show very low concentrations, with the presence of some shrubs and the complete disappearance of tropical plants (di Lernia, 1999b, 129). Similarly, in Uan Tabu, pollen spectra from stratigraphic units 2 and 1 reveal a significant decline in savanna vegetation and an increase in herbaceous species (Garcea, 2001a, 227–228).

These signals are likely linked to broader climatic changes across the region and appear to be synchronous. For instance, climatic fluctuations in the Middle Sahara correspond with reduced precipitation at Lake Chad around 8,500 years ago (Dallmeyer et al., 2020, 117–140) and a short-term drought in the Egyptian desert around 8,700–8,600 years ago. Lakes persisted in the region until approximately 8,500 years ago but dried up by the end of the ninth millennium BCE (Kutzbach et al., 2020, 2255–2264).

Typological and strategic analyses of settlement sites suggest clear differences in cultural content and settlement patterns, particularly regarding economic strategies. This differentiation is evident in Uan Afuda, which provides critical insight into Late Palaeolithic hunters with matrilineal traditions and, more broadly, into Early Holocene hunter-gatherers. The evolutionary trajectory observed at these sites offers a valuable model for understanding the increasing cultural complexity of Acacus groups in the Libyan Desert (di Lernia, 1999a, 5).

3-1: Animal Exploitation:

Economic strategies during the Late Acacus period exhibit marked differences from those of the Early Acacus period. For example, hunting of Barbary sheep (Amotragus lervia) declined to approximately 40% of the total exploited fauna, compared to 80% in the Early Acacus. Other species, such as wild rabbits, hyraxes, fish, and birds, were incorporated into the diet. Approximately 50 individual specimens representing different taxa were identified at Uan Afuda (di Lernia, 1999b, 130).

This shift has been interpreted in several ways. It may reflect increased settlement stability, with hunting strategies adapted to environmental changes and phenological events, such as climate-induced fluctuations in plant and animal populations. As hunter-gatherers could no longer rely on diets centered on specific species, they adopted new techniques and behaviors. The decline in Barbary sheep hunting may correspond to reduced sheep populations due to drought, as surface water bodies diminished. Alternatively, it may relate to the ecological behavior of the animals, which could have moved to more distant or higher-altitude areas, making hunting more difficult and time-consuming.

Evidence for specialized hunting is also observed along the Libyan coast. At **Haua Fteah Cave** in eastern Libya, remains indicate that Late Palaeolithic hunter-gatherers exploited Barbary sheep, gazelles, wild asses, marine molluscs, and shellfish (Douka et al., 2014, 60).

Regardless of debates over the origins of domesticated animals through genomic studies, the central role of animal exploitation in the Paleolithic and Neolithic reflects the dynamic interactions between humans, animals, and the environment. These interactions have become key foci of African archaeology, particularly in studies of pre-pastoral societies (Editorial, 2018, 1–5).

From a functional perspective, the observed changes in animal exploitation may reflect a deliberate cultural strategy aimed at sustainable resource management. The accumulation of manure and fodder in residential areas, concentrated in pen-like structures, suggests the early domestication and penning of animals. Barich notes that approximately 92.4% of the bones from the Late Acacus period belong to domesticated animals, compared to only 4.2% from wild species (Barich, 1984a, 405).

Comparative studies of Mesolithic sites near the Acacus range indicate similarities in economic strategies and techniques. Notably, sites such as Temet and Amekni in the Hoggar range and Milt Tagalagal in the Aïr-Tenniri range of Niger show strong parallels with Ti-n-Torha, Uan Afuda, and Uan Tabu (Barich, 1984a, 405–406; di Lernia & Savino, 1999a, 6).

In contrast, Early Holocene sites in the Sudanese Nile Valley display fewer similarities with the Middle Sahara. At Abudarbin and Atbara, subsistence focused primarily on aquatic resources. Fishing, exploiting around 30 species, was central, complemented by snails, molluscs, and river mussels, captured using nets, harpoons, and bone spears (van Neer, 1989, 50–55). The diet also included elephants, giraffes, African wild cattle, and small antelopes (Jesse, 2000, 78). Fishing activities were likely year-round, whereas other subsistence activities were seasonal. Consequently, Early Holocene Nile Valley cultures appear more closely aligned with the aquatic stone cultures of Central Africa than with the Early and Late Acacus cultures of the Middle Sahara (Sutton, 1977, p26–27).

3-2: Plant Exploitation:

According to archaic-botanical studies, the early Acacus landscape comprised a mixed and diverse plant environment, including elements from Mediterranean, desert, and coastal desert ecosystems (Figure 4), with a combination of savannah and tree grasses (Gallinaro, 2018, 2–3). Open vegetation predominated, notably Acacia–Panicum or Tamarix–Stipagrostis communities (Mercuria, 1999, 150–151; Wasylikowa, 1992, 126–127). Grasses dominated the pollen spectrum and were primarily harvested for food (Garcea, 2001b, 227).

Despite this diversity, early Acacus hunter-gatherers engaged in very limited plant exploitation. In contrast, wild plant use increased significantly in the late Acacus phase. Dense plant deposits from this period indicate extensive plant utilization. Laboratory analyses revealed large quantities of seeds, fruits, hay, and fodder, as well as grinding stones, some of which appear to have been used for processing non-food materials, such as red ochre (Garcea, 2004, 125–226).

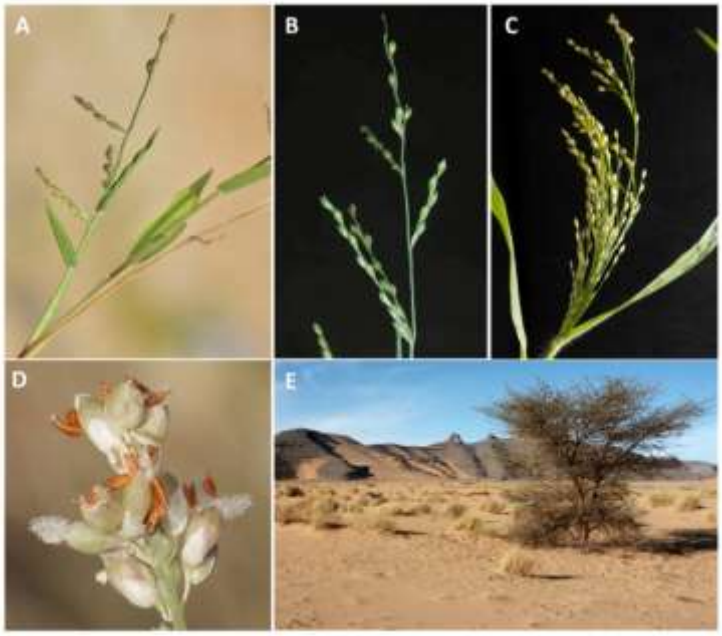

Figure 4| Millet species forming part of the savannah vegetation in the Sahel: A-Brachiaria. B-Urochloa. In the Sahara: D-flowers of Panicum turgidum Forssk; E-shrubs belonging to the Acacia–Panicum association (observed during the Archaeological Mission in the Sahara conducted by Sapienza University of Rome, documented by A.M.M.). (After Florenzano et al, 2025)

Evidence from Unit 2 at Uan Tabu, dated to 8,900–8,800 years ago, demonstrates that a wide range of plant resources was exploited and that the volume of plant accumulation doubled. Charred vegetation suggests a shift from short-term seasonal settlements to more permanent ones, coinciding with increased reliance on pond grasses (*Typha*), which were used for food, bedding, spinning, and construction (Garcea, 2001b, 230). Tifa stalks were combined with poles to construct hut roofs at Uan Tabu, with twisted ropes found nearby. These grasses were also employed with straw for tools, fodder, and medicinal purposes. Tamarisk wood was utilized both for tool production and as fuel (Garcea, 2001b, 230).

Late Acacus findings at Uan Afuda provide additional insights into heavily exploited plants, including Panicoideae (layers 1–3) and Boraginaceae (starflower), which were well preserved across all Mesolithic levels. Laboratory analysis of fossilized human and animal dung indicates that harvested grains were used for both human consumption and feeding Barbary sheep kept in pens inside the cave (di Lernia, 1999c, 232–233).

Castelletti and colleagues identified various *Ficus* species with distinct phenological traits, suggesting selective interest in edible species such as *Ficus salssulphuria* (Castelletti et al., 1999, 133–134). Mercuri's pollen data indicate human selection among weeds, implying early cultivation practices (Mercuri, 2008b, 1950–1967). Savoia di Lernia further argues that the presence of large seeds reflects early attempts at plant domestication in Uan Afuda, particularly of *Panicum*, a key cereal resource during the late Acacus phase (di Lernia, 1999c, 231). However, di Lernia notes that distinguishing between annual, biennial, or perennial grains and understanding harvesting strategies remains complex (di Lernia, 1999c, 232).

Wasylikowa's research confirms these findings through analysis of seeds, fruits, and pollen at Ti-n Torha/Two Caves, providing a detailed database of plant use across Ti-n Torha/East, Ti-n Torha/North, and Uan Muhuggiag. Plant abundance and diversity remained relatively constant across habitation levels, although vegetation was more open in the northeastern sector, with a noticeable decrease in mobile grasses from the eastern spectrum (level Rinf-RSup) to the northern spectrum (level I) (Wasylikowa, 1992, 127–128). The small tree *Balanites aegyptiaca* played a crucial role in the early Holocene diet of hunter-gatherers. Growing within Acacia–Panicum communities along desert valleys, its ripe fruit was eaten raw, its oil extracted, and its pulp used medicinally (Wasylikowa, 1993, 28–30).

In addition, Wasylikowa's findings support Barbara Barish's hypothesis, which challenges the conventional view of the Neolithic transition in the Acacus region. Rather than being influenced by Southwest Asia, the evidence suggests that the transition to food production, including animal domestication, had a local origin. Hunter-gatherers and fishermen who settled on the eastern slope of the Acacus Mountains may have pre-selected species suitable for domestication (Barich et al., 1984b, 31–35).

Hydrological conditions on the eastern slope of Ti-n Torha provided significant advantages for human settlement: better drainage, access to the western slope, and shallow groundwater. Marcolongo argues that groundwater reserves accumulated during wet Pleistocene phases were gradually consumed by flora and fauna, a

conclusion corroborated by MacDonald et al., who identified extensive groundwater reserves in the Middle Sahara and across Africa. These conditions facilitated adaptive, organized, and sustained settlement, culminating in a productive economy based on pastoralism (Marcolongo, 1987, 270; MacDonald et al., 2012, 1–7; Barich et al., 1984b, 416).

As well, Morcori proposed a comprehensive model of ancient food acquisition, highlighting human–plant interactions in Wadi Teshuinat through the systematic analysis of 13 sites, including Uan Afuda and Uan Tabu. Grounded in ethnobotanical principles and utilizing pollen spectra as behavioral proxies, her model demonstrated that plant resources were central to cultural development, with patterns of exploitation shaped by climatic variability and adaptive economic strategies (Mercuri et al., 2018, 71–81).

Furthermore, Morcori documented selective human choices in plant utilization. Examination of 748 plant samples from Uan Afuda (level UAF-PS 6) and Uan Tabu (levels UTB-PS 1 and UTB-PS 11), including pollen grains measuring 40–70 µm, indicates deliberate selection prior to their transport to residential contexts (Mercuri, 2008a, 1637–1638). Comparable instances include edible-seeded **Panicum** from Ounjougou, Mali (Huysecom et al., 2009, 915), and Mediterranean taxa such as aromatic cypress and pistachio at Ti-n-Hanakaten, Tassili n'Ajjer, Algeria (Amrani, 2018, 123–145).

Overall, hunter-gatherers exhibited detailed ecological knowledge, distinguishing between wild and aquatic plants, woody and herbaceous species. Such local expertise allowed communities to adapt to droughts and food scarcity, developing culturally informed strategies for resource management. Archaeological evidence from the Takarkori site in Acacus reinforces this conclusion, showing dynamic, selective exploitation based on accumulated environmental experience (Miras et al., 2018, 1106–1121; Salem et al, 2025, 145). Morphometric studies of spicule fossils from Takarkori reveal size variation in wild plants collected during the early Holocene, particularly in the late Acacus phase (Figure 5). Examination of 18 seed and fruit samples indicated consistent size and maturity, suggesting meticulous collection practices (Fornaciari et al., 2018, 100–122).

Recent advances in archaeobotany, including analyses of dental enamel, plant stones, and ancient biomolecules (DNA, amino acids, proteins, lipids, and pollen), have expanded understanding of hunter-gatherer plant use, enabling reassessment of past economic strategies (Miras et al., 2018, 1106–1121; Cappellini et al., 2018, 1029–1060).

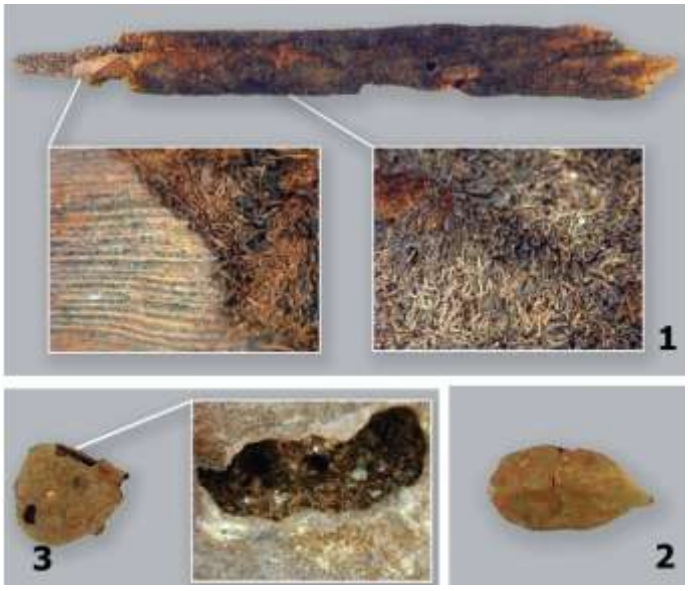

Figure 5| Laboratory analyses of microfossils and pollen from Takarkori demonstrate diverse plant use during the late Acacus period, including: (1) pond grasses (Typha), 6,800 years ago; (2) Egyptian hackberry (Balanites aegyptiaca), 6,800 years ago; and (3) fig tree seeds (Syconium), 7,500 years ago (Dunne et al., 2016, 2).

In conclusion, stratigraphic, micromorphological, and archaeological evidence from Ti-n Torha, Uan Afuda, Uan Tabu, and surrounding sites indicates diverse exploitation of plant and animal resources during the late Acacus period. Grass remains were predominant, while cereal pollen was highly diverse. Pond plants remained abundant and were intensively exploited, particularly during the late Acacus phase, as evidenced by Unit 2 at Uan Tabu (8,900–8,800 years ago), which shows both increased diversity and accumulation of plant resources.

4 .Man-Made Materials:

During the Late Acacus/Mesolithic period, a variety of man-made materials—including wooden tools, pottery, plant-based tools, bone implements, polished stone tools, and grinding stones—played a crucial role in daily life activities. Pottery, in particular, was extremely rare in the early Acacus period but became increasingly common in the late Acacus period. The scarcity of pottery in the early phase can be attributed to its limited relevance to the subsistence strategies of hunter-gatherers, such as cooking and food storage, and thus it did not constitute a fundamental component of the Palaeolithic economy. In some instances, the rarity of early pottery has also been interpreted in terms of social prestige, the accumulation of storable goods, and social interactions (Garcea, 2004, 132). By contrast, in the late Acacus period, pottery became commonplace and was employed primarily for practical daily functions, including food preparation and storage (Garcea, 2004, 132; Rotunno and Enrico, 2025).

Pottery from this period was frequently decorated using the Dotted Wavy Line technique, producing continuous wavy lines. At the Uan Tabu site, five cracks were documented in each of the first and second stratigraphic units. Some shards displayed dotted wavy lines, while others featured clear wavy lines on the rim (**Figure 6**) (Di Lernia & Garcea, 1997, 17). Petrographic analysis indicates that the clay paste used in early Acacus/Mesolithic pottery may have contained granite, which is absent in the Tadrart Acacus mountain range. The nearest known source is Tassili n'Ajjer, approximately 70 km west of the Acacus, near the Algerian border. Consequently, early pottery in the region likely represented a primarily imported product from nearby mountain ranges in the Middle Sahara rather than locally manufactured goods (Garcea, 2004, 132; Rotunno and Crema, 2025).

It is important to note that pottery from the pastoral phase differs substantially from late Acacus pottery in terms of manufacturing techniques, decorative motifs, source of raw materials, and function.

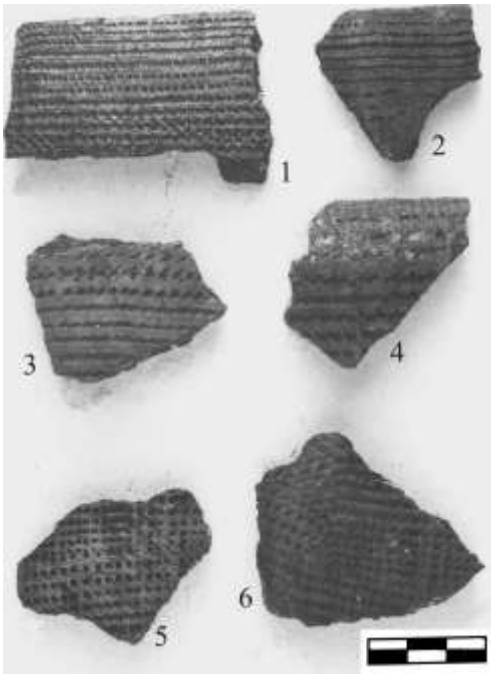

Figure 6| Late Acacus/Mesolithic pottery shards, decorated using compressed mould techniques, with dotted wavy lines and clear wavy lines on rims (Garcea, 2004, 132).

As previously noted, the presence of pottery and grinding stones provides critical evidence of a productive subsistence economy. Defining African cultures solely through artifacts or technical data risks misinterpreting these economic systems, as pottery appeared at numerous North African sites—including the central Sahara mountain ranges—well before the emergence of Neolithic societies or domesticated animals (Rotunno and Crema, 2025).

The history of pottery in Africa is complex, encompassing a range of functions from food storage and preparation to ritual, funerary, or symbolic uses. One prominent hypothesis suggests that pottery was first developed in the Sudanese Nile Valley and subsequently spread to other regions, including the central Sahara mountains, with characteristic multi-line decorations reflecting petrographic patterns and regional distinctions (Abbas & Khabir, 2003, 25–58). Alternatively, some researchers argue that pottery in the mountainous areas of the Middle Sahara was produced contemporaneously with the Sudanese Nile Valley, approximately 9,400 years

ago, with supporting evidence from pottery shards at the site of Ounjougou (Mali) (Huysecom et al., 2009, 912–917).

Wooden and plant-based tools—such as perforated implements, baskets, and ropes—were also common in the late Acacus period (**Figure 7**). These artifacts were associated with grain purification, sifting, and storage (Garcea, 2001a, 229). The stratigraphic record further documents polished and serrated bone tools (**Figure 8**), as well as decorated ostrich eggshells (Di Lernia, 1999b, 124–125).

Figure 7| (1) Wooden and antler tools from gazelles and Barbary sheep used for hunting; (2) Plant fiber baskets and ropes containing wild grains such as Panicoides (Di Lernia, 1999b, 125, 127).

Figure 8| Polished bone tools from the Uan Tabu site (Garcea, 2004, 132).

Polished stone tools, including scrapers and chisels made primarily from local sandstone, were abundant during this period. These tools, often produced from large flakes, included grooved implements, side scrapers, and serrated tools, and were employed for scraping, cutting, rubbing, and other daily tasks such as food preparation and secondary product manufacture (Garcea, 2001b, 102; Di Lernia, 1999c, 230). Grinding stones, also widely used, were recovered in large numbers at Uan Tabu: 46 pieces in Unit 3, 26 in Unit 2, and 14 in Unit 1 (Garcea, 2004, 133). They served to crush wild grains as well as ochre and other pigments for rock art (Di Lernia, 1999b, 126). While the overall techniques for stone tool manufacture remained consistent from the early Acacus to the early/middle pastoral phase, the main innovation of the late Acacus phase was the production of arrowheads (Garcea, 2004, 134).

The diversity of these artifacts, classified by form and function, reflects how hunter-gatherers adapted to environmental pressures and resource availability during the late Acacus period. Typological comparisons between mountain and lake site toolkits indicate a shared cultural identity. Some researchers suggest that settlement patterns were hierarchical, with multiple base camps concentrated in the mountain range.

5- **Results:**

In this study, I use the term **Late Acacus** to refer to a cultural phase that encompasses economic content, evolutionary trajectories, and chronological elements, representing a cultural continuity that brought with it numerous features in stratigraphic, typological, and morphological content. Within this geo-archaeological space, Early Holocene hunter-gatherers and fishers inhabited caves such as Uan Afuda, Uan Tabu, Ti-n-Torha, Messak Settafet, Wadi Tanezzuft, Erg Uan Kasa, Adhan Marzouk, and other sites in the mountain ranges of the central Sahara. They followed a semi-stable spatial organisation in a purely mountainous environment, within more complex structures, and maintained a specialised economy exploiting a wide range of plant and animal resources, large sandstone flakes, microlithic toolkits, and a crafted material assemblage including baskets and bone tools, while pottery was common and decorated using the stamping technique, and in some cases with dotted lines.

We also identified regional points of similarity between the sites of Uan Afuda, Uan Tabu, Ti-n-Torha, and their associated subsistence systems, evolutionary patterns, sedentary practices, and craft materials with sites documented in the Aïr-Ténéré region of Niger. This degree of similarity allows us to situate them within a single cultural complex. The paper also highlighted certain regional differences between Early Holocene cultures in the Acacus, the Hoggar, the Aïr-Ténéré of Niger, the Egyptian desert, and the Sudanese Nile Valley, especially regarding economic strategies and ecological mechanisms. Populations relied heavily on aquatic resources, particularly fish and molluscs, presenting themselves as model water-based cultures, analogous to the water-oriented stone-age cultures of Central Africa.

The spatial organisation of the Late Acacus included numerous hearths, stone alignments often used as windbreaks, and stone accumulation areas likely serving as workshops for tool assembly, shaping, and manufacture, along with grinding stones and primary dwellings. The stratigraphic evidence presented here indicates that diversified hunting of mammals and birds, as well as exploitation of a very wide range of plants—especially grains—were important subsistence activities carried out by the inhabitants of the excavated sites. It can be agreed that the development of such an adaptation to abundant resources was influenced by multiple ecological and behavioural factors and, naturally, was linked—directly or indirectly—to the emergence of a form of labour division within Late Acacus groups.

Phenological factors played a central role in shaping changes in settlement patterns and economic strategies during the Late Acacus. This can be summarized in two main points: first, the system of resource recycling and cultural regulation became a necessary organizational strategy to secure animal resources and meet increasing nutritional demands, particularly during periods of drought; second, human survival and continuity in the Acacus region relied on the development of lithic technologies, such as grinding stones.

In other words, phenological factors resulting from climatic fluctuations between wet and dry periods compelled humans/observers to continuously adjust their behavior toward higher levels of adaptation. This was achieved by surrounding themselves with assemblages of objects that acted as an energetic field, traceable and measurable through material culture and, in the Acacus region, through rock art across its chronological phases, frequencies, and thematic diversity. It is plausible to hypothesize that the settlement strategies adopted by Late Acacus groups—particularly during critical environmental shifts of the pre-pastoral stage and especially the Late Acacus phase—represented a form of stability aimed at minimizing effort and reducing the caloric expenditure of Libyan Desert communities in their pursuit of dispersed food resources scattered across small, isolated patches.

In conclusion, it is worth noting once again that the archaeological record is highly controversial, yet at the same time it is often surprising and open to new discoveries. With continued excavation, layer by layer, rigid definitions once considered self-evident and indisputable gradually collapse as new scientific findings emerge. This expands our knowledge and necessitates adjustments in researchers' methods. What Barbara Barich suggested regarding the independent development of food production in the Acacus, initially a hypothesis subject to testing, is now considered an established fact in African archaeology.

Disclosure on the Use of Artificial Intelligence Tools:

The author used ChatGPT solely for proofreading, enhancing writing, and improving clarity and readability, and did not employ it for any other purpose. Following the use of this tool, the author thoroughly reviewed, edited, and refined the content, and assumes full responsibility for the published material.

Compliance with ethical standards

Disclosure of conflict of interest

The author(s) declare that they have no conflict of interest.

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