Journal of Archaeological Method and Theory (2026) 33:29
https://doi.org/10.1007/s10816-025-09759-9

RESEARCH

Developing Geo-Ethnoarchaeological Methods for Studying Archaeological Pastoral Sites: the CAMP project

Stefano Biagetti · Abel Ruiz-Giralt · Keelie S. Rix · Antonios Koutroumpas · Jordi Ibañez-Insa · Carla Lancelotti, et al. ***[full author details at the end of the article]***

Received: 29 September 2025 / Accepted: 13 December 2025

Abstract

This paper presents the aims, methods, and some initial results of the project '(Re) Constructing the Archaeology of Mobile Pastoralism (CAMP)', a multi-disciplinary investigation into anthropogenic deposits from pastoral contexts in dryland regions. Ethnoarchaeology has played a pivotal role in transforming the study of pastoralism, particularly in environments where material traces are often ephemeral and underrepresented in the archaeological record. By linking contemporary practices with their material signatures, ethnoarchaeology has reshaped both the interpretation of pastoralist material remains and broader understandings of pastoral societies, revealing them as adaptive and innovative actors in highly variable environments. Building on recent theoretical and methodological advances—especially in geo-ethnoarchaeology—CAMP seeks to develop a robust interpretive framework for identifying chemical proxies that can be linked to specific human activities. Research in the first stage has focused on three ecologically and culturally distinct regions: Maitengwe (Tutume Dist., Botswana), Khor Rori (Dhofar, Oman), and Loreamatet (Turkana, Kenya), with supplementary test areas to evaluate the broader applicability of the developed protocol. Fieldwork has targeted three site categories: inhabited campsites, to document the relationship between activities and their anthropic markers; abandoned campsites, to assess post-depositional and diagenetic transformations; and key archaeological pastoral sites, to reinterpret ancient deposits using models derived from present-day contexts. Preliminary results presented in this paper highlight significant differences in the composition of chemical elements across activity areas within settlements, underscoring the potential of these proxies to distinguish activity-specific signatures. By integrating ethnoarchaeology, geoarchaeology, and geochemistry, the project advances methods for detecting and interpreting pastoral signatures in the archaeological record, while contributing to the repositioning of drylands as dynamic centers of resilience and innovation.

Published online: 10 February 2026

Keywords Geo-ethnoarchaeology · Multi-element analysis · PXRF · Geostatistics · Pastoralism

Introduction: Reframing Contemporary and Ancient Pastoralism

It has taken more than seventy years for the FAO (2021) to acknowledge that pastoralism is a rational and reasonable livelihood system, especially in drylands, where large-scale agriculture is not viable. The term 'pastoralism' refers to a wide range of livestock-based livelihood and food production systems, which are highly diverse, yet which all share a common specialization where animal welfare is improved by managing their grazing itineraries at a variety of scales in time and space. Pastoralism is a socio-ecological system based on animal husbandry, characterized by the predominant — albeit not exclusive — role of livestock from the economic, ideological, cultural, and social points of view. Nowadays, extensive pastoralism occurs on about 25% of Earth's land area, mostly across the drylands of Africa and the Arabian Peninsula, in the central Asian steppes, and in the highlands of Asia and Latin America (FAO, 2020). Pastoralists are the main producers in these areas of the world and create culturally unique and vibrant communities. Pastoral systems enable the exploitation of natural resources with high variability by the use of highly adaptive operational strategies, such as flexibility of movements, animal breeds, and labor force. These help to minimize potential fluctuations in animal production and health, and in households' food security.

'Poor understanding of pastoralism' has long remained the most repeated cause of setback in pastoral development, often resulting in maladaptive practices that generate, in a vicious cycle, further misunderstanding (FAO, 2020). Such misconceptions originated in the 'cattle complex' construct of Herskovits (1926) that described eastern African pastoralists as relentless accumulators of livestock with no concern for sustainability nor efficiency. These views were later upheld by the influential paper by the American ecologist G. Hardin (1968; see also Picardi & Selfert, 1977), where herders were taken as an example of the unavoidable maximal exploitation of common land in the 'tragedy of the commons' against the collective good (Boles et al., 2019). The idea that pastoralism was an irrational socio-ecological system, inherently tending to overstock and overgrazing (e.g., Davis, 2004), was progressively contrasted from the late 1980 s (Ellis & Swift, 1988; Sandford, 1983) with the developments of models of non-equilibrium ecosystem dynamics formalized by Behnke et al. (1993). Today, pastoralism is being re-evaluated as a time-tested, often undervalued alternative path to food production with largely untapped potential for income growth and employment in 'marginal' areas, such as arid or high altitude lands, where agriculture is not feasible or less productive (but see Biagetti et al., 2021a for a critique of the notion of drylands as marginal). According to supranational organizations (e.g., African Union, 2010; FAO, 2020, 2021), and specialists from different disciplines (e.g., Briske et al., 2020; Dong et al., 2016; Hesse & MacGregor, 2006; Homewood, 2008; Köhler-Rollefson, 2021; Scoones et al., 2020; Tessema et al., 2014), pastoralism has the potential to respond to the most compelling challenges of our times, including climate change (e.g., Balehegn et al., 2019;

Iticha & Huesen, 2019; Kratli et al., 2013), since it requires little fossil energy and livestock walks to their naturally grown feed, with no (or very limited) cultivation nor transportation of fodder required. Notwithstanding these latest developments, Boles and colleagues (2019) noted that stereotyped narratives about the shortcomings and drawbacks of pastoralism still plague academic (e.g., Hein, 2006) and public (e.g., Shanahan, 2013) debates, specifically in respect to land degradation and, as such, these stereotypes still influence policy interventions (Gilbert, 2013).

Current pastoralism is the legacy of the processes of animal domestication that started before the beginning of the Holocene in several parts of the world, and represents one of the most ancient food production systems. Such a system allowed humans to adapt and live in drylands and to produce food under often extreme and variable environmental conditions. During the last ten millennia, pastoral economies have evolved to function with the natural environment and therefore with high variability of ecological settings (e.g., Bollig et al., 2013; Capriles & Tripcevich, 2016; Kardulias, 2015). During the last thirty years, the archaeology of pastoral societies has seen the application of new techniques (e.g., remote sensing, ancient DNA, isotope analysis, dung studies) that have improved our understanding of the long-term dynamics of pastoral landscapes, patterns of mobility, and livestock management practices. For instance, large-scale studies of pastoral landscapes and land use (e.g., Boles et al., 2019; Phelps & Kaplan, 2017) and their influence on current ones (e.g., Marchant & Lane, 2014) have been essential to understand pastoral dynamics at macro-scale. The application of remote sensing and automatic detection techniques has improved the study of pastoral burial landscapes (e.g., Biagetti et al., 2017; Chen et al., 2021; Hildebrand et al., 2018). Advances in analytical approaches have enabled us to further expand our understanding of early pastoralism. For instance, the study of dung (e.g., Égüez & Makarewicz, 2018; Égüez et al., 2020; Makarewicz, 2016; Shahack-Gross et al., 2004, 2008) and isotopic analyses of faunal remains (Janzen, 2022; Janzen et al., 2020) have provided information on diet and mobility of ancient herds, and on the use of livestock byproducts (e.g., Amicone et al., 2021), while organic residues (e.g., Dunne et al., 2012; Grillo et al., 2020) are shedding light on ancient food preparation and consumption. Furthermore, new research programs in areas with an important archaeological presence of pastoral societies have brought to light the pivotal role of such societies in state formation (e.g., Gatto, 2011), the development of sedentary societies (Arbuckle & Hammer, 2019), the spread of domestic animals (e.g., Prendergast et al., 2019), and the shaping of trade routes and networks (Frachetti et al., 2017).

Between the macro (landscape) scale and the micro scale, the site level as a unit of analysis has been comparatively underexplored. The lifeways of pastoral societies have generated an unconventional and diverse archaeological record, markedly different from that of sedentary farmers living in towns and villages. Habitation sites of mobile pastoralists have long been regarded as producing only ephemeral traces: little or no permanent architecture, shallow or absent deposits, and scatters of mostly perishable materials. As a result, pastoral sites have traditionally been characterized as ‘invisible’ (Robertshaw, 1978), ‘leaving no traces’ (Smith, 1992), or ‘too ephemeral to be archaeologically recoverable’ (Smith, 1980). This elusiveness—together with the paucity of common archaeological markers—has frustrated

attempts to identify and interpret pastoralist domestic areas (Chang & Koster, 1986; Cribb, 1991).

Early ethnoarchaeological work in Africa reinforced this view by stressing the ephemerality of pastoralist homesteads (David, 1971; Robbins, 1973). Yet later studies highlighted that durable traces do exist, even if subtle, and can be detected through appropriate methods (Grillo, 2012, 2014; Mbae, 1990; Shahack–Gross et al., 2004). This shift reframed the problem: rather than assuming invisibility, the challenge lies in developing new techniques capable of identifying, recording, and interpretiKynčlováng these material signatures.

In recent decades, a wide range of techniques and approaches has pushed the study of pastoral archaeological sites to new limits. Houle's (2024) edited volume synthesizes recent advances, showing how microscopic and actualistic methods are transforming the study of pastoral contexts. Such approaches make it possible to reconstruct the complex and nuanced histories of mobile groups once thought to leave little trace. Ethnoarchaeology has been particularly influential in this transformation, especially in dryland regions where the record is subtle, fragmented, and difficult to interpret. By linking contemporary practices with material signatures, ethnoarchaeology has not only enhanced our capacity to read elusive remains but also reshaped broader understandings of pastoralist social, economic, and ecological strategies. This research has challenged enduring stereotypes, repositioning mobile pastoralists as adaptive innovators who developed flexible strategies for food security and social organization in some of the world's most variable environments.

Within this evolving framework, theoretical and methodological innovations have expanded the ways in which pastoral archaeological sites are approached. One particularly promising direction is geo-ethnoarchaeology, which applies geological principles to ethnographic contexts in order to link human activities with site formation processes (Friesem, 2016). First introduced in relation to the study of ancient pastoral deposits in Sicily (Brochier et al., 1992), geo-ethnoarchaeology was later applied to pastoralist sites in eastern Africa, particularly for identifying ancient livestock enclosures (Shahack-Gross et al., 2003, 2004; see also Shahack-Gross, 2011). As Shahack-Gross (2017) has argued, anthropogenic sediments should be understood as artifacts in their own right, providing a powerful basis for interpreting deposits beyond site-specific contexts and for building broadly applicable models of pastoral lifeways. New geochemical research has demonstrated that anthropogenic sediments (such as nutrient "hotspots") at pastoral sites can, in fact, persist for thousands of years (Marshall et al., 2018; Storozum et al., 2021).

Over the past decade, the archaeology of mobile pastoralism has increasingly emphasized the importance of habitation sites and household-level analysis within broader landscapes (Anthony et al., 2016; Biagetti, 2014; Frachetti & Mar'yashev, 2007; Grillo et al., 2018; Wright, 2016). New field and analytical methods now reveal domestic behaviors, socioeconomic activities, ritual practices, and political organization. Rather than focusing only on artifacts, researchers also investigate ecological impacts through soil and vegetation data—phytoliths, pollen, organic matter, and soil chemistry—which help reconstruct site use and identify variations across occupation areas (Boles & Lane, 2016; Marshall et al., 2018; Portillo et al., 2012; Shahack-Gross et al., 2003, 2004). Analyses of herbivore dung further illuminate

spatial organization, seasonality, and economic practices such as dung fuel use, manuring, and stabling (Biagetti et al., 2021b; Brochier et al., 1992; Égüez et al., 2018, 2020; Égüez & Makarewicz, 2018; Seitsonen & Égüez, 2021; Shahack-Gross, 2017; Shahack-Gross et al., 2008). Complementary techniques—such as fluxgate gradiometry to detect magnetic anomalies (Fitton et al., 2022; Hu et al., 2019) and soil geochemistry to distinguish activity areas—are expanding the methodological toolkit. Agent-based and other computational models now provide powerful means to explore pastoral household decision-making, adaptation, and resilience to climate and social challenges (Cioffi-Revilla et al., 2010; Clark & Crabtree, 2015; Kuznar & Sedlmeyer, 2008; Rogers et al., 2012, 2015). Multi-element geochemical analysis, combined with complementary proxies and post-processed using purpose-built geostatistical code, offers a sensitive approach for identifying anthropogenic signatures and distinguishing activity areas in pastoral contexts. Its application to pastoral archaeology remains limited, particularly in drylands. The CAMP project addresses this gap through a comparative, multi-regional framework.

Materials and Methods

Hypothesis

Mobile pastoralist groups tend to leave behind ephemeral material traces—such as dung layers, lightweight structures, and surface scatters—that are easily eroded or dispersed by environmental and human processes. Our project—(Re)Constructing the Archaeology of Mobile Pastoralism (CAMP)—focuses specifically on the anthropogenic deposits resulting from pastoral occupations. CAMP adopts a multidisciplinary approach that moves beyond traditional interpretations by identifying chemical proxies that can be directly linked to human activities within settlements. Such activities leave measurable signatures in the form of chemical elements (Oonk et al., 2009), which are incorporated into archaeological sediments through repeated and routine behaviors (Wilson et al., 2008). The interpretative framework we propose is grounded in two working assumptions. First, that specific and recurrent activities may generate recognizable chemical signatures, even when their cultural or procedural expression varies. Second, that these signatures may be expected to display a general consistency within and across sites, while still allowing for local variation (Lubos et al., 2016; Oonk et al., 2009). In order to build a robust reference framework for the spatial distribution of chemical elements at pastoral sites, our research begins in the ethnographic present, where observable practices can be directly linked to their sedimentary outcomes.

Case Studies

In the first stage of the project, research has focused on three distinct regions: Maitengwe, in the northern part of Botswana's Northeastern District; Khor Rori in the coastal area of Dhofar, in southern Oman; and Loreamatet, located in Turkana

County, Kenya (Fig. 1). Maitengwe is characterized by a semi-arid climate with low and unpredictable rainfall; Dhofar experiences a subtropical desert climate influenced by seasonal monsoons; while Loreamatet in Turkana is situated in a hot arid zone with extremely limited precipitation. These regions were selected for their ecological variability, cultural diversity, and long-standing pastoral traditions. In addition to these core study areas, supplementary test locations have been established to broaden the dataset and assess the wider applicability of the analytical protocol across diverse environmental and cultural contexts.

Area 1—Botswana

In northeastern Botswana, the CAMP project collaborates with Bakalanga agro-pastoralists living in Maitengwe village (Northeast District), first contacted in late 2021. This community practices opportunistic mobility, primarily centered on cattle herding. While the main settlement is permanent, cattle are often relocated to secondary settlements (cattle posts) located 15–30 km away, where they may remain for most of the year. Archaeologically, the project focuses on Makolontwane, a Stone Walled Site dated to 1700–1800 CE (Huffman, 2007; Morton, 2014) set in southern Botswana. This agro-pastoral settlement is characterized by monophasic occupation spans of approximately 15 years, represented by thin yet extensive anthropogenic deposits. A successful pilot study conducted at the similar stone-walled site of Seoke (Biagetti et al., 2021b) served to test the methodological approach proposed for CAMP.

Area 2—Oman

In the Khor Rhori area of southern Oman, pastoralists follow a seasonal transhumant regime shaped by the khareef, a monsoonal period occurring from mid-June to mid-September (Ball & Tzanopoulos, 2020). During this time, excessive moisture, saturated soils, and biting flies make conditions unsuitable—especially for camels, which are relocated alongside goats and cattle to the plateau or coastal plains. Following the khareef (September–January), livestock descend to graze on natural vegetation, supplemented by feedstuff. During the dry season (January–June), herds are kept near camps or villages and rely largely on stored feed. Archaeological research in the region, led by the DHOfar Map and Inqitat Archaeological Project (DHOMIAP, Lischi, 2025), focuses on human occupation of the area from the Bronze Age through Late Antiquity and has revealed a landscape characterized by permanent settlements with monumental architecture and seasonal open-air sites.

Area 3—Kenya

In northwestern Kenya, the Turkana pastoralists of the Loreamatet area primarily raise sheep, goats, and camels, which have largely replaced cattle. The area lies within the Turkana Basin, a region currently under investigation by the multidisciplinary Later Prehistory of West Turkana (LPWT) project. Their research explores the development of pastoral social, ecological, and mortuary landscapes

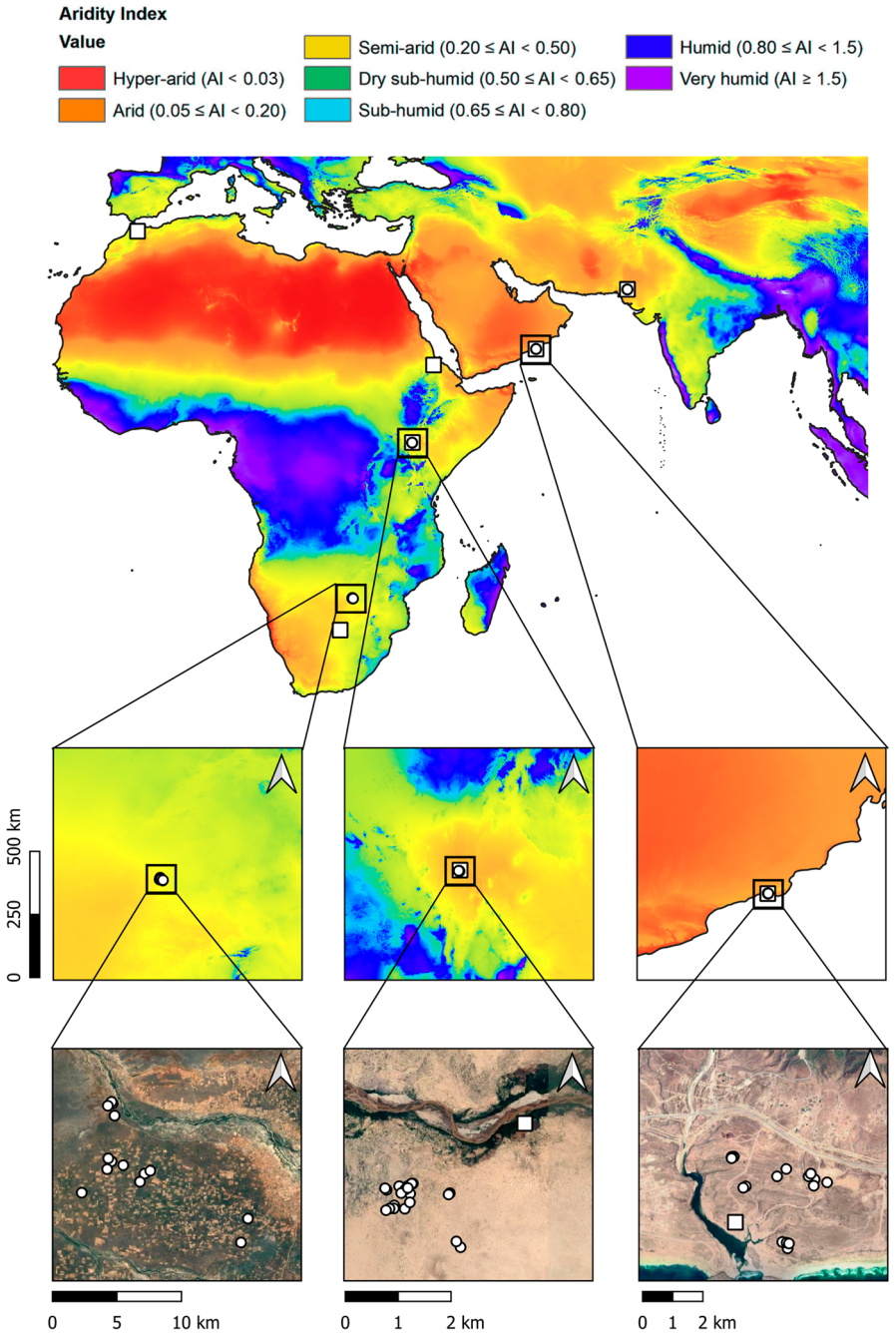

Fig. 1 CAMP case studies and main areas with respect to aridity zones. Ethnographic sites are represented by white dots, archaeological sites by white squares

during the Pastoral Neolithic (PN, ca. 5000 BP) in the Turkana Basin. Known open-air settlement sites from the PN in the Turkana Basin are very rare (see only Dongodien on the eastern side of Lake Turkana (Ashley et al., 2017; Marshall et al., 1984) and recently identified sites located in the Nakwaperit area on the western side of Lake Turkana (Hildebrand et al., 2022), underscoring a need for additional archaeological survey and investigation.

The selection of inhabited and abandoned campsites was guided by the need to capture the diversity of pastoral settlement types and their associated anthropogenic signatures (see Table 1). In each study area, inhabited campsites were chosen to reflect the range of activities and spatial configurations typical of settlements, as identified through ethnographic observation. These sites provide the basis for documenting the relationship between daily practices and the chemical, biological, and physical markers they produce. Abandoned campsites were selected to represent different stages of abandonment and varying environmental exposures, allowing for the assessment of how anthropogenic chemical signatures change or persist over time. Together, these site types offer a diachronic perspective on the formation and transformation of pastoral sites, essential for developing robust interpretive models applicable to the archaeological record. Finally, key archaeological sites associated with pastoralism are being studied, with anthropogenic deposits reinterpreted through analytical models developed from the ethnographic present. Together, this multi-tiered approach bridges present-day pastoral practices with archaeological contexts, providing a robust framework for identifying and interpreting pastoral signatures in the archaeological record.

Between 2024 and 2025, fieldwork was conducted in the three main study regions. In Botswana, two separate expeditions were executed: the first, an ethnoarchaeological campaign in June 2024, and the second, an archaeological campaign in November 2024. Fieldwork in Oman was carried out in January 2025, while research in Kenya took place in June 2025. In Kenya, in addition to the successful fulfillment of the planned ethnographic investigations, chemical analysis of samples from the archaeological site of Nakwaperit, excavated in 2023 by E. Hildebrand and the LPWT team, was carried out as well.

Table 1 Summary of samples collected so far

Location	Ethno inhabited	Ethno abandoned	Archaeological	Control samples	N total
Central/SE Botswana	10	4	1	300	4399
Dhofar, Oman	10	5	1	150	1441
Turkana, Kenya	10	10	1	150	2759
Sindh, Pakistan	1	-	1	41	209
Tigray, Ethiopia	1	-	1 (to be sampled)	-	220
W. Maghreb, Morocco	-	-	1 (to be sampled)	-	-
Total	**32**	**19**	**5**	**641**	**9,028**

Beyond the three core regions, CAMP has also integrated comparative material from other contexts. These include samples collected in 2021 by A. Ruiz-Giralt and S. Biagetti from an ethnographic settlement in Ethiopia, as well as material gathered in 2025 by M. Madella and his team from an ethnographic settlement in Pakistan. So far, CAMP has amassed a corpus of 9,055 sediment samples from a wide range of ethnographic and archaeological contexts (Table 1). To date, fieldwork has covered 32 inhabited settlements, 19 abandoned settlements, and 5 archaeological sites across Botswana, Oman, Kenya, Pakistan, Ethiopia, and Morocco. For each major study area, a series of control samples (c. 150 per region) were collected off-site to provide comparative baselines against which anthropogenic signatures can be assessed. While most ethnographic and archaeological samples from Botswana, Kenya, and test areas have already been measured with portable X-ray fluorescence (pXRF), those from Oman and other regions are currently under study.

Methods

Fieldwork

In each of the study areas, we collaborate with local authorities and local communities. Initial meetings and encounters are organized, where the project is explained with the help of interpreters. Once the settlements have been identified (Fig. 2), they are surveyed and topographically mapped on-site using a high-precision differential GPS. Such maps (Fig. 3a and b) incorporate all the macro features such as visible domestic structures (e.g., huts, kitchens, stores, fireplace) as well as the diverse activity areas identified with the support of local informants (areas of food preparation and consumption, workshops, middens, etc.). Furthermore, the maps include livestock structures and features (e.g., pens, corrals, secondary areas of dung accumulation) along with scatters of portable artifacts. These digital products represent the working baseline within which data can be contextualized throughout the project. Samples are collected following a multi-scalar approach. Regular lattice grids are employed across the area, while samples from anthropogenic deposits are taken at variable intervals to adapt to specific contexts (see for instance Save et al., 2020). For large areas, such as open spaces between structures, a 4×4 m or 2×2 m grid is used, whereas smaller features are sampled with finer grids of 1×1 m or even 0.5×0.5 m. This flexible strategy avoids excessive sampling in large areas but also ensures sufficient resolution within small and often ephemeral structures, which would otherwise yield only a single data point under a coarser lattice. Each sample is geolocated using the DGPS and consists of c. 20 g of sediment that have been stored in sealed double polyethylene bags.

In order to meaningfully compare the elemental composition of on-site samples, a series of off-site soil samples from the areas surrounding both the ethnographic settlements (inhabited and abandoned) and the archaeological sites are additionally collected. These control samples are essential for distinguishing anthropogenic signatures from background geochemical variability, allowing us to identify which chemical signals are the direct result of specific human activities. A total of 150

Fig. 2 An inhabited ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

off-site samples are collected in each study area (see Table 1), providing a robust comparative dataset between zones affected by settlement activities and those without persistent anthropogenic presence. The sampling strategy is designed to minimize potential contamination or bias. Areas showing clear evidence of modern occupation (e.g., recently abandoned villages), heavily disturbed zones (such as dirt roads or pathways), and landscapes altered by extractive activities (including tree cutting, overgrazed pastures, charcoal production areas, or cultivated fields) are systematically avoided.

Multi-element Analysis by pXRF

The study of chemical elements in anthropogenic sediments is a fundamental advance of current archaeological research. Since the seminal works of Barba and Ortiz (1992) and Middleton and Price (1996), the analysis of chemical elements in anthropogenic sediments has found a variety of applications in archaeology (e.g., Biagetti et al., 2021a, 2021b; Save et al., 2020) and ethnoarchaeology (Lancelotti et al., 2017; Negre et al., 2016; Rondelli et al., 2014) with the particular aim of identifying the chemical signatures of human activities (see Bintliff & Degryse, 2022 for a recent review). Indeed, chemical markers represent an invaluable proxy to bring to light past and recent activities, to understand the spatial dynamics of such activities, and to interpret architectural structures in relation to their functions.

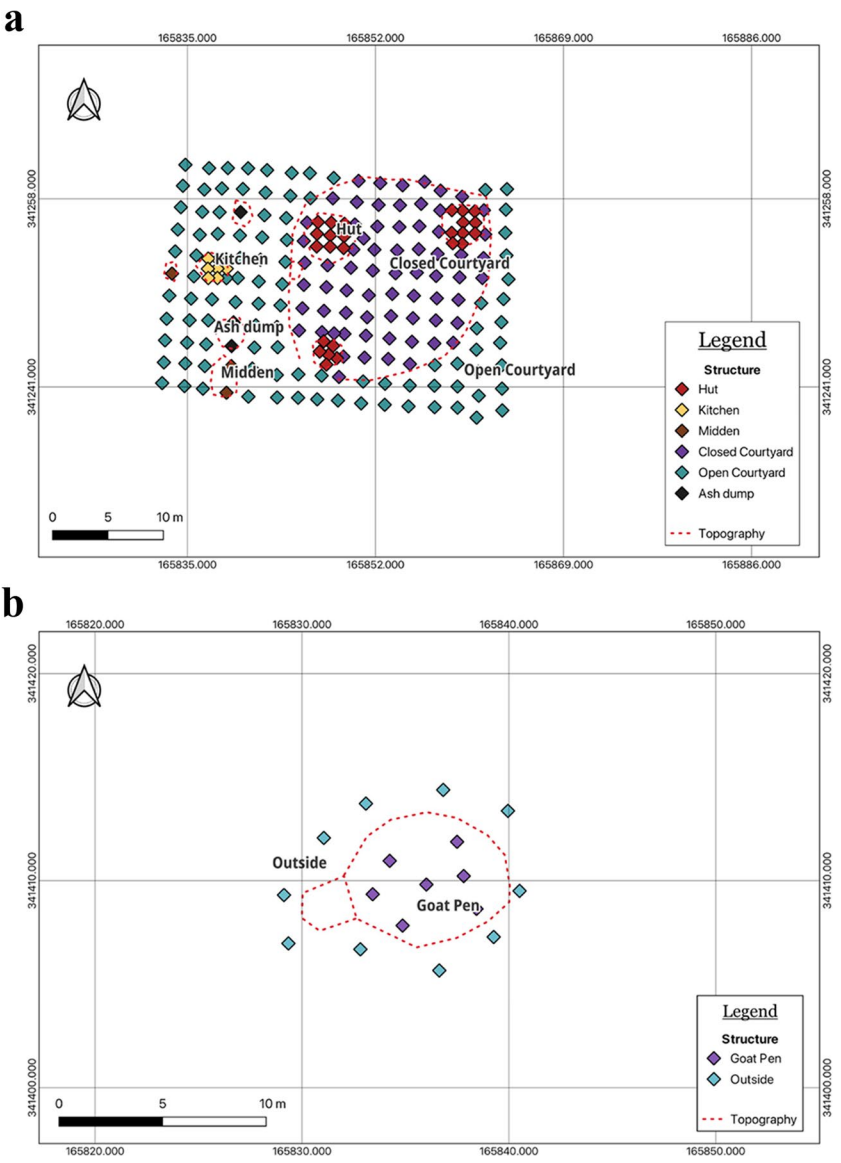

Fig. 3 **a, b** Examples of mapping and sampling strategy followed at an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

The potential of this approach resides in that the elemental chemical signatures are proxies for activities that were carried out in a repetitive way in a determined space (Rondelli et al., 2014). Contrary to many other approaches, the chemical signature is not defined by the absolute value of a given chemical element or elements, but by their combination and, especially, by the anomalies created by the deviation from the average of the samples. The archaeological use of portable X-ray fluorescence

devices (pXRF) is rapidly growing because of the advantages offered by portable devices that provide inexpensive and fast results. Such characteristics as well as the non-destructive nature of pXRF are obvious benefits for examining archaeological items that must not be damaged or cannot easily be transported to a laboratory, and its potentials have been widely demonstrated also for the study of archaeological sediments (e.g., Davis et al., 2012; Ginau et al., 2020; Janovski et al., 2022). More specifically, pXRF is currently being used for site prospection and for the characterization of activity areas in different archaeological contexts. Lubos et al. (2016) and Frahm et al. (2016) compared the performance of pXRF analysis on sediment samples in respect to other techniques and found that the current generation of pXRF instruments is highly suitable for multi-element analysis. Other studies focused on the use of pXRF to reconstruct prehistoric settlement patterns (Gauss et al., 2013), to map anthropogenic deposits (Šmejda et al., 2018), and to perform large-scale surveys (Hayes et al., 2013; Poggi et al., 2025; Save et al., 2020). Furthermore, the combined use of pXRF and geostatistical techniques to analyze archaeological sites spatially, represents a promising field for the interpretation of past human occupations (Biagetti et al., 2021b; Williams et al., 2021).

The use of pXRF in archaeological settings raises technical and methodological concerns. Since the 2010 s, scholars have called for the elaboration of standardized and systematized protocols in the use of pXRF for archaeological purposes (e.g., Frahm, 2013, 2024; Goff et al., 2020; Hunt & Speakman, 2015; Johnson et al., 2024; Shackley, 2010; Williams et al., 2020). In any case, it is clear that pXRF enables rapid, non-destructive, and cost-effective analysis of massive amounts of samples, which would be challenging to analyze with alternative, though more accurate, techniques such as mass spectrometry or laboratory XRF. In the course of our fieldwork, we have both exported sediment samples (Botswana, Oman) and analyzed them in our lab at UPF, or brought the machine to the field (Turkana) and set it up in the facilities of the Turkana Basin Institute. This choice of on-field or laboratory analysis was largely influenced by the ability to import and export sediments from a given country and has resulted in an adapted on-field protocol in addition to our standard laboratory protocol.

The chemical analyses of this project are performed using a Bruker CTX 800 portable benchtop XRF analyzer (pXRF), which is equipped with a Rh target X–Ray Tube (4 W, 6–50 kV, 5–200 μA) and a large-area silicon drift detector (SDD). The Bruker CTX 800 instrument was chosen for the project due to its versatility. This contained unit (which does not feature an open beam of radiation compared to the design of hand-held units) provided a portable and safe solution, allowing for its use by multiple operators either in a laboratory setting or in-field when the exportation of samples is not possible.

The laboratory protocol consists of sieving air-dried bulk sediment samples with a 1 mm sieve directly into plastic sample cups prepared with polypropylene 4.0 μm thin film. Sieving is conducted in order to increase reliability and reproducibility, to reduce variation, and to provide a level of homogenization of the samples by removing any potential large plant materials within the soil samples and casts larger than sand (Middleton, 2004; Williams et al., 2020). Sieves and funnels are then cleaned between each sample to remove dust from the previous sample. The pXRF machine

is set to the Bruker application 'GeoExploration', using the 'Oxide3phase' method (calibrated for SiO_2-rich samples), which combines the results of three different measurements performed with different filters, applied voltages and currents, allowing for the detection of up to 48 elements, from Mg to U. The integration time for each measurement range is adjusted with the following settings: Phase 1 (Voltage: 30 kV, Current: 12 µA, Filter: Ti/Al) and Phase 2 (Voltage: 50 kV, Current: 17 µA, Filter: Cu/Ti/Al), which are optimized to detect intermediate and heavy elements, respectively, are set to run for 30 s each. Phase 3 (Voltage: 15 kV, Current: 10 µA, Filter: N/A), which corresponds to the light element range, is set to run for 100 s to allow for more reliable readings from light elements such as Mg and P which lie on the edge of the detection limits for pXRF. In total, each reading takes 160 s. Initially, the pXRF is warmed up for about 10–15 min using Bruker check samples before the first sediment samples are measured. The main difference between the laboratory and in-field protocol is the reduction in cleaning of sieving materials between samples and the time spent to warm up the detector, which is reduced to around 5 min. It must be borne in mind that the method of pXRF is semi-quantitative due to a number of factors including pore space and particle size, considering factory calibrations are based on ideal (flat, dense, homogenous) samples. The employed protocol aims to balance these limitations through minimal sample preparation while remaining convenient given the large quantity of samples measured for the project.

Geostatistics

The CAMP project employs a structured workflow in R for analyzing the multi-element datasets generated through portable X-Ray Fluorescence (pXRF), publicly available at https://github.com/project-camp/camp-public. The process begins with data preparation, which involves pre-processing and systematically organizing the measurement data to ensure quality, consistency, and comparability (see Filmozer et al., 2018; Pawlowsky-Glahn & Buccianti, 2011). pXRF instruments using Bruker calibration settings produce a report on all elements within the elemental detection range (Mg to U). These results of all data will report no empty values unless the detected signal is below the limit of detection (LOD) of the device. The report will consequently include records of element measurements with a large error or which are below the LOD (< LOD). Therefore, elements that are reported below the LOD or below the confidence range (*i.e.*, when the measured compositional value is lower than three times the reported error) are not included in subsequent statistical analyses. Also, possible interferences between XRF signals of different elements (like, for instance, Cl and Rh or Sr and Zr) are taken into account by direct inspection of the XRF spectra.

To ensure data closure to 100%, a residual component ("Res") is introduced, representing the proportion of unaccounted elements. This is necessary to maintain the mathematical requirements of compositional data analysis and prevent statistical distortions or spurious correlations in subsequent log-ratio analyses (see Martín-Fernández et al., 2015 for further details). Because the data are inherently compositional—*i.e.*, carrying only relative information—the use of log-ratio coordinates ensures that closure no longer affects their covariance structure, allowing

multivariate statistics to be performed in a valid Euclidean space. The structure of the data was opened using log-ratio transformations from the Aitchison geometry. Different transformations were applied depending on the type of analysis. Centered log-ratio (CLR) coordinates were used for PCA and cluster analysis. Isometric log-ratio (ILR) coordinates were used for outlier detection as well as for Inverse Distance Weighting (IDW) and cokriging, due to their suitability for modeling covariance structures in Euclidean space. For correlation analysis we applied the symmetric-balance transformation proposed by Kynčlová et al. (2017), which provides valid correlation coefficients for compositional data. Below limit of detection (<LOD) replacement is carried out using multiplicative replacement or log-ratio expectation–maximization (EM) algorithms depending on the number of values to be imputed. Mahalanobis distances are used to detect multivariate outliers and identify data anomalies that may indicate potential sampling or measurement errors. Exploratory data analyses are subsequently applied. This involves calculating descriptive statistics as well as applying correlation analysis (Fig. 4 left), principal component analysis (Fig. 4 right), and unsupervised cluster analysis to detect broader patterns of elemental compositional covariance (see Filzmoser et al., 2018). Together, these steps clarify the internal structure of the dataset and allow us to identify which elements are most informative for subsequent spatial and functional interpretations. All these steps are implemented in modular R scripts, allowing users to adapt thresholds, transformations, and imputation strategies as needed.

Building on this foundation, exploratory spatial analyses are carried out (see Tolosana-Delgado & Mueller, 2021). This stage includes the creation of elemental maps, including the application of Inverse Distance Weighting (IDW) interpolation, which transforms point-based pXRF measurements into continuous surface models (Fig. 5). These interpolated maps reveal concentration gradients across the study area and make visible spatial patterning that corresponds to human activity. In the workflow, however, IDW is used as an exploratory; therefore, the resulting maps are descriptive rather than inferential and are not used for statistical interpretation. Still, because IDW is computationally light and straightforward to implement,

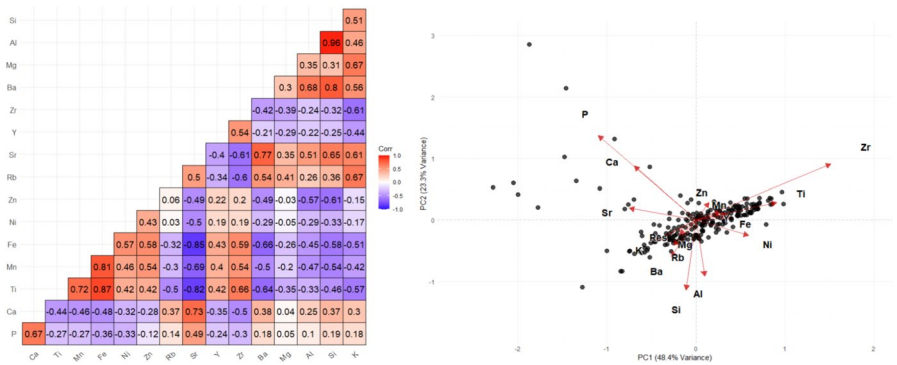

Fig. 4 Examples of (left) compositional correlation analysis and (right) principal component analysis from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

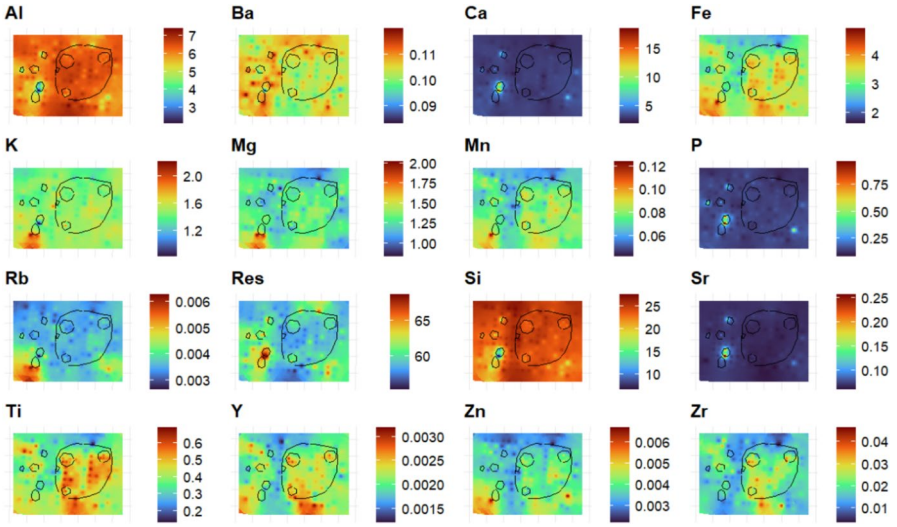

Fig. 5 Example of IDW applied to a domestic area from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya). All data are given in weight percent

it provides an efficient way to obtain preliminary spatial visualizations, allowing functional zones such as cooking areas, living spaces, and external open areas to be distinguished on the basis of elemental distributions. Alongside IDW, swath plots and spatial anisotropy analysis are used to examine directional variation and assess whether spatial patterns are isotropic or influenced by orientation (Fig. 6).

In addition to these exploratory stages, the project also incorporates full geostatistical modeling to refine and validate spatial interpretations (see Tolosana-Delgado & Mueller, 2021). Pre-processed data obtained from multi-element analysis

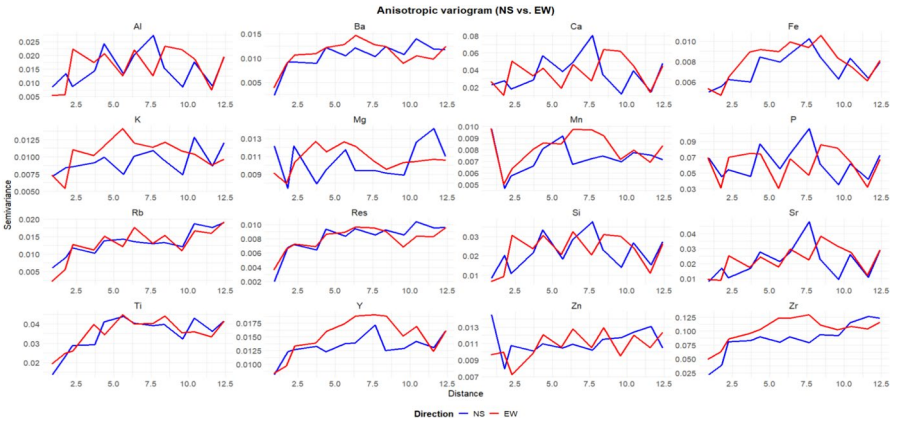

Fig. 6 Example of anisotropy analysis applied to a domestic area from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

are analyzed using multivariate geostatistics, specifically kriging techniques. Since we work with multivariate data, we apply cokriging: spatial continuity is modeled through a linear model of coregionalization (LMC), which extends univariate variogram modeling to multiple variables by jointly describing their spatial autocorrelation and cross-correlations (Fig. 7). The statistical assumptions relevant to cokriging —including second-order stationarity, coherent and positive-definite cross-covariance structures, linearity of the estimator, the presence of spatial cross-correlation between variables, and the use of variables defined in an appropriate Euclidean space—are evaluated through the inspection of empirical variograms and cross-variograms, the successful fitting of a Linear Model of Coregionalization (LMC), and the use of ILR coordinates, which provide approximately Gaussian behavior. Fitting an LMC involves computing experimental and cross-variograms, selecting base models (e.g., spherical, exponential, Gaussian), and ensuring coherence of the coregionalization matrix. In the proposed workflow, we do this automatically by fitting direct and cross-variograms for all variables, selecting candidate models based on their empirical fit, and then applying the Goulard and Voltz (1992) algorithm to enforce positive-definite sill matrices and a coherent multivariate structure (see Biagetti et al., 2021b for further details). Only LMCs that successfully converge and meet these constraints are retained for cokriging prediction. This procedure iteratively adjusts the nested components until a valid multivariate model is obtained, ensuring that shared ranges and nested structures remain geostatistically admissible. This automated approach reduces subjective model selection and provides a reproducible foundation for cokriging across heterogeneous archaeological datasets. In

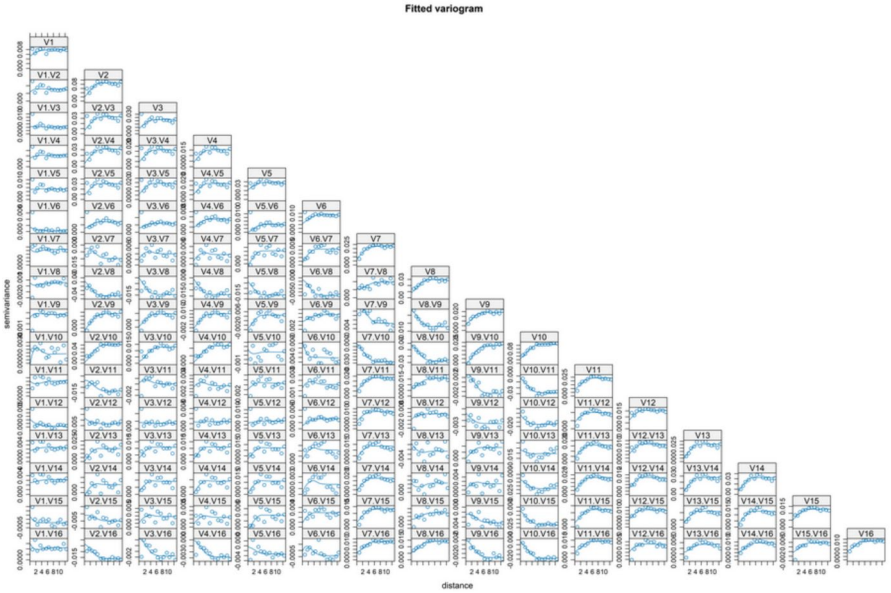

Fig. 7 Example of experimental and cross-variograms with fitted LMC from a domestic area from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

some cases, we apply Maximum/Minimum Autocorrelation Factors (MAF) before cokriging to reduce noise and emphasize structured spatial signals. By extracting linear combinations of variables with maximal or minimal spatial autocorrelation, MAF can improve the robustness and performance of the subsequent cokriging analysis. Once the LMC is established, it provides the basis for cokriging (CK), which incorporates both the spatial structure of each variable and their cross-correlations to predict chemical element distributions (Figs. 8 and 9). Model quality is assessed through cross-validation and standardized residual diagnostics implemented directly in the R pipeline, which outputs error metrics and variance surfaces for inspection following the procedure outlined by Tolosana-Delgado and Mueller (2021).

Although more computationally demanding than simpler interpolation methods, CK explicitly models spatial autocorrelation, integrates relationships between elements, and generates uncertainty estimates. This makes it especially suited to linking geochemical patterns generated by anthropic activities to settlement features such as architectural structures, while producing more precise predictions at unsampled locations. Widely employed in soil science and geology, kriging techniques generate estimated surfaces from scattered points, under the assumption that the distance between samples reflects a spatial correlation that can explain broader variation. These techniques have already shown promise in archaeological contexts, having been pioneered at a small scale to model chemical markers from a contemporary house in Northern India (Rondelli et al., 2014) and later applied to the archaeological site of Seoke in Botswana (Biagetti et al., 2021b). In both cases, kriging proved effective in identifying activity areas and distinguishing between different domestic spaces, demonstrating its potential for advancing the study of pastoral settlements.

Further Laboratory Work: Phytoliths, Organic Residues, Mineralogy, Stable Isotopes, aDNA, and Remote Sensing

Building on the multi-element dataset generated through pXRF and subsequent geostatistical modeling, CAMP will pursue additional lines of analysis designed to capture different dimensions of pastoral lifeways. These include phytolith and organic residue analysis, as well as mineralogy, stable isotope analysis, and aDNA. By focusing on well-contextualized samples that already display relevant chemical signals, these complementary approaches will maximize interpretative potential and ensure a robust integration of botanical, biomolecular, and geochemical evidence.

Although pastoralism is often conceived as revolving primarily around animals, recent research has highlighted the central role of plants in sustaining pastoral livelihoods, even in drylands (FAO, 2020). The disregard of plant use has sometimes contributed to misunderstandings of pastoral socio-economic systems, as reflected in long-standing debates over the idea of "pure pastoralism" (Salzman, 1972). CAMP addresses this by producing activity signatures for plant proxies, particularly phytoliths, in order to reconstruct how plants were used in daily life—whether as fodder, food, fuel, dung temper, or raw materials for craft and construction. Phytoliths, which are microscopic opal silica bodies formed in plant tissues, are highly informative because they can provide taxonomic and anatomical information, offering important insights into plant use and related activities. More importantly, they

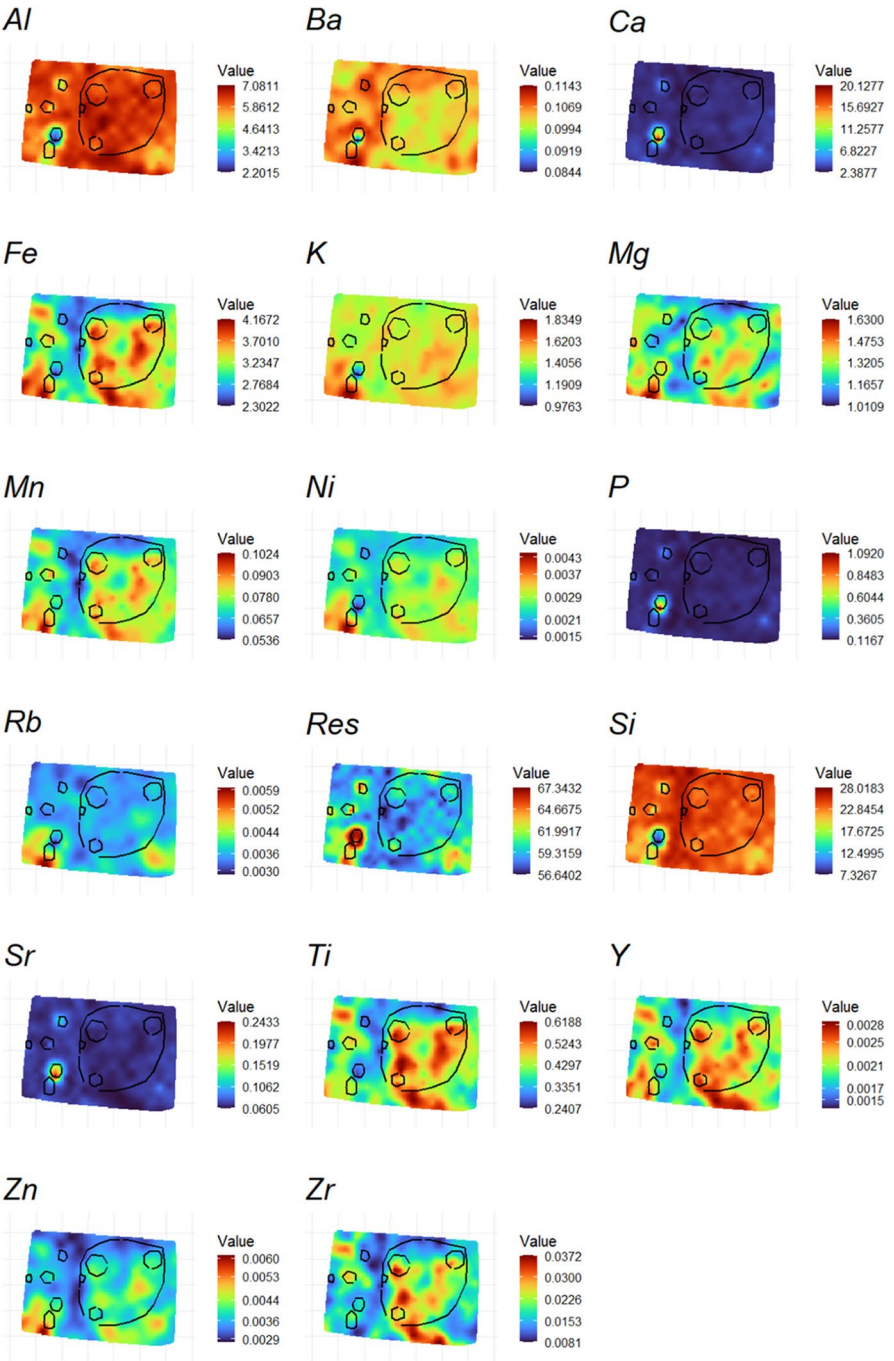

Fig. 8 Example of cokriging analysis applied to a domestic area from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

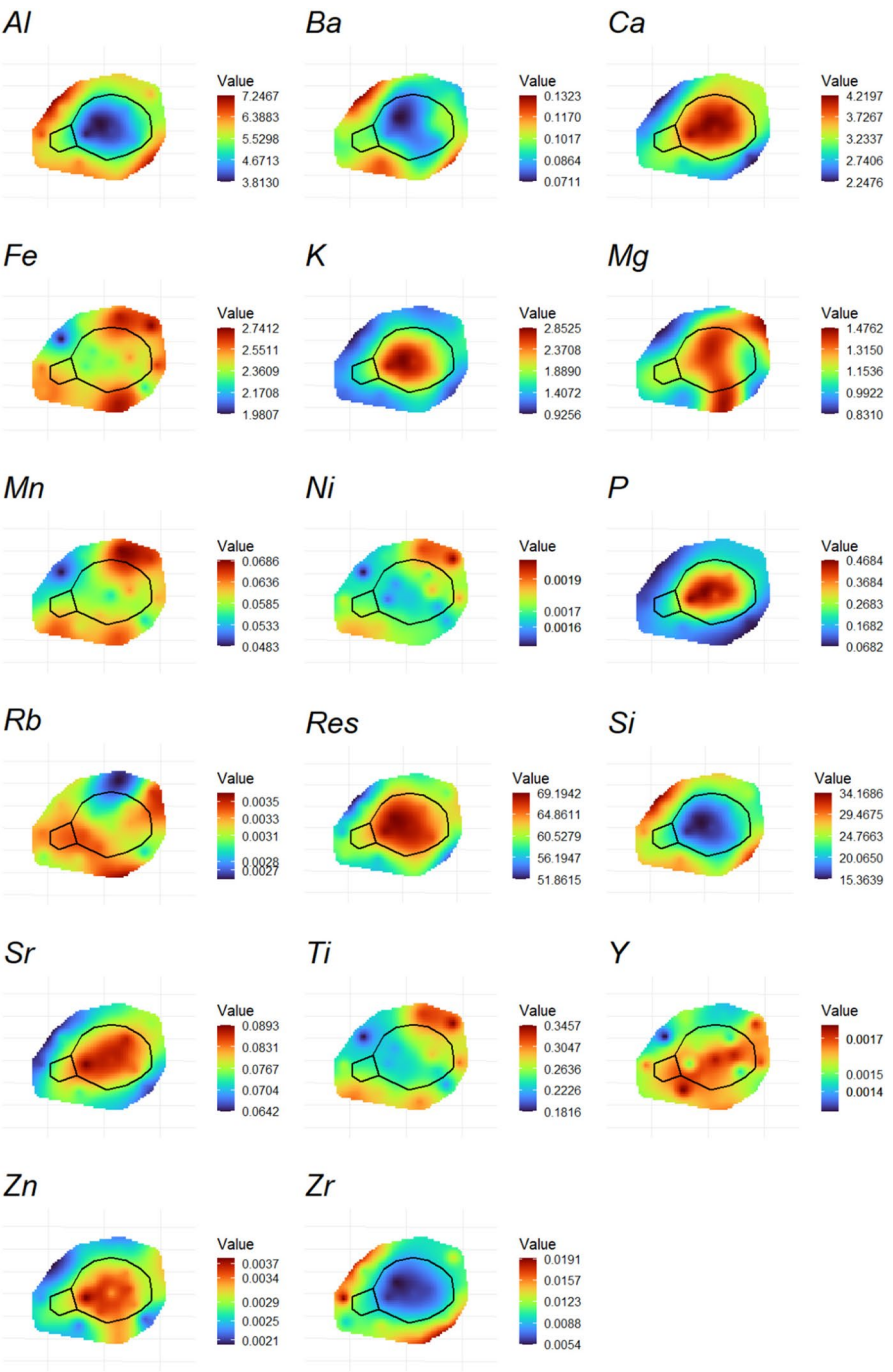

Fig. 9 Example of cokriging analysis applied to a goat corral from an ethnographic settlement (E1) in Loreamatet, Turkana (Kenya)

survive in sediments almost regardless of preservation conditions, making them one of the most ubiquitous remains in archaeological sites (Lancelotti & Madella 2012).

In parallel, CAMP will explore whether organic residue analysis can shed light on pastoral uses of livestock byproducts, particularly dairying and food preparation. While this method has most commonly been applied on pottery (e.g., Dunne et al., 2012, 2018), here we extend its application to ethnographic contexts in order to explore whether residues can also be recovered from anthropogenic sediments. This line of inquiry has the potential to broaden the scope of residue analysis, offering new possibilities for identifying activity areas and reconstructing food practices. The arid environments of our study regions may favor the preservation of lipids, and although systematic applications to sediments remain rare (Bull et al., 1999; Heron et al., 2010; Kanthilatha et al., 2014), the field is clearly expanding (Mallol et al., 2025). By means of gas chromatography–mass spectrometry (GC–MS) analyses of lipids, particularly fatty acids, we aim to assess whether diagnostic differences between mammalian, plant, and fish fats (Barnard et al., 2007) can be meaningfully applied to anthropogenic soils.

In the later stages of the project, we will also evaluate whether more experimental lines of research—such as stable isotope analysis, aDNA, and mineralogy—can be applied to well-preserved ethnographic and archaeological contexts. Stable isotopes may help identify dung inputs and reconstruct animal feeding regimes (Shahack-Gross, 2011), while aDNA could provide taxonomic information about livestock and plant species (Gu et al., 2023; Shillito et al., 2020). Yet both approaches are sensitive to contamination, and ethnographic contexts provide an ideal testing ground for assessing these challenges (see Gur-Arieh & Madella, 2024). Mineralogical characterization by powder x-ray diffraction of control sediments will assist in ascertaining what elements are most related to the geological background of the areas to distinguish them from those of anthropogenic origin, while the characterization of corral sediments may additionally aid in the identification of archaeological livestock enclosures or dung deposits through mineralogical indicators such as opal or calcium phosphates (Shahack-Gross, 2011; Shahack-Gross et al., 2003, 2008). Ultimately, the aim is to use the ethnographic record both to explore the methodological feasibility of these approaches and to provide a comparative framework for interpreting the archaeological record.

To address the challenge of landscape-scale detection in pastoral contexts, remote sensing techniques will be employed to investigate whether macro-scale insights can be obtained. Remote sensing offers a potential solution to the logistical constraints of extensive ground survey by enabling the analysis of large areas through satellite data. Building on studies by Chabrillat et al. (2020, 2024) and Gomez et al. (2018), which successfully characterized soil properties utilizing hyperspectral imagery, this research will develop a Random Forest classification model. The model will integrate ground-truthing pXRF geochemical data with corresponding hyperspectral data to evaluate the potential for scaling site-specific chemical patterns to regional detection capabilities (Thabeng et al., 2020). In parallel with the geochemical remote sensing analysis, an automated detection methodology for pastoral structures will be developed using high-resolution (30 cm) optical satellite imagery. This spatial resolution theoretically enables the potential identification of architectural features,

including stone alignments and foundation structures. The research will prioritize the detection of livestock enclosures (corrals), employing both computer vision algorithms and remote sensing techniques to systematically identify these features across the landscape.

Discussion

The methodological framework presented here demonstrates the potential of integrating standardized pXRF protocols, systematic baseline sampling, and geostatistical approaches for the study of pastoral archaeological sites in dryland regions. While the data presented are preliminary and not yet intended as definitive results, the initial outcomes indicate that rigorous field protocols are essential for ensuring data reliability, particularly given the compositional variability and context-dependent nature of elemental signals (Wells, 2010). These procedures are therefore foundational in building a comparative geoarchaeological dataset capable of supporting future analytical and interpretive work across multiple pastoral landscapes.

Early applications of this framework at Maitengwe (Botswana), Khor Rori (Oman), and Loreamatet (Kenya) indicate the presence of significant geochemical variability, which may ultimately relate to differences in local geology, environmental conditions, and cultural practices. However, at this stage, such variability cannot yet be confirmed or attributed with confidence, underscoring the importance of maintaining methodological rigor to distinguish natural background signatures from culturally derived signals. This highlights the necessity of well-designed control samples surrounding both inhabited and abandoned settlements. Such controls are critical for establishing geochemical baselines that allow the differentiation between anthropogenic enrichment and natural background conditions—an especially important step in dryland contexts where taphonomic processes (e.g., leaching, sediment reworking, bioturbation) can obscure or modify original chemical signatures.

Early spatial results indicate that the integration of geochemical, ethnographic, and ethnoarchaeological data provides a robust analytical pathway for detecting and interpreting pastoral activity areas. In the published example, distinct enrichment patterns clearly correspond to livestock enclosures and waste-related activities, mirroring known pastoral practices. These findings strongly suggest that such activity-linked geochemical signatures represent a reproducible pattern and are therefore likely to emerge across additional sites sampled within the project. The key challenge moving forward will be to scale up this approach across further settlements and regions, ensuring that methodological consistency is maintained while accommodating local environmental and cultural variability. While such observations cannot yet be interpreted as definitive behavioral signatures, they point to promising avenues for refining proxies—particularly phosphates, carbonates, and lipid-related compounds—linked to livestock management, stabling, resource processing, and other domestic activities.

Given the exploratory nature of these initial results, we emphasize that interpretations remain provisional and must be validated through expanded datasets, laboratory confirmation (e.g., lipid residue, phytolith, and mineralogical analyses), and

further ethnographic alignment. The discussion presented here should therefore be understood as a methodological proof of concept rather than a complete interpretive framework.

Despite these limitations, this work demonstrates that pastoral sites—often considered materially subtle and archaeologically "invisible"—present recoverable and meaningful geochemical signatures when investigated through integrated geo-ethnoarchaeological strategies. By establishing standardized methodological foundations, this study contributes to future comparative research and strengthens the analytical potential of dryland pastoral archaeology. As the project progresses, expanded sampling, multi-scalar comparison, and refined data modeling will be essential for moving from preliminary observations to robust, regionally and culturally grounded interpretations of pastoral lifeways.

Concluding Remarks

Limited archaeological visibility has historically contributed to the underrepresentation of pastoral societies in archaeological narratives. Ethnoarchaeological approaches, by linking contemporary practices with material signatures, have not only enhanced our capacity to interpret these elusive remains but also reshaped our broader understanding of pastoralist social, economic, and ecological strategies. Crucially, this line of research has challenged enduring stereotypes, recasting mobile pastoralists not as marginal or static populations but as adaptive innovators who developed flexible strategies for food security and social organization in some of the world's most variable environments. This shift has refined archaeological methods—especially for investigating non-permanent settlements—and contributed to broader epistemological changes that question Eurocentric assumptions and reposition drylands as dynamic centers of resilience and innovation. Ethnoarchaeology has played a crucial role in transforming the study of pastoralism, particularly in dryland regions where the archaeological record is often subtle, fragmented, or difficult to interpret. CAMP addresses the challenges posed by typically elusive pastoral sites by developing a standardized and adaptable research protocol. Although originally tailored to capture the subtle material traces of mobile pastoral communities, this protocol is designed to be transferable to archaeological sites from other socio-economic groups across different chronological and geographic contexts. The combination of a repository of chemical signatures from anthropogenic deposits and geostatistical tools provides archaeologists with innovative resources to investigate complex site formation processes. Once fully implemented, the protocol will allow real-time, in-situ pXRF analyses, guiding prospection and excavation with immediate data on deposit composition. By making these tools and methods widely applicable, CAMP not only advances the archaeology of pastoralism but also offers a versatile framework for studying human occupation and activity in a variety of archaeological settings.

In this regard, CAMP can be considered transformative in three aspects. First, the proposed methodology enables rapid visualization of chemical patterning with direct implications for prospection and excavation. Also, it provides a

standardized geostatistical modeling workflow that facilitates post-excavation interpretation and comparison between sites. Second, it produces a cumulative repository of chemical signatures, offering a comparative reference framework that can be used beyond case studies, as it is based on ethnographic information and complemented by robust off-site baselines. Third, CAMP provides a diachronic bridge between human activities and their materiality, which will make post-depositional trajectories an explicit part of interpretation rather than an afterthought.

At the same time, we highlight the most important constraints that must guide future applications. Elemental signals are compositional and context-dependent; hence their interpretive strength lies in multivariate relative patterns rather than absolute values. Further, pXRF data require transparent reporting and processing to ensure data quality. Geographical setting is important since background geology, soil composition, as well as pre- and post-depositional processes can strongly affect elemental distributions and even mask anthropogenic signals if not carefully controlled for. Similarly, cultural variability matters: the same activity can involve different materials depending on cultural contexts, and models must remain sensitive to such diversity. CAMP therefore treats its protocol as a reference framework—structured enough to ensure comparability but adaptable to local practices and geology.

Finally, the project is committed to openness and collaboration. Standard operating procedures, code for data processing and spatial modeling, and (where permissions allow) anonymized datasets will be shared to produce a database that facilitates data FAIRification to promote reutilisation and comparability. Equally, the protocol has been developed with, and will continue to rely on, partnerships with pastoral communities and local institutions; ethical engagement and co-production of knowledge are integral to both data quality and interpretive relevance.

Acknowledgements This work is supported by ERC grant (CAMP ERC-CoG, n. 101088842, PI Stefano Biagetti), funded by the European Union. Views and opinions expressed are however those of the author only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. We are grateful to the PALARQ Foundation (Spain) which provided financial support for the development of a pilot project between 2020-23. SB, AR-G, KSR, AK, CL, MM are members of CASEs, a Quality Research Group recognized by the Agencia de Gestión de Ayudas Universitarias y de Investigación (the Catalan Agency for Research) (AGAUR-SGR 212). Research in Kenya was conducted under research permit NACOSTI/P/25/417020 and we thank the Turkana Basin Institute for their logistical support. Research in Botswana was conducted under the research permit ENT 8/36/4 LIII(15), and we thank The Botswana Society for their logistical support. Research in Oman was conducted under the agreement granted by the Ministry of Heritage and Tourism of the Sultanate of Oman, to the DHOMIAP Project. We are also grateful to the Department of Frankincense Land Sites in Salalah, for their logistical support. We are also thankful to Hamza Benattia, Cyprian Broodbank, Fred Morton, Phenyo Thebe, Luis Mphala, Soledad Alvarez, Bono Mmusi, Marco Moderato, and Paola Iacumin for providing support to our research project at various stages.

Author Contribution S.B. designed the study. C.L., A.R.–G., J.I.–I., and M.M. supervised the implementation. All authors collected data for analysis. A.R.–G. and A.K. wrote the code. A.R.–G. prepared Figs. 1 and 3–9. S.B., A.R.–G., K.S.R., and A.K. wrote the main manuscript text. All authors reviewed and approved the final manuscript.

Funding Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature. Horizon 2020 Framework Programme, CAMP ERC-CoG, n. 101088842

Data Availability Data that support the findings of this study have been deposited here: https://github.com/project-camp/camp-public

Declarations

Conflict of interest The authors declare no competing interests.

References

African Union. (2010). *POLICY FRAMEWORK FOR PASTORALISM IN AFRICA: Securing, Protecting and Improving the Lives, Livelihoods and Rights of Pastoralist Communities*. Department of Rural Economy and Agriculture. https://au.int/sites/default/files/documents/30240-doc-policy_framework_for_pastoralism.pdf

Amicone, S., Morandi, L. F., & Gur-Arieh, S. (2021). 'Seeing shit': Assessing the visibility of dung tempering in ancient pottery using an experimental approach. *Environmental Archaeology, 26*(4), 423–438. https://doi.org/10.1080/14614103.2020.1852758

Anthony, D. W., Brown, D. R., & Mochalov, O. D. (Eds.). (2016). *A Bronze Age landscape in the Russian steppes: The Samara Valley Project*. UCLA Cotsen Institute of Archaeology Press.

Arbuckle, B. S., & Hammer, E. L. (2019). The rise of pastoralism in the Ancient Near East. *Journal of Archaeological Research, 27*(3), 391–449. https://doi.org/10.1007/s10814-018-9124-8

Ashley, G. M., Ndiema, E. K., Spencer, J. Q. G., Harris, J. W. K., Kiura, P. W., Dibble, L., Du, A., & Lordan, P. T. (2017). Paleoenvironmental reconstruction of Dongodien, Lake Turkana, Kenya and OSL dating of site occupation during late Holocene climate change. *African Archaeological Review, 34*(3), 345–362. https://doi.org/10.1007/s10437-017-9260-4

Balehegn, M., Balehey, S., Fu, C., & Liang, W. (2019). Indigenous weather and climate forecasting knowledge among Afar pastoralists of north eastern Ethiopia: Role in adaptation to weather and climate variability. *Pastoralism, 9*(1), 8. https://doi.org/10.1186/s13570-019-0143-y

Ball, L., & Tzanopoulos, J. (2020). Livestock browsing affects the species composition and structure of cloud forest in the Dhofar Mountains of Oman. *Applied Vegetation Science, 23*(3), 363–376. https://doi.org/10.1111/avsc.12493

Barba, L., & Ortiz, A. (1992). Analisis Quimico de Pisos de Ocupacion: Un Caso Etnografico en Tlaxcala, Mexico. *Latin American Antiquity, 3*(1), 63–82. https://doi.org/10.2307/971930

Barnard, H., Shoemake, L., Craig, O. E., Rider, M., Parr, R. E., Sutton, M. Q., & Yohe, Robert M.. (2007). *Introduction to the Analysis of Protein Residues in Archaeological Ceramics*. Archaeopress.

Behnke, R. H., Scoones, I. (ed), & Kerven, C. (ed). (1993). *Range Ecology at Disequilibrium: New models of Natural Variability and Pastoral Adaptation in African Savannas*. http://hdl.handle.net/10919/66476

Biagetti, S. (2014). *Ethnoarchaeology of the Kel Tadrart Tuareg. Pastoralism and Resilience in Central Sahara*. Springer International Publishing.

Biagetti, S., Alcaina-Mateos, J., Ruiz-Giralt, A., Lancelotti, C., Groenewald, P., Ibañez-Insa, J., Gur-Arie, S., Morton, F., & Merlo, S. (2021b). Identifying anthropogenic features at Seoke (Botswana) using pXRF: Expanding the record of southern African stone walled sites. *PLoS One, 16*(5), Article e0250776. https://doi.org/10.1371/journal.pone.0250776

Biagetti, S., Merlo, S., Adam, E., Lobo, A., Conesa, F. C., Knight, J., Bekrani, H., Crema, E. R., Alcaina-Mateos, J., & Madella, M. (2017). High and medium resolution satellite imagery to evaluate late Holocene human-environment interactions in arid lands: A case study from the Central Sahara. *Remote Sensing, 9*(4), 351. https://doi.org/10.3390/rs9040351

Biagetti, S., Ruiz-Giralt, A., Madella, M., Khalid Magzoub, M., Meresa, Y., Gebreselassie, M. H., Veesar, G. M., Abro, T. A., Chandio, A., & Lancelotti, C. (2021a). No rain, no grain? Ethnoarchaeology of sorghum and millet cultivation in dryland environments of Sudan, Pakistan, and Ethiopia. *Ethnoarchaeology, 13*(1–2), 80–104. https://doi.org/10.1080/19442890.2022.2059994

Bintliff, J., & Degryse, P. (2022). A review of soil geochemistry in archaeology. *Journal of Archaeological Science: Reports, 43*, Article 103419. https://doi.org/10.1016/j.jasrep.2022.103419

Boles, O. J. C., & Lane, P. J. (2016). The green, green grass of home: An archaeo-ecological approach to pastoralist settlement in central Kenya. *Azania: Archaeological Research in Africa, 51*(4), 507–530. https://doi.org/10.1080/0067270X.2016.1249587

Boles, O. J. C., Shoemaker, A., Courtney Mustaphi, C. J., Petek, N., Ekblom, A., & Lane, P. J. (2019). Historical ecologies of pastoralist overgrazing in Kenya: Long-term perspectives on cause and effect. *Human Ecology, 47*(3), 419–434. https://doi.org/10.1007/s10745-019-0072-9

Bollig, M., Schnegg, M., & Wotzka, H.-P. (Eds.). (2013). *Pastoralism in Africa: Past, Present and Future* (1st ed.). Berghahn Books. https://www.jstor.org/stable/j.ctt9qcrb7

Briske, D. D., Coppock, D. L., Illius, A. W., & Fuhlendorf, S. D. (2020). Strategies for global rangeland stewardship: Assessment through the lens of the equilibrium–non-equilibrium debate. *Journal of Applied Ecology, 57*(6), 1056–1067. https://doi.org/10.1111/1365-2664.13610

Brochier, J. E., Villa, P., Giacomarra, M., & Tagliacozzo, A. (1992). Shepherds and sediments: Geo-ethnoarchaeology of pastoral sites. *Journal of Anthropological Archaeology, 11*(1), 47–102. https://doi.org/10.1016/0278-4165(92)90010-9

Bull, I. D., Simpson, I. A., Van Bergen, P. F., & Evershed, R. P. (1999). Muck "n" molecules: Organic geochemical methods for detecting ancient manuring. *Antiquity, 73*(279), 86–96.

Capriles, J. M., & Tripcevich, N. (Eds.). (2016). *The Archaeology of Andean Pastoralism*. University of New Mexico Press.

Chabrillat, S., Foerster, S., Segl, K., Beamish, A., Brell, M., Asadzadeh, S., Milewski, R., Ward, K. J., Brosinsky, A., Koch, K., Scheffler, D., Guillaso, S., Kokhanovsky, A., Roessner, S., Guanter, L., Kaufmann, H., Pinnel, N., Carmona, E., Storch, T., & Fischer, S. (2024). The EnMAP spaceborne imaging spectroscopy mission: Initial scientific results two years after launch. *Remote Sensing of Environment, 315*, Article 114379. https://doi.org/10.1016/j.rse.2024.114379

Chabrillat, S., Guanter, L., Segl, K., Foerster, S., Fischer, S., Rossner, G., Schickling, A., LaPorta, L., Honold, H.-P., & Storch, T. (2020). The Enmap German Spaceborne Imaging Spectroscopy Mission: Update and Highlights of Recent Preparatory Activities. *IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium*, 3278–3281. https://doi.org/10.1109/IGARSS39084.2020.9324006

Chang, C., & Koster, H. A. (1986). Beyond Bones: Toward an Archaeology of Pastoralism. *Advances in Archaeological Method and Theory*, 97–148. https://doi.org/10.1016/B978-0-12-003109-2.50006-4

Chen, F., Zhou, R., Van de Voorde, T., Chen, X., Bourgeois, J., Gheyle, W., Goossens, R., Yang, J., & Xu, W. (2021). Automatic detection of burial mounds (kurgans) in the Altai Mountains. *ISPRS Journal of Photogrammetry and Remote Sensing, 177*, 217–237. https://doi.org/10.1016/j.isprsjprs.2021.05.010

Cioffi-Revilla, C., Rogers, J. D., & Latek, M. (2010). The MASON HouseholdsWorld Model of Pastoral Nomad Societies. In K. Takadama, C. Cioffi-Revilla, & G. Deffuant (Eds.),

Clark, J., & Crabtree, S. (2015). Examining social adaptations in a volatile landscape in northern Mongolia via the agent-based model Ger Grouper. *Land, 4*(1), 157–181. https://doi.org/10.3390/land4010157

Cribb, R. (1991). *Nomads in Archaeology*. Cambridge University Press.

David, N. (1971). The Fulani compound and the archaeologist. *World Archaeology, 3*, 111–131.

Davis, D. K. (2004). Desert 'wastes' of the Maghreb: Desertification narratives in French colonial environmental history of North Africa. *Cultural Geographies, 11*(4), 359–387. https://doi.org/10.1191/1474474004eu313oa

Davis, L. G., Macfarlan, S. J., & Henrickson, C. N. (2012). A PXRF-based chemostratigraphy and provenience system for the Cooper's Ferry site. Idaho. *Journal of Archaeological Science, 39*(3), 663–671. https://doi.org/10.1016/j.jas.2011.10.029

Dong, S., Kassam, K.-A. S., Tourrand, J. F., & Boone, R. B. (Eds.). (2016). *Building Resilience of Human-Natural Systems of Pastoralism in the Developing World*. Springer International Publishing. https://doi.org/10.1007/978-3-319-30732-9

Dunne, J., Evershed, R. P., Salque, M., Cramp, L., Bruni, S., Ryan, K., Biagetti, S., & di Lernia, S. (2012). First dairying in "Green" Saharan Africa in the 5th millennium BC. *Nature, 486*(7403), 390–394. https://doi.org/10.1038/nature11186

Dunne, J., Grillo, K. M., Casanova, E., Whelton, H. L., & Evershed, R. P. (2018). Pastoralist foodways recorded in organic residues from pottery vessels of modern communities in Samburu, Kenya. *Journal of Archaeological Method and Theory*. https://doi.org/10.1007/s10816-018-9384-0

Égüez, N., Dal Corso, M., Wieckowska-Lüth, M., Delpino, C., Tarantini, M., & Biagetti, S. (2020). A pilot geo-ethnoarchaeological study of dung deposits from pastoral rock shelters in the Monti Sibillini (central Italy). *Archaeological and Anthropological Sciences, 12*(6), 114. https://doi.org/10.1007/s12520-020-01076-4

Égüez, N., & Makarewicz, C. (2018). Carbon isotope ratios of plant n-alkanes and microstratigraphy analyses of dung accumulations in a pastoral nomadic winter campsite (Eastern Mongolia). *Ethnoarchaeology, 10*(2), 141–158.

Égüez, N., Zerboni, A., & Biagetti, S. (2018). Microstratigraphic analysis on a modern central Saharan pastoral campsite. Ovicaprine pellets and stabling floors as ethnographic and archaeological referential data. *Quaternary International, 483*, 180–193. https://doi.org/10.1016/j.quaint.2017.12.016

Ellis, J. E., & Swift, D. M. (1988). Stability of African pastoral ecosystems: Alternate paradigms and implications for development. *Journal of Range Management, 41*(6), 450–459. https://doi.org/10.2307/3899515

FAO. (2020). *Innovative Pastoralism. Achieving productivity and sustainability for food security |Policy Support and Governance| Food and Agriculture Organization of the United Nations*. https://www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1310374/

FAO. (2021). *Pastoralism—Making variability work*. FAO ; https://openknowledge.fao.org/handle/20.500.14283/cb5855en

Filzmoser, P., Hron, K., & Templ, M. (2018). Applied compositional data analysis: With worked examples in R. *Springer International Publishing*. https://doi.org/10.1007/978-3-319-96422-5

Fitton, T., Contreras, D. A., Gidna, A. O., Mabulla, A. Z. P., Prendergast, M. E., & Grillo, K. M. (2022). Detecting and mapping the 'ephemeral': Magnetometric survey of a Pastoral Neolithic settlement at Luxmanda, Tanzania. *Antiquity, 96*(386), 298–318. https://doi.org/10.15184/aqy.2021.59

Frachetti, M. D., & Mar'yashev, A. N. (2007). Long-term occupation and seasonal settlement of eastern Eurasian pastoralists at Begash, Kazakhstan. *Journal of Field Archaeology, 32*(3), 221–242.

Frachetti, M. D., Smith, C. E., Traub, C. M., & Williams, T. (2017). Nomadic ecology shaped the highland geography of Asia's Silk Roads. *Nature, 543*(7644), 193–198. https://doi.org/10.1038/nature21696

Frahm, E. (2013). Validity of "off-the-shelf" handheld portable XRF for sourcing Near Eastern obsidian chip debris. *Journal of Archaeological Science, 40*(2), 1080–1092. https://doi.org/10.1016/j.jas.2012.06.038

Frahm, E. (2024). Protocols, pitfalls, and publishing for pXRF analyses: From "know how" to "best practices." *Journal of Archaeological Science: Reports, 60*, Article 104831. https://doi.org/10.1016/j.jasrep.2024.104831

Frahm, E., Monnier, G. F., Jelinski, N. A., Fleming, E. P., Barber, B. L., & Lambon, J. B. (2016). Chemical soil surveys at the Bremer Site (Dakota county, Minnesota, USA): Measuring phosphorous content of sediment by portable XRF and ICP-OES. *Journal of Archaeological Science, 75*, 115–138. https://doi.org/10.1016/j.jas.2016.10.004

Friesem, D. E. (2016). Geo-ethnoarchaeology in action. *Journal of Archaeological Science, 70*, 145–157. https://doi.org/10.1016/j.jas.2016.05.004

Gatto, M. C. (2011). The relative chronology of Nubia. *Archéo-Nil. Revue De La Société Pour L'étude Des Cultures Prépharaoniques De La Vallée Du Nil*. https://doi.org/10.3406/arnil.2011.1028

Gauss, R. K., Bátora, J., Nowaczinski, E., Rassmann, K., & Schukraft, G. (2013). The early bronze age settlement of Fidvár, Vráble (Slovakia): Reconstructing prehistoric settlement patterns using portable XRF. *Journal of Archaeological Science, 40*(7), 2942–2960. https://doi.org/10.1016/j.jas.2013.01.029

Gilbert, H. (2013). 'Bedouin overgrazing' and conservation politics: Challenging ideas of pastoral destruction in South Sinai. *Biological Conservation, 160*, 59–69. https://doi.org/10.1016/j.biocon.2012.12.022

Ginau, A., Steiniger, D., Hartmann, R., Hartung, U., Schiestl, R., Altmeyer, M., Seeliger, M., & Wunderlich, J. (2020). What settlements leave behind—pXRF compositional data analysis of archaeological layers from Tell el-Fara'in (Buto, Egypt) using machine learning. *Palaeogeography, Palaeoclimatology, Palaeoecology, 546*, Article 109666. https://doi.org/10.1016/j.palaeo.2020.109666

Goff, K., Schaetzl, R. J., Chakraborty, S., Weindorf, D. C., Kasmerchak, C., & Bettis, E. A. (2020). Impact of sample preparation methods for characterizing the geochemistry of soils and sediments by portable X-ray fluorescence. *Soil Science Society of America Journal, 84*(1), 131–143. https://doi.org/10.1002/saj2.20004

Gomez, C., Adeline, K., Bacha, S., Driessen, B., Gorretta, N., Lagacherie, P., Roger, J. M., & Briottet, X. (2018). Sensitivity of clay content prediction to spectral configuration of VNIR/SWIR imaging data, from multispectral to hyperspectral scenarios. *Remote Sensing of Environment, 204*, 18–30. https://doi.org/10.1016/j.rse.2017.10.047

Goulard, M., & Voltz, M. (1992). Linear coregionalization model: Tools for estimation and choice of cross-variogram matrix. *Mathematical Geology, 24*, 269–286. https://doi.org/10.1007/BF00893750

Grillo, K. (2012). *The Materiality of Mobile Pastoralism: Ethnoarchaeological Perspectives from Samburu, Kenya* [All Theses and Dissertations (ETDs), Washington University in St. Louis]. https://openscholarship.wustl.edu/etd/956

Grillo, K. M. (2014). Pastoralism and pottery use: An ethnoarchaeological study in Samburu. *Kenya. African Archaeological Review, 31*(2), 105–130. https://doi.org/10.1007/s10437-014-9147-6

Grillo, K. M., Dunne, J., Marshall, F., Prendergast, M. E., Casanova, E., Gidna, A. O., Janzen, A., Karega-Munene, Keute, J., Mabulla, A. Z. P., Robertshaw, P., Gillard, T., Walton-Doyle, C., Whelton, H. L., Ryan, K., & Evershed, R. P. (2020). Molecular and isotopic evidence for milk, meat, and plants in prehistoric eastern African herder food systems. *Proceedings of the National Academy of Sciences*, *117*(18), 9793–9799. https://doi.org/10.1073/pnas.1920309117

Grillo, K. M., Prendergast, M. E., Contreras, D. A., Fitton, T., Gidna, A. O., Goldstein, S. T., Knisley, M. C., Langley, M. C., & Mabulla, A. Z. P. (2018). Pastoral neolithic settlement at Luxmanda, Tanzania. *Journal of Field Archaeology, 43*(2), 102–120. https://doi.org/10.1080/00934690.2018.1431476

Gu, S., Deng, Y., Wang, P., Li, C., Shi, D., & Wang, S. (2023). Assessing riverine fish community diversity and stability by edna metabarcoding. *Ecological Indicators, 157*, Article 111222. https://doi.org/10.1016/j.ecolind.2023.111222

Gur-Arieh, S., & Madella, M. (2024). Beyond identification: Human use of animal dung in the past. *Journal of Anthropological Archaeology, 75*, Article 101601. https://doi.org/10.1016/j.jaa.2024.101601

Hardin, G. (1968). The tragedy of the commons. *Science, 162*(3859), 1243–1248.

Hayes, K. (2013). Parameters in the use of pXRF for archaeological site prospection: A case study at the Reaume Fort Site, Central Minnesota. *Journal of Archaeological Science, 40*(8), 3193–3211. https://doi.org/10.1016/j.jas.2013.04.008

Hein, L. (2006). The impacts of grazing and rainfall variability on the dynamics of a Sahelian rangeland. *Journal of Arid Environments, 64*(3), 488–504. https://doi.org/10.1016/j.jaridenv.2005.06.014

Heron, C., Nilsen, G., Stern, B., Craig, O., & Nordby, C. (2010). Application of lipid biomarker analysis to evaluate the function of 'slab-lined pits' in Arctic Norway. *Journal of Archaeological Science, 37*(9), 2188–2197. https://doi.org/10.1016/j.jas.2010.03.016

Herskovits, M. J. (1926). The cattle complex in East Africa. *American Anthropologist, 28*(1), 230–272.

Hesse, C., & MacGregor, J. (2006). Pastoralism: Drylands' invisible asset? Developing a framework for assessing the value of pastoralism in East Africa. *IIED Publications*. https://www.iied.org/12534iied

Hildebrand, E. A., Grillo, K. M., Sawchuk, E. A., Pfeiffer, S. K., Conyers, L. B., Goldstein, S. T., Hill, A. C., Janzen, A., Klehm, C. E., & Helper, M. (2018). A monumental cemetery built by eastern Africa's first herders near Lake Turkana, Kenya. *Proceedings of the National Academy of Sciences of the United States of America, 115*(36), 8942–8947.

Hildebrand, E., Grillo, K. M., Chritz, K. L., Fischer, M. L., Goldstein, S. T., Janzen, A., Junginger, A., Kinyanjui, R. N., Ndiema, E., Sawchuk, E., Beyin, A., & Pfeiffer, S. K. (2022). Buffering new risks? Environmental, social and economic changes in the Turkana Basin during and after the African Humid Period. *Holocene, 32*(12), 1373–1392. https://doi.org/10.1177/09596836221121766

Homewood, K. (2008). *Ecology of African Pastoralist Societies*. Ohio University Press; Unisa Press.
Houle, J.-L. (2024). *Mobile Pastoralist Households: Archaeological and Ethnoarchaeological Perspectives*.
Hu, S., Tang, J., Ren, Z., Chen, C., Zhou, C., Xiao, X., & Zhao, T. (2019). Multiple underwater objects localization with magnetic gradiometry. *IEEE Geoscience and Remote Sensing Letters, 16*(2), 296–300. https://doi.org/10.1109/LGRS.2018.2870839
Huffman, T. N. (2007). *Handbook to the Iron Age: The archaeology of pre-colonial farming societies in Southern Africa*. University of KwaZulu-Natal Press.
Hunt, A. M. W., & Speakman, R. J. (2015). Portable XRF analysis of archaeological sediments and ceramics. *Journal of Archaeological Science, 53*, 626–638. https://doi.org/10.1016/j.jas.2014.11.031
Iticha, B., & Husen, A. (2019). Adaptation to climate change using indigenous weather forecasting systems in Borana pastoralists of southern Ethiopia. *Climate and Development, 11*(7), 564–573. https://doi.org/10.1080/17565529.2018.1507896
Janovský, M. P., Horák, J., Ackermann, O., Tavger, A., Cassuto, D., Šmejda, L., Hejcman, M., Anker, Y., & Shai, I. (2022). The contribution of POSL and PXRF to the discussion on sedimentary and site formation processes in archaeological contexts of the southern Levant and the interpretation of biblical strata at Tel Burna. *Quaternary International, 618*, 24–34. https://doi.org/10.1016/j.quaint.2020.11.045
Janzen, A. (2022). Exploring Ancient Pastoralism in Africa through Stable Isotope Analysis. In A. E. Sharpe & J. Krigbaum (Eds.), *Isotope Research in Zooarchaeology: Methods, Applications, and Advances* (pp. 116–144). University Press of Florida.
Janzen, A., Balasse, M., & Ambrose, S. H. (2020). Early pastoral mobility and seasonality in Kenya assessed through stable isotope analysis. *Journal of Archaeological Science, 117*, Article 105099. https://doi.org/10.1016/j.jas.2020.105099
Johnson, K., Quinn, C. P., Goodale, N., & Conrey, R. (2024). Best practices for publishing pXRF analyses. *Advances in Archaeological Practice, 12*(2), 156–162. https://doi.org/10.1017/aap.2024.6
Kanthilatha, N., Boyd, W., Dowell, A., Mann, A., Chang, N., Wohlmuth, H., & Parr, J. (2014). Identification of preserved fatty acids in archaeological floor sediments from prehistoric sites at Ban Non Wat and Nong Hua Raet in northeast Thailand using gas chromatography. *Journal of Archaeological Science, 46*, 353–362. https://doi.org/10.1016/j.jas.2014.03.033
Kardulias, P. N. (2015). *The Ecology of Pastoralism*. University Press of Colorado.
Köhler-Rollefson, I. (2021). *Livestock for a small planet*. League for Pastoral Peoples and Endogenous Livestock Development.
Kratli, S., Monimart, M., Jallo, B., Swift, J., & Hesse, C. (2013). *Evaluation of AFD Group interventions in pastoral water development in Chad over the last 20 years*. International Institute for Environment and Development.
Kuznar, L. A., & Sedlmeyer, R. (2008). NOMAD. An Agent-Based Model (ABM) of pastoralist-agriculturalist interaction. In H. Barnard & W. Wendrich (Eds.), *The Archaeology of Mobility: Old World and New World Nomadism* (pp. 557–583). The Cotsen Institute of Archaeology Press.
Kynčlová, P., Hron, K., & Filzmoser, P. (2017). Correlation between compositional parts based on symmetric balances. *Mathematical Geosciences, 49*, 777–796. https://doi.org/10.1007/s11004-016-9669-3
Lancelotti, C., & Madella, M. (2012). The 'invisible' product: Developing markers for identifying dung in archaeological contexts. *Journal of Archaeological Science, 39*(4), 953–963. https://doi.org/10.1016/j.jas.2011.11.007
Lancelotti, C., Negre Pérez, J., Alcaina-Mateos, J., & Carrer, F. (2017). Intra-site spatial analysis in ethnoarchaeology. *Environmental Archaeology, 22*(4), 354–364. https://doi.org/10.1080/14614103.2017.1299908
Lischi, S. (2025). DHOMIAP project (2022–23): New archaeological discoveries in Dhofar. *Athar - Bulletin of Archaeological Research in the Sultanate of Oman, 1*, 134–140.
Lubos, C., Dreibrodt, S., & Bahr, A. (2016). Analysing spatio-temporal patterns of archaeological soils and sediments by comparing pXRF and different ICP-OES extraction methods. *Journal of Archaeological Science: Reports, 9*, 44–53. https://doi.org/10.1016/j.jasrep.2016.06.037
Makarewicz, C. A. (2016). Toward an Integrated Isotope Zooarchaeology. In G. Grupe & G. C. McGlynn (Eds.),
Mallol, C., Égüez, N., Jambrina-Enríquez, M., & Herrera-Herrera, A. V. (2025). Advancing archaeological sedimentary lipid biomarker analysis: A review of recent developments and methodological guidelines. *iScience, 28*(3), Article 112064. https://doi.org/10.1016/j.isci.2025.112064

Marchant, R., & Lane, P. (2014). Past perspectives for the future: Foundations for sustainable development in East Africa. *Journal of Archaeological Science, 51*, 12–21. https://doi.org/10.1016/j.jas.2013.07.005

Marshall, F. B., Barthelme, J. W., & Stewart, K. (1984). *Early Domestic Stock at Dongodien in Northern Kenya*. Azania 19.

Marshall, F., Reid, R. E. B., Goldstein, S., Storozum, M., Wreschnig, A., Hu, L., Kiura, P., Shahack-Gross, R., & Ambrose, S. H. (2018). Ancient herders enriched and restructured African grasslands. *Nature, 561*(7723), 387–390. https://doi.org/10.1038/s41586-018-0456-9

Martín-Fernández, J. A., Garrigós, J. B. i, & Pawlowsky-Glahn, V. (2015). Logratio Analysis in Archeometry: Principles and Methods. In *Mathematics and Archaeology* (1st Edition). CRC Press.

Mbae, N. B. (1990). The ethnoarchaeology of Maasai settlements and refuse disposal patterns in the Lemek area. In P. T. Robertshaw (Ed.), *Early pastoralists of south-western Kenya* (pp. 279–292). British Institute in Eastern Africa.

Middleton, W. D. (2004). Identifying chemical activity residues on prehistoric house floors: A methodology and rationale for multi-elemental characterization of a mild acid extract of anthropogenic sediments. *Archaeometry, 46*(1), 47–65. https://doi.org/10.1111/j.1475-4754.2004.00143.x

Middleton, W. D., & Price, T. D. (1996). Identification of activity areas by multi-element characterization of sediments from modern and archaeological house floors using inductively coupled plasma-atomic emission spectroscopy. *Journal of Archaeological Science, 23*(5), 673–687.

Morton, F. (2014). The rise of a raiding state: Makaba II's Ngwaketse, c. 1780–1824. *New Contree, 71*, 25–40.

Negre, J., Muñoz, F., & Lancelotti, C. (2016). Geostatistical modelling of chemical residues on archaeological floors in the presence of barriers. *Journal of Archaeological Science, 70*, 91–101. https://doi.org/10.1016/j.jas.2016.04.016

Oonk, S., Slomp, C. P., & Huisman, D. J. (2009). Geochemistry as an aid in archaeological prospection and site interpretation: Current issues and research directions. *Archaeological Prospection, 16*(1), 35–51. https://doi.org/10.1002/arp.344

Pawlowsky-Glahn, V., & Buccianti, A. (2011). *Compositional Data Analysis: Theory and Applications* (1st ed). Wiley. https://doi.org/10.1002/9781119976462

Phelps, L. N., & Kaplan, J. O. (2017). Land use for animal production in global change studies: Defining and characterizing a framework. *Global Change Biology, 23*(11), 4457–4471. https://doi.org/10.1111/gcb.13732

Picardi, A. C., & Seifert, W. W. (1977). A tragedy of the commons in the Sahel. *Technology Review*, *78*. https://www.jstor.org/stable/43618844

Poggi, G., Volpi, V., & Dallai, L. (2025). Tracing natural and anthropic dynamics in alluvial and coastal plain through multidisciplinary sources: A new protocol for the study of historical landscapes in Val di Cornia (southern Tuscany, Italy). *Quaternary International, 728*, Article 109725. https://doi.org/10.1016/j.quaint.2025.109725

Portillo, M., Valenzuela, S., & Albert, R. M. (2012). Domestic patterns in the Numidian site of Althiburos (northern Tunisia): The results from a combined study of animal bones, dung and plant remains. *Quaternary International, 275*, 84–96. https://doi.org/10.1016/j.quaint.2012.01.024

Prendergast, M. E., Lipson, M., Sawchuk, E. A., Olalde, I., Ogola, C. A., Rohland, N., Sirak, K. A., Adamski, N., Bernardos, R., Broomandkhoshbacht, N., Callan, K., Culleton, B. J., Eccles, L., Harper, T. K., Lawson, A. M., Mah, M., Oppenheimer, J., Stewardson, K., Zalzala, F., … Reich, D. (2019). Ancient DNA reveals a multistep spread of the first herders into sub-Saharan Africa. *Science, 365*(6448), Article eaaw6275. https://doi.org/10.1126/science.aaw6275

Robbins, L. H. (1973). Turkana material culture viewed from an archaeological perspective. *World Archaeology, 5*, 209–214.

Robertshaw, P. T. (1978). The archaeology of an abandoned pastoralist camp-site. *South African Journal of Science, 74*, 29–31.

Rogers, J. D., Cioffi-Revilla, C., & Linford, S. J. (2015). *The Sustainability of Wealth among Nomads: An Agent-Based Approach*. CRC Press.

Rogers, J. D., Nichols, T., Emmerich, T., Latek, M., & Cioffi-Revilla, C. (2012). Modeling scale and variability in human–environmental interactions in Inner Asia. *Ecological Modelling, 241*, 5–14. https://doi.org/10.1016/j.ecolmodel.2011.11.025

Rondelli, B., Lancelotti, C., Madella, M., Pecci, A., Balbo, A., Pérez, J. R., Inserra, F., Gadekar, C., Ontiveros, M. Á. C., & Ajithprasad, P. (2014). Anthropic activity markers and spatial variability: An

ethnoarchaeological experiment in a domestic unit of Northern Gujarat (India). *Journal of Archaeological Science, 41*, 482–492. https://doi.org/10.1016/j.jas.2013.09.008

Salzman, P. C. (1972). Multi-resource nomadism in Iranian Baluchistan. *Journal of Asian and African Studies, 7*(1–2), 60–68.

Sandford, S. (1983). *Management of Pastoral Development in the Third World*.

Save, S., Kovacik, J., Demarly-Cresp, F., Issenmann, R., Poirier, S., Sedlbauer, S., & Teyssonneyre, Y. (2020). Large-scale geochemical survey by pXRF spectrometry of archaeological settlements and features: New perspectives on the method. *Archaeological Prospection*. https://doi.org/10.1002/arp.1773

Scoones, I., Lind, J., Maru, N., Nori, M., Pappagallo, L., Shariff, T., Simula, G., Swift, J., Taye, M., & Tsering, P. (2020). Pastoralism and Development: Fifty Years of Dynamic Change. *Institute of Development Studies*, *56*(1A). https://opendocs.ids.ac.uk/articles/journal_contribution/Pastoralism_and_Development_Fifty_Years_of_Dynamic_Change/26427913

Seitsonen, O., & Égüez, N. (2021). Here be reindeer: Geoarchaeological approaches to the transspecies lifeworlds of the sámi reindeer herder camps on the tundra. *Iskos, 24*, 123–145.

Shackley, M. S. (2010). Is there reliability and validity in portable X-ray fluorescence spectrometry (PXRF)? *SAA Archaeological Record, 10*(5), 17–20.

Shahack-Gross, R. (2011). Herbivorous livestock dung: Formation, taphonomy, methods for identification, and archaeological significance. *Journal of Archaeological Science, 38*(2), 205–218. https://doi.org/10.1016/j.jas.2010.09.019

Shahack-Gross, R. (2017). Archaeological formation theory and geoarchaeology: State-of-the-art in 2016. *Journal of Archaeological Science, 79*, 36–43. https://doi.org/10.1016/j.jas.2017.01.004

Shahack-Gross, R., Marshall, F., Ryan, K., & Weiner, S. (2004). Reconstruction of spatial organization in abandoned Maasai settlements: Implications for site structure in the Pastoral Neolithic of East Africa. *Journal of Archaeological Science, 31*(10), 1395–1411. https://doi.org/10.1016/j.jas.2004.03.003

Shahack-Gross, R., Marshall, F., & Weiner, S. (2003). Geo-ethnoarchaeology of pastoral sites: The identification of livestock enclosures in abandoned Maasai settlements. *Journal of Archaeological Science, 30*(4), 439–459. https://doi.org/10.1006/jasc.2002.0853

Shahack-Gross, R., Simons, A., & Ambrose, S. H. (2008). Identification of pastoral sites using stable nitrogen and carbon isotopes from bulk sediment samples: A case study in modern and archaeological pastoral settlements in Kenya. *Journal of Archaeological Science, 35*(4), 983–990. https://doi.org/10.1016/j.jas.2007.07.002

Shanahan, M. (2013). *Media Perceptions and Portrayals of Pastoralists in Kenya, India and China*. IIED. https://www.iied.org/14623iied

Shillito, L.-M., Blong, J. C., Green, E. J., & Van Asperen, E. N. (2020). The what, how and why of archaeological coprolite analysis. *Earth-Science Reviews, 207*, Article 103196. https://doi.org/10.1016/j.earscirev.2020.103196

Šmejda, L., Hejcman, M., Horák, J., & Shai, I. (2018). Multi-element mapping of anthropogenically modified soils and sediments at the Bronze to Iron Ages site of Tel Burna in the southern Levant. *Quaternary International, 483*, 111–123. https://doi.org/10.1016/j.quaint.2017.11.005

Smith, A. B. (1992). *Pastoralism in Africa: Origins and Development Ecology*. Hurst & Co.

Smith, S. E. (1980). The environmental adaptation of nomads in the West African Sahel: A key to understanding prehistoric pastoralists. In M. Williams & H. Faure (Eds.), *The Sahara and the Nile: Quarternary Environments and Prehistoric Occupation in Northern Africa* (pp. 467–487). A.A. Balkema.

Storozum, M. J., Goldstein, S. T., Contreras, D. A., Gidna, A. O., Mabulla, A. Z. P., Grillo, K. M., & Prendergast, M. E. (2021). The influence of ancient herders on soil development at Luxmanda, Mbulu Plateau, Tanzania. *Catena, 204*, Article 105376. https://doi.org/10.1016/j.catena.2021.105376

Tessema, W. K., Ingenbleek, P. T. M., & van Trijp, H. C. M. (2014). Pastoralism, sustainability, and marketing. A review. *Agronomy for Sustainable Development, 34*(1), 75–92. https://doi.org/10.1007/s13593-013-0167-4

Thabeng, O. L., Merlo, S., & Adam, E. (2020). From the bottom up: Assessing the spectral ability of common multispectral sensors to detect surface archaeological deposits using field spectrometry and advanced classifiers in the Shashi-Limpopo Confluence Area. *African Archaeological Review, 37*(1), 25–49. https://doi.org/10.1007/s10437-020-09372-z

Tolosana-Delgado, R., & Mueller, U. (2021). Geostatistics for compositional data with R. *Springer International Publishing*. https://doi.org/10.1007/978-3-030-82568-3

Wells, E. C. (2010). Sampling design and inferential bias in archaeological soil chemistry. *Journal of Archaeological Method and Theory, 17*, 209–230. https://doi.org/10.1007/s10816-010-9087-7

Williams, R., Errickson, D., & Taylor, G. (2021). Mapping an archaeological site: Interpreting portable X-ray fluorescence (pXRF) soil analysis at Boroughgate, Skelton, UK. *Journal of Archaeological Science: Reports, 38*, Article 103109. https://doi.org/10.1016/j.jasrep.2021.103109

Williams, R., Taylor, G., & Orr, C. (2020). PXRf method development for elemental analysis of archaeological soil. *Archaeometry, 62*(6), 1145–1163. https://doi.org/10.1111/arcm.12583

Wilson, C. A., Davidson, D. A., & Cresser, M. S. (2008). Multi-element soil analysis: An assessment of its potential as an aid to archaeological interpretation. *Journal of Archaeological Science, 35*(2), 412–424. https://doi.org/10.1016/j.jas.2007.04.006

Wright, J. (2016). Households without houses: Mobility and moorings on the Eurasian Steppe. *Journal of Anthropological Research, 72*(2), 133–157. https://doi.org/10.1086/686297

Authors and Affiliations

Stefano Biagetti[1,2,3] · Abel Ruiz-Giralt[1] · Keelie S. Rix[1,14] · Antonios Koutroumpas[1] · Jordi Ibañez-Insa[4] · Carla Lancelotti[1,2] · Nuria Garcia-Tuset[1] · Celine Emmanuelle Kerfant[1,9] · Katherine M. Grillo[5,6] · Elisabeth A. Hildebrand[7] · John Lonyala[8] · Malebogo Mvimi[3] · Stefania Merlo[10] · Giulio Lucarini[11] · Silvia Lischi[12,13] · Marco Madella[1,2,3]

✉ Stefano Biagetti
stefano.biagetti@upf.edu

1 CASEs Research Group, Universitat Pompeu Fabra, C. Ramon Trias Fargas 25-27, 08005 Barcelona, Spain

2 ICREA, Passeig Lluís Companys 23, Barcelona, Spain

3 School of Geography, Archaeology and Environmental Studies (GAES), University of the Witwatersrand, 1 Jan Smuts Avenue, Braamfontein 2000, Johannesburg, South Africa

4 Geosciences Barcelona (GEO3BCN-CSIC), Lluís Solé I Sabarís S/N, 08028 Barcelona, Spain

5 Department of Anthropology, University of Florida, Gainesville, FL, USA

6 Archéosciences Bordeaux, Université Bordeaux Montaigne, Bordeaux, France

7 Department of Anthropology, Stony Brook University, Stony Brook, NY, USA

8 TBI-Turkwel, Turkana Basin Institute, Nairobi, Kenya

9 Institut Català de Paleoecologia Humana i Evolució Social (IPHES-CERCA), Tarragona, Spain

10 McDonald Institute for Archaeological Research, Downing Street, Cambridge CB2 3ER, UK

11 Institute of Heritage Science, National Research Council of Italy (CNR-ISPC), Montelibretti, Rome, Italy

12 Centre de Recherche Archéologique Jaussen et Savignac, Université Paris 1 – Panthéon-Sorbonne, 3 Rue Michelet, 75006 Paris, France

13 CNRS – UMR 8167 Orient & Méditerranée, 7 Rue Guy Môquet, 94800 Villejuif, France

14 Department of Chemical, Life and Environmental Sustainability Sciences, University of Parma, Parma, Italy