Ancient herders enriched and restructured African grasslands

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SUPPLEMENTARY INFORMATION

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Supplementary Notes

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SUPPLEMENTARY NOTE

We provide information on nutrient rich soil patches and savannah ecology, Pastoral Neolithic and Iron Age archaeological sequences, and the geography of excavated sites. Under Excavation Results we detail sites, stratigraphic descriptions and radiocarbon dates. Analyses of sediments and elemental compositions are discussed in Geoarchaeology and Geochemistry. We present data
on spatial patterns and satellite image analysis. Additional methodological details are also described. Information is provided on nutrient-rich soils and savannah biome structure.

PART A. THE INFLUENCE OF NUTRIENT RICH SOILS ON SAVANNAH BIOME STRUCTURE

Our research is designed to investigate the longevity of anthropogenic nutrient hotspots and the role of Pastoral Neolithic herders in the structure and function of modern African savannah grassland ecosystems. Syntheses of the ecology of African savannahs demonstrate that soil fertility is a primary determinant of variation in ecosystem structure and function not explained by rainfall and fire. In nutrient poor African savannahs, relationships among soil parent material properties, slope, climate, soil texture and soil fertility structure plant community composition, forage quality and herbivore communities at the macro-regional landscape scale.

To contextualize the significance of high nutrient anthropogenic patches in African savannahs, we briefly summarize fundamental relationships among nutrient rich soils and savannah biome structure. As described by Bell, also Scholes and Walker, savannah plant community structures and food chains differ substantially with levels of soil fertility. Sandy parent bedrock materials, including coarse-grained quartzites, sandstones, and metamorphic and granitic rocks, tend to produce low fertility soils. In contrast, fine-grained, rapidly weathering volcanic and other volcanic extrusive lavas and pyroclastic ashes and tuffs produce more fertile loamy and clayey soils associated with higher grass/tree ratios and higher wild herbivore biomass (mechanisms detailed in Part H.). Anthropogenic nutrient hotspots influence plant community structure and food chains in similar ways to high nutrient savannah soils. However, even on
fertile soils, nitrogen and phosphate levels on anthropogenic nutrient hotspots may be as much as 100 times background.

Modern pastoralist settlements become nutrient hotspots upon abandonment. Herders corral animals in settlements at night for protection from predation (lion, leopard, hyaena) and raiding, which concentrates nutrients from daily savannah grazing orbits, and produces greatly enriched sediments (Supplementary Table 2). Highly fertile settlement soils initiate formation of distinctive plant and animal communities and ecological cascades. Grass-dominated (glade) plant communities tend to outcompete woody vegetation in fertile corral soils. Higher plant nutrient quality (high leaf nitrogen and phosphorus), lower amounts of toxic secondary compounds, soil invertebrates and edge effects attract diverse wildlife, including herbivores, rodents (e.g. elephant shrews), birds, and arboreal reptiles. Domestic livestock and wild herbivores (e.g. gazelle, wildebeest, zebra, warthog) are attracted to glade vegetation and decreased predation risks in open areas. Preferential foraging influences herbivore effects on plant productivity and nutrient turnover, and reduces woody colonization. Deposition of dung and urine reinforces hotspot fertility.

By creating ecologically important nutrient concentrations in landscapes attractive to mobile herders, dispersed anthropogenic nutrient hotspots increase nutrient availability and provide broadly distributed islands of open, palatable grazing in tree-grass savannah ecosystems. Hotspot fertility generates rapid plant regrowth after rains, provides essential nutrients for pregnant and lactating ungulates, and influences herbivore movements. Pastoral settlements of the last century have hectare-scale effects on savannah heterogeneity, biodiversity, ecosystem structure and function. Supplementary Table 2 provides summary descriptions...
and references to primary studies of modern and Iron Age herder hotspots in the Sahel, eastern and southern Africa.

PART B. ARCHAEOLOGICAL SEQUENCE

The extent of ancient pastoral influences on nutrient flows and savannah ecology are determined by regional histories. Pastoralism developed in the Green Sahara and spread southward 6000-5000 B.P. The productive savannahs of southern Kenya and northern Tanzania were settled >3500 B.P. Episodic small-scale southward movements over the millennia created mosaics of herders with varied histories (Fig. 1). Savannah Pastoral Neolithic (SPN) and Elmenteitan Pastoral Neolithic sites date to ~3500-1500 cal. B.P. These traditions differed in terms of stone tool technologies, pottery traditions, burial practices and territorial ranges, but overlap spatially and often temporally. Pastoral Neolithic open air sites are not deeply stratified, suggesting short term (<decade), sometimes palimpsests of occupation. Site perimeters encompass ancient corral and midden deposits, postholes and rare hearths and hut floors (Ngamuriak and Sugenia, Fig. 1a).

Early Iron Age (EIA) farming settlements with Urewe ceramics and distinctive technology and material culture post-date pastoralism in East Africa, first appearing in the Lake Victoria Basin ~2000 years ago. EIA sites do not preserve large numbers of livestock and are largely distributed in more mesic, higher elevation, wooded environments than pastoralist sites. In the savannahs, stone using Pastoral Neolithic herders adopted iron during the Pastoral Iron Age (the last two millennia) in dynamic ecological and political landscapes associated with historic herder expansions (e.g. Maasai and Turkana). Southward movements from the
equator ~2000 B.P. lead to the appearance of traces of Neolithic herders and widespread
distribution of Iron Age agropastoralists in southern Africa. As a result, pastoral influences are
later in southern than eastern Africa. We present primary data on Kenyan Pastoral Neolithic sites
and discuss comparative research on East African Pastoral Iron Age sites and agropastoral Later
Iron Age sites in southern Africa (sites, dates, and micronutrient enrichment data summarized in
Extended Data Table 1, Extended Data Table 2, Supplementary Table 2).

PART C. EXCAVATED SITES, GEOGRAPHY

Study areas. Site location and geography are discussed here and background information relevant
to relations among soil parent properties, plants and herbivores. Pastoral Neolithic herder sites
were sampled in savannah grasslands on the volcanic plateaus east and west of the southern Rift
Valley of Kenya. The Ntuka area of Narok County is located within the northeastern corner of the
Serengeti-Mara-Loita Plains grassland/wooded grassland savannah ecosystem of northern
Tanzania and southwestern Kenya. In the Ntuka area, fine-grained, relatively fertile loam to
silty and clayey loam soils developed on Miocene to Quaternary lavas, tuffs and more recent
airfall volcanic ashes. The western margin of the Loita Plains in the Ntuka River catchment
(elevation ~1850 m) is bounded by the Loita Hills, a N/S-trending mountain range of Archaean
Basement System quartzites, gneisses and schists. Archaeological sites sampled in the Ntuka
area include Indapi Dapo (GvJh121), Oloika 1 (GvJh85), Oloika 2 (GvJh86) (Fig. 1, Extended
Data Fig. 2, Extended Data Table 1).

Lukenya Hill is a N/S trending inselberg of Archaean Basement System granitoid gneiss
that rises above the eastern side of the Athi-Kapiti Plains east of the Rift Valley in Machakos
County. The Athi-Kapiti Plains extend 46 km west, rising gradually to 2000 m at the edge of the
eastern escarpment of the southern Rift Valley. Dark cracking clay vertisols (black cotton soils)
formed on later Miocene to Quaternary lavas and tuffs appear on the plains within 500 m of
Lukenya Hill and other Archaean inselbergs. Sandy clay-loams support patchy *Acacia* bush.
Clay dominated soils (vertisols) on flatter landscapes support open to scattered tree grasslands\(^5^1\).
Neolithic sites are found on the reddish brown sandy clay-loam soils of the footslopes of the
inselberg less than 150 m from the steep rocky face of the inselberg at elevations of 1600-1700
m. Two Pastoral Neolithic sites (GvJm44 and GvJm48) were sampled on the east side of
Lukenya Hill (Fig. 1, Extended Data Fig. 2, Extended Data Table 1).

Rainfall is bimodal in both areas, with long rains in April/May and short rains in
October/November. Annual totals have high variance, averaging 510 mm at Lukenya, and 600
mm at Ntuka, increasing gradually to ~1000 mm 70 km west in the Lemek area at the north edge
of the Serengeti/Mara ecosystem, where the Elmenteitan Neolithic site of Sugenya is located. The
eco-climatic zone is semi-arid to sub-humid. Slopes support wooded vegetation. In Narok,
leleshwa (*Tarchonanthus camphoratus*) is the most abundant small tree/shrub species with
*Acacia* present in wooded grasslands\(^4^9^,5^2\). In the Ntuka area open grassy patches are distinctive of
current pastoral settlement and Pastoral Neolithic sites and visible on satellite imagery. We
observed (2011-2017) that the Ntuka study area and Lukenya Hill, still support wildebeest, red
hartebeest, zebra, grant's gazelle and thompson's gazelle in open grasslands, as well as eland,
impala, giraffe and warthog. Elephant and Cape buffalo are now absent from the Lukenya and the
Athi-Kapiti Plains and are rarely seen in the Loita/Ntuka area.
Until recent years, many Maasai families still practiced mobile pastoralism in parts of the Loita/Mara Plains, including the Ntuka area. In the Lukenya area of the Athi-Kapiti Plains, traditional herding has not been practiced since 1915 when the Maasai pastoralists were displaced from productive rangelands during the early years of the British colonial era\textsuperscript{53}.

**PART D. EXCAVATION RESULTS**

*Ntuka Archaeological Sites.* Indapi Dapo (GvJh121) is a treeless, oval-shaped, short grass clearing in surrounding bush and small-tree-dominated (*Acacia, Commiphora, Balanites*) savannah. The archaeological site has short grass cover with several small surface exposures of pale gray ashy archaeological sediments. It lies at an elevation of 1648 m above sea level (a.s.l.) on a gentle slope (0.03°) on the edge of the eastern footslopes of Legorinyo Hill, 3.5 km west of the Ewaso Ngiro River (Fig. 1g). The size of the site (~160 x 120 m diameter) and shallow deposits with a single layer of fine-grained pale gray dung derived deposits suggest occupation covering an area (~15,000 m\(^2\)), which is equivalent to one large or two or three small modern Maasai settlements. The artifacts are characteristic of the Savannah Pastoral Neolithic (SPN) tradition, including comb-stamp decorated pottery of the Narosura tradition, and Later Stone Age flaked stone artifacts of the SPN lithic industry, made mainly on translucent gray obsidian. Fragments of several stone bowls made of soft gray volcanic tuffs were collected on the site surface. Faunal remains are dominated by fragmentary bones and teeth of cattle, sheep and goat (Extended Data Table 1).

In order to document distinctive dung-derived on-site deposits and compare to non-anthropogenic off-site soil profiles, in June 2011 we excavated a one m\(^2\) trench (northeast co-
ordinate in Extended Data Table 1) in the central area of short grass with pale gray silts and high densities of archaeological artifacts, bones and teeth. An off-site trench was selected where red-brown soils support sparse grass, abundant shrubs and small trees and cultural materials were absent (Extended Data Fig. 1). We obtained a radiocarbon date on tooth dentine collagen of 2461-2364 cal. B.P. from the pale gray silt layer (Extended Data Table 2).

The sites of Oloika 1 (GvJh85) and Oloika 2 (GvJh86) are located ~8 km due west of Indapi Dapo, west of the Legorinyo Hills, on nearly level ground in a wooded grassland area traversed by small seasonal drainages that feed into the Ntuka River (Fig. 1e). Both sites are clearly visible as open grassy glades in bushland ~1 km east of the Ntuka River, and close to a modern Maasai settlement (Fig. 1f). Oloika 2 lies 240 m south of Oloika 1. These sites are ~110 and ~90 m in diameter, with areas of ~9500 m² and ~6300 m², respectively. Their archaeological remains are characterized by Elmenteitan tradition undecorated mica-tempered pottery, and flaked stone tools made predominantly on dark green obsidian. One fragment of a stone bowl was collected on the surface of Oloika 2. Cattle, sheep and goat dominate the faunal assemblages. We excavated single one m² square trenches in potential corral areas in each site (co-ordinates in Extended Data Table 1), within areas with pale gray silts exposed by erosion and animal burrows. Radiocarbon dates of 2461-2364 cal. B.P. on charcoal from Oloika 1, and 2113-2011 cal. B.P. on tooth enamel apatite from Oloika 2 were obtained from the gray dung-derived layers (Extended Data Table 2).

The silty gray levels in all three sites tested in the Ntuka area (GvJh85, 86 and 121) are underlain by a dense hard reddish brown silty loam layer 2-5 cm thick with reddened oxidized iron traces in some places. The upper surface of this layer is cemented by carbonate, which forms
a thin (1-2 mm) dense white layer. Artifacts and bones are rare to absent within and beneath this layer.

**Lukenya Hill Archaeological Sites.** At Lukenya Hill we sampled two sites, GvJm44 and GvJm48. They lie on the relatively steep slopes of the sandy clay sedimentary apron of the eastern footslopes of Lukenya Hill, 50-100 m downslope from the base of the granitoid gneiss rock outcrops of the inselberg (Extended Data Fig. 2a). Vegetation on recent Maasai settlement on the nearby Athi Plains is dominated by *Cynodon* grasses\(^5\), patches of which exist on the Neolithic sites. Numerous Pastoral Neolithic (PN) settlement sites and Pleistocene Later Stone Age open sites surround the base of Lukenya Hill, as well as several rockshelters with Middle and Later Stone Age (MSA and LSA) occupations and Pastoral Neolithic cairn burials\(^3,8,53\).

GvJm44 (Vaave Makongo) is an open-air multi-component SPN site (Extended Data Table 1) first excavated in 1975 by The University of Massachusetts’ Later Stone Age/Pastoral Neolithic comparative study project, directed by Charles M. Nelson and John R.F. Bower\(^3,8\). Brief descriptions of fauna, artifacts and radiocarbon dates are provided by Bower et al.\(^8\) and Nelson and Kimengich\(^3\). The site is bisected by a vertical-walled gully, which has completely destroyed the eastern half of the site but has exposed a complete cross-section of the stratigraphy (Extended Data Fig. 2b). The archaeological sediments are very dark gray-brown clay loams, forming a flattened 1-2-m-thick mound, resembling the typically thick accumulations of decomposed dung in modern Maasai settlement central stock enclosures. The lower occupation horizon (level 2) is dated to 3703-3361 cal. B.P. (3290 ± 145 bp uncalibrated) on charcoal collected in-situ by one of us (SA) who excavated this area in 1976-77 (Extended Data Table 2).
This is one of the oldest uncalibrated radiocarbon dates for an SPN site in the highlands of southern Kenya and northern Tanzania. Lower levels at the site contain pottery of the Nderit tradition (cuneiform impressed decoration, internal scoring), and SPN-tradition flaked stone tools, with moderately large crescentic backed microliths typical of the local LSA and SPN. Domestic species (cattle and sheep/goat) comprise 98% of the identifiable bones and teeth\textsuperscript{37}. The upper occupation horizon (levels 3-5) has several radiocarbon dates on bone apatite and collagen, and one on charcoal of 2714-2345 cal B.P. (Extended Data Table 2).

Pottery of the Lukenya variant of the SPN Narosura tradition, characterized by incised and comb-stamped decoration in a narrow horizontal band below the rim, occurs in the upper levels of the center and west side of GvJm44. The upper occupation horizon at the south edge of the site contains small fragments of very thin, fragile, burnished, deeply incised potsherds of the Akira tradition variant of the SPN. The upper SPN horizon is concentrated at 15-30 cm below the surface and is continuous across the site. This suggests a single occupation whose occupants discarded these different ceramic traditions at different points on the site perimeter. However, multiple occupations cannot be discounted without more fine-grained analyses. The associated flaked stone assemblage throughout the upper horizon belongs to the SPN lithic tradition, with relatively small backed microliths, scrapers and bipolar flaked tools and cores on obsidian, chert, and quartz. The faunas of levels 3-5 are dominated by cattle (67-92%) and sheep or goat (6-18%)\textsuperscript{37}.

We excavated a step trench sampling a profile at the south edge of the site, ~5 m west of the gully edge, aligned with the 1975-1977 excavation N/S trench line from which the level 2 date was obtained. No visually distinct dung layer was identified in the first excavation.
However, large quantities of dense fragments of pale gray fine grained sediments, possibly from dung, were observed in several squares 10-15 m closer to the center of the site on this trench axis during excavations in 1976-77, and a few smaller pieces of this material were found in the 2011 step trench. The presence of phosphate minerals in one sample (mineralogy section below) is consistent with decomposed dung. The dark gray-brown soil color compared to the surrounding off-site and sub-site soils (SI Fig. 2b) may be due to decomposition of unburned dung.

Site GvJm48 lies ~450 m NE from GvJm44 (Extended data. Fig. 2a). It is a large, open SPN site, first excavated in 1978\textsuperscript{37,38}. This site contains mainly domestic fauna, incised decoration pottery of the Lukenya variant of the Narosura tradition, and flaked stone artifacts similar to those from GvJm44. GvJm48 is dated to 1879-1569 cal. B.P. on bone collagen; the apatite carbonate fraction of this sample dates to 1685-1354 cal. B.P. (Extended Data Table 2). Underlying deposits derived from rockshelter GvJm19, located about 30 m upslope from the road cut, contain earlier Holocene to terminal Pleistocene LSA flaked stone artifacts and wild fauna\textsuperscript{37}.

Pale gray sediments with small comminuted carbonized grass stem fragments resembling those found in cow dung were present in the trench shown in Extended Data Fig. 2c. A more diffuse gray layer is well-exposed horizontally in the road cut on the upslope edge of the site, and vertically in the upslope wall of this road cut. This bed of fine grained pale sediments is not underlain by the distinctive hard reddened soil observed at the Narok sites. However, at Lukenya site GvJm52, located 2.3 km north of GvJm48, a continuous dense layer with a carbonate-cemented surface underlies a pale gray silty layer over large areas of the excavation. Sediment samples from GvJm48 analyzed in this report were collected in a section excavated 15 cm into
the 115 cm-deep vertical section exposed in the upslope side of the road cut. This gray silt midden is exposed horizontally in the road bed over a distance of ~30 m.

*Lemek Valley Archaeological Sites* The site of Sugenia, a large open Elmenteitan Neolithic site in the Lemek Valley ca 70 km west of Ntuka on the northern edge of the Mara Plains (Fig 1a) provides the only available comparative data for Lukenya in terms of geomorphic/geologic setting\(^{18,36}\). The site lies at the western end of the Lemek Valley, at the base of a steep Basement System hill composed of quartzites and schists. Sugenia is a multicomponent site that preserves dung-derived sediments identified by micromorphological, mineralogical and isotopic analyses\(^{18}\). Dates for Sugenia range between 2167-2312 cal. B.P. in the upper deposits, and 2764-2853 cal. B.P. at the bottom\(^{36}\) (Extended Data Table 2).

*Archaeological Site Stratigraphic Descriptions.* At Indapi Dapo (GvJh121), the archaeological layer is close to the surface, with 5-10 cm of topsoil overlaying a 35 cm-thick gray dung-derived deposit that is partially reworked by vertical root channels (Extended Data Fig. 1a). The surface of the dung layer is undulating and is light gray to light yellowish brown silty loam. A carbonate layer a few mm thick marks the base of this dung-derived layer. This carbonate crust caps a hard, and in some cases reddened layer 2-6 cm thick. The underlying massive brown silt grades downward to a fine to medium loam at the base of the excavation. Most of the artifacts were recovered from the dung-derived layer and overlying deposits. The 35 cm-deep offsite profile comprises massive brown loams with carbonate nodules that increase with depth.

The excavated profile at Oloika 1 (GvJh85) is 55 cm thick, with a largely intact dung
derived layer underlying 20 cm of silty light gray-brown topsoil (Extended Data Fig. 1b). The base of this layer is marked by a thin (2-3 mm) carbonate layer that caps a hard, undulating trampled surface. The underlying brown loam has strong large crumb structure and few artifacts or faunal remains. The offsite trench at Oloika 1 exposed a 55 cm thick light brown massive loam with carbonate nodule frequencies increasing with depth.

The dung-derived layer at Oloika 2 (GvJh86) is especially well preserved. The excavated section is 45 cm thick. The top 10 cm is mainly massive light gray-brown silty topsoil, and purer massive fine gray sediment from 10-30 cm below the surface (Extended Data Fig. 1c). The thin hard carbonate crust at the base of the dung derived layer is particularly distinctive, preserving an undulating, apparently trampled dense, reddened surface up to 5 cm thick with a few embedded artifacts. An AMS radiocarbon date of 2113-2011 cal. B.P. was obtained from this layer (Extended Data Table 2). The offsite trench was 40 cm deep, characterized by silty gray-brown soil with carbonate nodules (Extended Data Fig. 1c).

At GvJm44, the excavated step trench was 60 cm wide and sampled a 110 cm-thick profile at the southern edge of the site (northeast trench co-ordinate in Extended Data Table 1). Lying beneath the top soil is archaeological horizon A, 12-53 cm below surface (BS) (equivalent to levels 3-5 in Nelson's stratigraphic numbering system). The sedimentary matrix is a dark clay loam grading to silty loam, with Akira ceramics, small quantities of SPN lithics, and fragments of domestic fauna (Extended Data Fig 1d). Horizon B lies 53-90 cm BS and contains very few artifacts in this part of the site. No visually distinct dung layer was identified, but small chunks of dense fine-grained pale gray sediment were observed in the 2011 step trench. These chunks are abundant ~10-15 m upslope in this quadrant of the site, in association with Nderit tradition
ceramics, flaked stone and fauna. Charcoal from the lower levels associated with Nderit pottery was recovered in-situ in the Nelson excavation trench ~15 m upslope from the 2011 sampling spot. It dates to 3703-3361 cal. B.P. A charcoal date of 2714-2345 cal. B.P. was obtained in 1977 from the Akira levels close to the area that we sampled (Extended Data Table 2).

One offsite sample for comparison with GvJm44 and GvJm 48 was excavated approximately 40 m upslope from the gully bisecting GvJm44 (S 1.47611°, E 37.0745°, 1682 m). This 60-cm-deep profile was dominated by dark brown to redder brown loam (Extended Data Fig. 1d). Due to disturbance, offsite sampling possibilities close to GvJm48 are limited.

The stratigraphic section of the west side of GvJm48, closer to the rocky outcrops, is exposed in a recently graded road cut bisecting the northern sector of the site (Fig. 1, Extended Data Fig. 1d). We sampled the 115 cm vertical face of this section. Samples 5 cm-thick were collected at 10 cm intervals along this section. This profile begins with top soil from 0-5 cm BS, underlain by grey brown silty loam through 40-45 cm. From 55 cm to 75 cm BS a diffuse pale fine grained gray silty loam layer is evident, underlain by redder brown loam from 75-115 cm BS. Sediments below 80 cm contain few artifacts or fauna, and can serve as a proxy for an undisturbed off-site sample close to the site.

**PART E. GEOARCHAEOLOGY AND GEOCHEMISTRY.**

Below we provide results of bulk sediment analyses, followed by a contextual explanation of all sedimentary lines of evidence supported by thin section micromorphology.
Particle size analysis (PSA). Particle size analysis (PSA) demonstrates on-site sediments are dominated by silt relative to the coarser off-site samples (Supplementary Table 1). The sediments largely clustered as either silty loams or loams based on their ratio of sands, silts, and clays, as measured by a particle size analyzer. On-site anthropogenic layers tend to cluster toward silty loams, with higher ratios of silt, whereas off-site samples tend to feature higher ratios of sand, and cluster toward loams (Extended Data Fig. 4). Off-site samples from the Lukenya sites, Oloika 1 and Oloika 2 all show increasing ratios of sand, a decrease in silt, and a slight decrease in clay, with depth. Sediments from the archaeological layers do not show substantial change in particle size either within the anthropogenic horizons, or between these horizons and their overlying topsoils. Lukenya (GvJm44) is the only exception where the sample taken at 20 cm BS features very high clay content, and the sample taken at 40 cm BS. is closer in particle size composition to the archaeological contexts from the Narok sites.

Loss-on-ignition (LOI). Results of LOI analyses show the total percentage of sediment organic matter (loss at 550˚C), and carbonate (CO$_2$ loss at 1000˚C). Organic matter concentrations are overall higher in the anthropogenic contexts and remain high throughout the archaeological horizons. In some cases, the lower parts of the archaeological horizons have higher organic contents. This contrasts with off-site sections, where organic contents are high in the first 20 cm but decrease substantially with depth. Carbonate content varies widely among off-site contexts but is consistently lower (<0.6%) in the upper to middle portions of the archaeological horizons. At both Oloika 1 and Oloika 2 the bottom portions of the archaeological horizons have much higher (500-600%) carbonate contents.
**Magnetic susceptibility.** Both low- and high-frequency readings are higher in the archaeological layers relative to off-site samples at Oloika 1, Oloika 2, and GvJm48 (Supplementary Table 1). Off-site sediment samples exhibited relatively higher magnetic susceptibility readings at Indapidapo and GvJm44. With the exception of GvJm44, the on-site samples demonstrate relatively higher overall magnetic susceptibility values relative to iron content in the layer (3571 ppm at GvJm44 vs. 6206-17806 ppm at other sites). The correlation between magnetic susceptibility and iron content is relatively weak with low statistical significance (Spearman's rho =0.375, p=0.154). Magnetic susceptibility readings do not demonstrate any clear on- versus off-site patterning, and it is likely these values are affected by a wide range of natural and anthropogenic factors.

**Mineralogy.** Mineralogy was determined through Fourier Transform Infrared (FTIR) spectroscopy. Off-site samples are dominated by clay, quartz and feldspars. On-site samples also include opal and calcite at Oloika 1, 2 and Indapi Dapo. The Lukenya Hill sites do not show mineralogical differences from off-site samples. There is no evidence for heated clay minerals in the on-site samples (i.e., no indication for burning of dung). A light-colored sediment chunk from GvJm44 includes a phosphate mineral, supporting origin from degraded dung.

**Elemental composition (ICP-MS).** Elemental composition of the dung layers from all sampled archaeological contexts and from off-site sediment profiles were determined using inductively-coupled plasma mass spectrometry (ICP-MS) analysis in order to compare differences between
on-site and off-site elemental composition signatures (Supplementary Table 1). ICP-MS analysis reveals substantial elemental differences between on- and off-site samples. On-site samples have substantially higher concentrations of phosphorus (Fig. 2) and often magnesium (Supplementary Table 1). In some cases, calcium values were elevated by 200-1000%, as at Indapi Dapo (off-site: 591-879 mg kg\(^{-1}\) vs. on-site: 7467-8355 mg kg\(^{-1}\)). Concentrations of potassium, strontium, sodium, and zinc are high, and vanadium, cobalt, nickel, zirconium, and lead are low relative to off-site soils. Aluminum is elevated at Oloika (Supplementary Table 1). At Lukenya, degraded dung deposits are enriched in phosphorous (GvJm44) and calcium (GvJm48). Cobalt depletion fits with manuring signatures\(^{24,54-56}\).

The magnitude of these differences varied substantially by element, within and among sites. For example, on-site Ca concentrations at Indapi Dapo were over 1000% higher than the off-site samples whereas at Oloika and Lukenya sites, calcium values ranged from 10-50% higher within the archaeological layers. Phosphorus concentrations were 200% higher in the Oloika site dung layers (535-890 mg/kg\(^{-1}\) vs. 1150-1800 mg/kg\(^{-1}\)), but 400-800% higher at Indapi Dapo and the Lukenya sites relative to their respective off-site samples. Elemental compositions vary by depth within sites, with on-site elemental enrichment generally being highest in the middle to bottom of the dung layer and decreasing toward the topsoil. Some of this variation may derive from differences in the diet and species composition of the livestock (e.g., ref. 24), however large differences in the elemental composition from the various off-site locations suggests that local geology, ecology, and taphonomy likely play major roles as well.

Principal components analyses (PCA) of the elemental signatures from both the Lukenya and Narok sites revealed patterns. The first principal component (PC1) loaded heavily on calcium
and explained 67.75% of the variance, and the second principal component (PC2) loaded largely on iron and accounted for 29.75% of the sample variance. Bivariate plots using these two components (cumulatively accounting for 97.5% of the total variance) consistently separate anthropogenic dung-derived layers and off-site sediment column samples into distinct clusters. The archaeological deposits therefore constitute a set of elemental concentrations that differ significantly from the non-archaeological off-site samples, with specific enrichments and depletions that match expectations for dung accumulations.

*Nitrogen and carbon elemental and isotopic analyses.* On-site profiles have higher $\delta^{15}$N values than off-site profiles by 2.3 ± 0.8‰ ($X^2 = 5.4, p = 0.02$, 8.9-13.4‰ on-site and 6.3-10.0‰ off-site) (Fig. 3, Supplementary Table 1). On-site samples also have significantly higher weight percent nitrogen (wt. % N) ($X^2 = 5.7, p = 0.017$, 0.05 - 0.25% on-site and 0.02 - 0.13% off-site). Lukenya sites show less difference between on- and off-site samples. On-site soil organic matter $^{13}$C$_{SOM}$ values are higher than off-site samples by 1.9 ± 0.6‰ ($X^2 = 4.7, p = 0.03$, on-site -18.5 to -15.0‰; off-site -17.3 to -14.1‰). The difference in $\delta^{15}$N$_{SOM}$ values in on-site relative to off-site samples from Indapi Dapo, Oloika 1 and Oloika 2 are both statistically and ecologically significant.

*Micromorphology.* Color and structure differences between on- and off-site sediments are marked. The microphotograph of on-site sediments (Indapi Dapo site) (Extended Data Fig. 3) shows manganese-oxide florets. Phytoliths of different types and dung spherulites are present. Opal originates from grass phytoliths and calcite appears in thin sections either in the form of
dung spherulites or as microspar. PSA on-site shows siltier deposits than off-site samples owing to large amounts of plant phytoliths left after degradation of herbivore excrement\textsuperscript{24}. Dung spherulites are present but most calcite is, in fact, microspar suggesting that spherulites dissolved and calcite re-precipitated as microspar. This suggestion fits with the micromorphological observations of Mn-oxide florets indicating episodes of water saturation, the likely cause for dissolution of dung spherulites. Down-section infiltration of carbonate-rich solutions probably resulted in the formation of the basal calcite crust typical of the on-site deposits. There is no indication for temperatures above 500°C. Micromorphology does not show sealing of sediment or vitrification.

All sites show bioturbation but this is most marked at Indapi Dapo where the granular microstructure is associated with large voids. Bioturbation disaggregated the deposits to the degree that micro-laminated structure typical of enclosure deposits is no longer present.

\textit{Integrating mineralogy, microscopy, sedimentology, geochemistry, sedimentology, and field observations}. Although elemental analyses show clear enrichment in phosphorous in on-site deposits, this was detected mineralogically only at GvJm44. Phosphorous was probably not present in a mineral form in other sites. Overall, there is a good match between P and \textsuperscript{15}N enrichments, phytoliths and dung spherulites (Oloika 1, 2 and Indapi Dapo).

We found high nutrient levels in dung-derived sediment profiles in volcanic and metamorphic soil parent material settings, with variability influenced by slope and parent soil characteristics. Depletion of micronutrients at Lukenya may reflect steep slope, coarse sandy matrix and high water-infiltration rate. However, results from both Lukenya and Narok indicate
widespread preservation of high nutrient levels and distinctive elemental signatures on Pastoral Neolithic occupations.

PART F. SPATIAL PATTERNS AND SATELLITE IMAGE ANALYSIS

Satellite imagery reveals spatial patterns relating to ancient and modern pastoral settlement in the Ntuka study area. Coordinates of fenced modern settlements (enclosing small houses surrounding central and subsidiary corrals) obtained from Terra Serva online data were incorporated into a settlement site layer on an Arc GIS model with a base 30m resolution digital elevation model, with coordinates for the five Pastoral Neolithic sites identified in the field. Image analysis revealed 116 modern Maasai pastoral settlements in the study area (Extended Data Fig. 5), with an average density of pastoral settlement of 1 per 5.41 square kilometers. The settlements plotted in this figure can be compared to those in the semi-false-color satellite image of Fig. 1e and the natural color images in Fig. 1f-g and Extended Data Fig. 2d.

Settlements are visible in satellite images as open patches in bush and woodlands (Fig. 1f-g, Extended Data Figure 2d). Settlement and site vegetation characteristics key to spatial variability (glades or closed bush) were noted on the ground. Dry season foot survey revealed that open grassy patches (Digitaria and other grasses) are characteristic of SPN and Elmenteitan sites at Ntuka. Savannah Pastoral Neolithic sites include Indapi Dapo and Ole Pariata (GvJh73). Elmenteitan sites include Oloika 1 and Oloika 2, and Ol Owarukeri (GvJh 108) (Extended Data Fig. 2d). Sites form distinctive spatial features in tree dominated savannah areas, with leleshwa (Tarchonanthus camphoratus), Balanites aegyptiaca and Commiphora africana shrubs and small trees.
PART G. METHODS

Particle size analysis, sequential loss on ignition, and magnetic susceptibility were conducted at the Geoarchaeology Laboratory in Washington University in St. Louis. Stable isotope analyses were conducted at the Laboratory for the Analysis of Ancient Food Webs and Geographical information system analysis was conducted at the Spatial Analysis Laboratory (SAIE) laboratory, both at Washington University in St Louis. Micromorphology and FTIR analyses were conducted at the Laboratory for Sedimentary Archaeology, University of Haifa. Faunal collagen and enamel apatite samples were prepared for radiocarbon dating at the Environmental Isotope Paleobiogeochemistry Laboratory, Department of Anthropology, University of Illinois, Urbana, and the Radiocarbon Laboratory of the Illinois State Geological Survey at the University of Illinois. Dates were analyzed at the University of California, Irvine, Accelerator Mass Spectrometry radiocarbon laboratory.

Radiocarbon dating. Collagen was prepared following methods described elsewhere in detail\(^57\), with two differences that increase collagen yield and purity. First, dentine was demineralized using 0.2 M rather than 1.0 M HCl. Second, collagen was hydrolyzed at 70°C rather than 90-95°C. Freeze-dried collagen was converted to CO\textsubscript{2} using sealed tube combustion and cryogenically distilled for AMS dating.

Enamel was separated from dentine and cementum and abraded with carbide and diamond dental handpiece rotary tool burrs, using a Kupa\textregistered Mani-Pro KP-5000 handpiece drill at very low speed to remove adhering contaminants. Enamel fragments were hand-ground in an agate mortar. A \(\sim 400\) mg sample was treated with 25 ml 2.63% NaHClO\textsubscript{3} (Clorox bleach) for \(\sim 24\) hours to
remove organic matter, and rinsed 5x with distilled H₂O. The sample was reacted with 25 ml 0.1M acetic acid under vacuum to remove adsorbed and diagenetic carbonate, alternating with return to atmospheric pressure with CO₂-free N₂ drawn from the headspace of a liquid N dewar. Cycling between vacuum and N₂ continued at ~15-30 minute intervals until bubbling reaction ceased (~3-4 hours). Samples were rinsed 5x in distilled water and freeze dried. Purified samples were reacted with 100% H₃PO₄ to liberate CO₂ from structural carbonate. CO₂ was purified by cryogenic distillation for AMS dating.

Particle size analysis (PSA). Sediment samples for PSA were air dried and then analyzed using a Micromeritics Saturn II laser diffraction system to calculate particle size. Other than removing large organic inclusions by hand, and gently disaggregating sediment lumps with a mortar and pestle, we did not use any chemical pre-treatment protocols.⁵⁸

Loss on ignition (LOI). To calculate organic and calcium carbonate content, we conducted sequential loss on ignition. First, we weighed samples in pre-weighed ceramic crucibles. Samples were air-dried at 100-105°C to remove water and reweighed after cooling to calculate water loss. Samples were then heated at 550 °C for 4 hours to oxidize organic matter (following ref. 59). After cooling, samples were reweighed to determine organic matter weight loss. Samples were then heated to 1000 °C for two hours to convert calcium carbonate (CaCO₃) to calcium oxide (CaO) plus CO₂ gas. Samples were weighed after cooling to determine the amount of inorganic (carbonate) carbon lost as CO₂ from each sample. Standard protocols (following ref. 60) were followed for calculating the percentage of carbonate, which is assumed here to be mainly CaCO₃, with minor contributions from Mg, Sr and other carbonate forming elements.
**Magnetic susceptibility (MS).** We used a Bartington MS2B magnetic susceptibility sensor to determine the low and high field magnetic susceptibility as well as frequency dependence of all bulk samples\(^6\).

**Micromorphology.** Undisturbed sediment blocks were resin impregnated, sliced and ground into thin sections at Spectrum Petrographic Inc. Thin sections were observed using a polarized light microscope (Nikon Eclipse 50i POL). Observations and interpretations are based on descriptive guides given in ref. 62.

**Mineralogy (FTIR spectroscopy).** Samples for Fourier Transform Infrared spectroscopy were prepared using the KBr method and spectra were obtained between 4000 and 400 cm\(^{-1}\) using a Thermo Fisher Nicolet iS5 infrared spectrometer. Spectra were analyzed using the Thermo Fisher Omnic software and interpretation was aided by an internal reference library.

**Stable isotope composition of soil organic matter.** Samples for nitrogen isotope analysis were not pretreated, so results represent total organic and inorganic N isotopic composition. Soil organic matter was treated with 2 M HCl to remove carbonates, so the analyzed fraction is carbonate-free whole soil.

Isotope ratios are expressed using the delta (\(\delta\)) notation in parts per thousand (permil: ‰) relative to a standard, as follows: 
\[
\delta (\text{‰}) = \left[\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1\right] \times 1000
\]
where R is the ratio of the heavier to the lighter isotope. The Peedee Formation \textit{Belemnitella americana} marine fossil limestone (PDB) from South Carolina is the standard reference material for carbon and oxygen isotope ratios in carbonates and organic matter; atmospheric N2 (AIR) is the standard for nitrogen.

We used the lme4 package in R to perform a linear mixed effects analysis of the relationship between sediment $\delta^{15}$N and $\delta^{13}$C values, and the presence of a dung profile. In our model, we included on-site (henceforth “dung profile”) vs off-site status and the depth in the sampling profile (without interaction term) as fixed effects. We included a random intercept for sites as well as a by-site random slope for the effect of a dung profile. Visual inspection of the residual plots did not reveal any obvious deviations from homoscedasticity or normality. We obtained p-values by conducting likelihood ratio tests of the full model with the effect in question against the model without the effect in question.

\textit{Spatial patterns and Satellite Imagery}. Coordinates of fenced modern settlements were obtained from the TerraServer online viewer. KML waypoints were imported to a settlement site layer in an ArcGIS model with a base 30m resolution digital elevation model derived from the Shuttle Radar Topography Mission. Data on soil, environmental data and rainfall were obtained from the Kenya Soil Survey and the World Resource Institute. The study area encompassed the Ntuka River Valley including the archaeological sites of Indapi Dapo, Oloika 1 and Oloika 2, and Ole Pariata.

\textbf{PART H. MACROREGIONAL INFORMATION ON NUTRIENT-RICH SOILS AND SAVANNAH BIOME STRUCTURE.}
As discussed above, parent geology and levels of soil fertility fundamentally affect savannah biome structure. The volcanic regions of eastern Africa, including the study area in the Serengeti/Mara/Loita, Athi-Kapiti plains, as well as the Laikipia Plains and southern African Karroo and Transvaal grasslands on base cation-enriched ancient marine sedimentary rocks, support fertile nutritious grasslands with high total biomasses of gregarious herds of wild ruminant herbivores.

Sandy soils with coarse particle size and high water-infiltration rates tend to have low pH. Because exchangeable bases are acid-soluble, sandy soils tend to have low fertility. Acidic soils occur predominantly on steeper slopes with high rainwater runoff and water infiltration rates. Coarse-grained quartzites, and sandstones have insignificant concentrations of exchangeable bases, and metamorphic and granitic rocks have low mineral weathering rates and slow release of exchangeable bases to the soil. Conversely, volcanic rocks with high concentrations of basic cations release mineral nutrients at higher rates and produce more fertile loamy and clayey soils. Clayey soils on lower slopes and level ground, however, impede water infiltration, and favor accumulation of exchangeable bases.

High water infiltration rates in sandy soils flush mineral nutrients to depths below the rooting zone of most grasses, as a result, deeply rooted plants can outcompete grasses. Sandy, acidic infertile soils on steeper slopes, therefore, support plants communities with high savannah tree/grass ratios. Because base cations for cellular cytoplasm functions cannot be readily replaced where soil nutrients are scarce, broadleaf plants on infertile soils also tend to have high concentrations of toxic secondary chemical compounds. In addition, grasses on infertile soils tend to have higher fiber and lower digestibility, which require longer gut retention times for
effective digestion by ruminant herbivores. Consequently, larger species such as elephant and Cape buffalo are abundant members on nutrient-depleted soils, and the total herbivore biomass tends to be low\textsuperscript{4,5}. The converse is true on soils on low slopes with finer particle size that support low tree/grass ratios, produce high quality forage, and support a high herbivore biomass\textsuperscript{4,5}. Livestock mediated nutrient flows and pastoral settlement hotspots function in similar ways to fertile soils produced by soil parent material properties, slope and climate. However, spatial effects are smaller, patches are widely dispersed and patterned by herder ecological and social preferences. The magnitude of enrichment is also greater. As a result, anthropogenic nutrient hotspots have distinctive meso-scale effects on landscape heterogeneity.

**Supplementary References**


