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From Wild Foods to Mixed Subsistence: Nonlinear Nutrition Transition among Hadzabe Foragers

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Research Article

Keywords:

Posted Date: July 31st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9685353/v1

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Additional Declarations: No competing interests reported.

Abstract

Nutrition transition is often framed as a linear replacement of wild foods by market commodities. However, in contemporary small-scale societies embedded in dynamic social-ecological systems, dietary change is typically hybrid, reflecting reconfiguration of food environments rather than linear substitution. We analyze repeated cross-sectional 24-hour dietary recalls from Hadzabe adults (2015, 2019, 2025; n=202), classifying intake into locally salient wild foods (e.g., tubers, game, honey, fruits) and agricultural/processed categories to assess change in dietary composition and diversity. To contextualize interannual variability, we situate focal years within long-term hydroclimatic conditions (1981-2025) using CHIRPS rainfall and NASA MERRA-2 soil moisture and temperature data, while also considering regional tourism trends as coarse proxies of market access and cash income. Dietary change was strongly nonlinear: 2019 was the lowest-diversity year, while 2025 exhibited cross-domain dietary broadening, with expanded wild plant and honey consumption alongside increased agricultural foods, processed items, sweetened beverages, and alcohol. These patterns do not support steady erosion of wild subsistence; rather, wild foods persisted as market foods increased. Hydroclimatic and tourism data showed only partial correspondence with dietary patterns, suggesting that broad ecological and economic proxies incompletely capture how environmental and market change is mediated through provisioning decisions. Taken together, these findings indicate that nutrition transition in foraging populations is best understood as a socially mediated reconfiguration of mixed food systems.

INTRODUCTION

Understanding how dietary change unfolds in small-scale and hunting and gathering societies has important implications for health transitions, environmental adaptation, and food sovereignty among subsistence-level communities. Such changes are often interpreted through nutrition transition models that assume gradual replacement of wild foods by market commodities. Classic nutrition transition models describe shifts away from fiber-rich, minimally processed foods toward diets higher in refined carbohydrates, fats, sugars, often alongside changing activity patterns and rising chronic disease risk (Popkin et al., 2020). However, recent work shows that dietary transitions are rarely linear or uniform particularly in small-scale societies where subsistence remain flexible and market integration is uneven (Dufour & Piperata, 2023). In these contexts, market foods are incorporated alongside continued reliance on wild and locally produced foods, resulting in mixed dietary profiles. These patterns have been documented across contemporary small-scale populations, where market integration is associated with increased consumption of purchased foods alongside continued reliance on wild resources, producing non-linear effects on dietary diversity (Dufour & Piperata, 2023; Reyes-García et al., 2019). Such mixed-subsistence strategies are not a transitional stage, but a persistent and adaptive configuration of contemporary food systems, particularly among foraging or former-foraging populations with long-standing engagement in exchange, trade, and intermittent cultivation (Crittenden & Schnorr, 2017; Mabulla, 2007; Pollom et al., 2021). This perspective reframes “transition” as a shifting food environment in which the relative balance among wild, cultivated, and purchased foods is reconfigured over time (Donders & Barriocanal, 2020; Zeitler et al., 2024). This process is often structured by broader political-

ecological dynamics, which can shape the availability of both wild resources and market or agricultural foods (Crittenden, 2019; Huff, 2014; Leatherman et al., 2016).

Comparable research suggests that market integration often enters diets through storable commodities (e.g., flours, oils, sugar), while wild foods persist as nutritionally and culturally important resources (Donders & Barriocanal, 2020; Reyes-García et al., 2019). Outcomes vary widely across settings, reflecting differences in affordability, convenience, cultural preferences, and access to resources (Karanja et al., 2022; Piperata et al., 2023). Where access to wild resources remains viable, dietary change may take the form of cross-domain broadening, in which market foods expand without immediate collapse of wild food use (Broegaard et al., 2017; Kramer & Greaves, 2017). In other cases, structural constraints (e.g., land dispossession, restrictive governance, and livelihood disruption) can reduce access to wild foods while simultaneously limiting agricultural and/or market substitutions (Huff, 2014; Safari et al., 2021). In this vein, ecological conditions alone are likely insufficient to explain dietary outcomes among small-scale communities experiencing change (Piperata et al., 2023; Wutich & Brewis, 2014). Distinguishing between these trajectories requires empirical descriptions of diets that are sensitive to locally salient food categories and to the ecological and anthropogenic conditions shaping availability and access to resources.

The Hadzabe of northern Tanzania provide an important case for evaluating these dynamics because their food system is strongly seasonal and increasingly entangled with shifting livelihood opportunities (Crittenden, 2019; Gibbons, 2018; Marlowe, 2010; Pollom et al., 2021; Woodburn, 1968; Yatsuka, 2015, 2018). Ethnographic and nutritional research has long emphasized that Hadzabe subsistence unfolds in a seasonally dynamic savanna-woodland mosaic where rainfall and water availability structure mobility, camp aggregation and dispersal, and the spatial distribution of key resources (Marlowe, 2010; Woodburn, 1968). At the same time, expanding access to agricultural foods and market goods, livelihood diversification, and tourism-linked income are reshaping settlement patterns and provisioning, while simultaneously reinforcing the community's foraging identity (Crittenden, 2019; Yatsuka, 2015, 2018).

Current literature suggests that tourism is a pathway for Hadzabe households to access cash and market goods (Mabulla, 2012; Mollel, 2020; Yatsuka, 2015, 2018). This reshapes how food is acquired without directly replacing the centrality of wild foods (Crittenden & Schnorr, 2017; Pollom et al., 2020; Yatsuka, 2015, 2018). Income from guiding, camp entry fees, and cultural demonstrations provides episodic access to cash and in-kind goods (e.g., maize), which are commonly used to purchase agricultural foods and alcohol (Mabulla, 2012; Mollel, 2020; Pollom et al., 2020; Yatsuka, 2015, 2018). Additionally, engagement in tourism-related activities may shift time allocation and labor away from daily foraging, contributing to reduced participation in wild food acquisition (Joachim & Zahor, 2022; Pollom et al., 2020). Tourism is also associated with changes in settlement and mobility patterns, including increased aggregation near accessible areas, which can facilitate the movement of agricultural goods throughout the community (Blurton-Jones, 2016; Crittenden, 2019; Mabulla, 2012). Importantly, these effects are likely context-dependent: tourism may support continued reliance on wild foods in some settings while contributing to reduced foraging in others (Mabulla, 2012; Yatsuka, 2015, 2018).

Ecological variability contributes to year-to-year dietary differences in foraging and mixed-subsistence systems, but isolating its effects empirically is challenging (Gallois et al., 2020; Reyes-García et al., 2019). Gridded hydroclimatic datasets, including CHIRPS precipitation and MERRA-2 temperature and soil moisture, provide multi-decadal environmental indicators widely used in data-sparse regions (Funk et al., 2015; Gelaro et al., 2017). However, they operate at spatial and temporal scales that may not correspond closely to the fine-grained patchiness of foraging returns. Furthermore, broad climatic trends may not translate directly into dietary outcomes if access and mobility mediate how environmental variation is experienced (Turner et al., 2003). In the Hadzabe region of Northern Tanzania specifically, landscape change is also shaped by anthropogenic processes, including migration and contested land-use governance, which alter resource distributions and mobility independent of, or interacting with, climate variability (Caro et al., 2017; Mabulla, 2007; Pollom, 2022). Such changes impact both wild plant and animal resources, as recent work demonstrates reduced availability of wild game alongside increased presence of domesticated livestock (Wood et al., 2021).

Ecological variability is frequently invoked as a key factor shaping resource availability in the Hadzabe foraging system (Joachim & Zahor, 2022; Mabulla, 2007; Mabulla, 2012; Pollom, 2022). However, empirical evaluation of correspondence to observed dietary patterns remains limited. While hydroclimatic datasets provide standardized measures of environmental variability, they operate at spatial and temporal scales that may not align with fine-grained ecological heterogeneity and constraints that structure daily provisioning decisions. As a result, the extent to which commonly used ecological data can detect meaningful signals in fine-grained dietary data remains unclear. This raises a key methodological question: can commonly used ecological indicators detect meaningful signals of fine-grained dietary change in highly patchy, access-mediated systems? We similarly evaluate whether tourism trends correspond to dietary change, given their well-documented role in shaping access to market goods.

The current study analyzes repeated cross-sectional 24-hour dietary recalls collected among Hadzabe adults during the dry seasons of 2015, 2019, and 2025 using consistent field protocols adapted for rural East African conditions. Dietary change is characterized by using presence-absence indicators and dietary diversity metrics that distinguish wild-sourced foods (tubers, game meat, honey, wild fruits) from agricultural and processed items, consistent with locally salient food categories. Comparable approaches have been used in other Indigenous contexts (Reyes-García et al., 2019). We contextualize these dietary patterns using hydroclimatic indicators from satellite-derived precipitation data (CHIRPS) and NASA's MERRA-2 reanalysis for soil moisture and temperature metrics (Gelaro et al., 2017), alongside coarse proxies of market integration (e.g. regional tourism), given evidence that tourism contributes substantially to cash access and intake of agricultural and/or market goods (Joachim & Zahor, 2022; Yatsuka, 2015, 2018).

Specifically, we ask whether Hadzabe dietary change from 2015 to 2025 is best characterized as (i) substitution away from wild foods toward agricultural and processed foods, (ii) cross-domain dietary broadening in which market and processed foods expand alongside continued or increased wild food

use, or (iii) an uneven pattern in which different food domains move in different directions across years and residential contexts, and lastly (iv) whether hydroclimatic indicators and tourism corresponds to dietary changes observed between 2015 and 2025. By integrating dietary evidence with hydroclimatic context and proxies of cash income, this paper provides an empirically grounded description of contemporary Hadzabe dietary transition while also demonstrating the analytical limits of commonly available datasets for interpreting fine-scale food system change in foraging populations. Even where correspondence is weak, identifying that mismatch is itself informative for guiding future research, and considering ethnoecological and food-environment approaches that operate at scales closer to daily provisioning decisions (Bateson, 1976; Zeitler et al., 2024).

Study population: The Hadzabe, a small community (~ 1,000 individuals), reside in northern Tanzania and continue to rely substantially on wild foods within the highly seasonal savanna-woodland mosaic surrounding Lake Eyasi, degrees of market engagement vary by region and settlement context (Blurton-Jones, 2016; Marlowe, 2002, 2010; Pollom et al., 2021; Woodburn, 1968). Their subsistence system is organized around five principal food categories: tubers (underground storage units), berries, baobab fruit, meat (small, medium, large game), and honey (stingless and stinging bees) (Schnorr et al., 2014). The relative contributions of these food categories fluctuate across seasons and landscapes (Blurton-Jones, 2016; Crittenden, 2016). Historically, rainfall and surface water availability structure camp aggregation and dispersal, hunting opportunities, and berry abundance, producing marked intra-annual dietary variability (O'Connell et al., 2024; Woodburn, 1968).

Wild foods differ in reliability and variance. Tubers are widely described as continuously available, and resistant to most ecological perturbation (Marlowe & Berbesque, 2009; Murray et al., 2001; Schoeninger et al., 2001; Vincent, 1985). Berries and baobab fluctuate with rainfall and phenology, while honey and large game exhibit substantial day-to-day variability in acquisition (Marlowe, 2010; O'Connell et al., 2024). There is a pronounced sexual division of labor in daily foraging roles. Women disproportionately target plant foods that are spatially predictable, often foraging in groups within known resource patches (Hawkes et al., 1989, 1997), whereas men range more widely and pursue dispersed, higher-variance resources such as honey and game (Apicella et al., 2017; Hawkes et al., 1991, 2001). Although debate persists regarding the degree to which male hunting preferentially benefits households (Hawkes et al., 2014; O'Connell et al., 2024; Wood & Marlowe, 2013), multiple studies demonstrate cultural expectations of meat and honey redistribution (Hawkes et al., 2001; O'Connell et al., 2025). Nutritional outcomes therefore likely emerge from patterns of sharing and pooled acquisition rather than individual returns alone.

Long-term research indicates that Hadzabe foraging systems were historically characterized by high dietary diversity, flexible mobility, and reliable access to wild plant foods, with limited evidence of chronic nutritional stress despite pronounced seasonal variability (Blurton-Jones, 2016; Marlowe, 2010; Woodburn, 1968). However, long-standing interaction with agricultural and pastoral neighbors, tourism-linked income, wage labor, and the increasing availability of domesticated cultigens have introduced additional pathways for food acquisition (Crittenden, 2019; Crittenden et al., 2017; Gibbons, 2018;

Mabulla, 2012; Pollom, 2022; Pollom et al., 2021; Wood et al., 2021). These processes do not eliminate reliance on wild foods but may reconfigure their contributions within an increasingly mixed food environment (Crittenden & Schnorr, 2017; Pollom et al., 2021).

METHODS

Dietary Data: Dietary intake was assessed using 24-hour dietary recalls following the USDA multiple-pass method (Conway et al., 2003, 2004), adapted for rural East African field conditions and implemented with trained Hadzabe collaborators. The multiple-pass sequence included: (1) an uninterrupted list of all foods and beverages consumed in the past 24 hours, (2) detailed probing, and (3) a final review to improve completeness and accuracy. Portion sizes of beverages were estimated using culturally salient, widely available commercial containers (e.g., commercial bottles in mL) that Hadzabe participants use to drink alcohol and soda. These methods have been shown to minimize measurement error in low-income settings (Gibson et al., 2017). All dietary data was collected across the June-July dry seasons in 2015, 2019, and 2025.

Climatic Data: To assess hydroclimatic conditions relevant to the local wild food system in the Mang'ola region, we combined satellite-derived precipitation estimates with reanalysis-based temperature and soil moisture data. Monthly rainfall was obtained from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS v2.0), a satellite- and station-based precipitation product designed for high-resolution climate monitoring in data sparse regions (Funk et al., 2015). CHIRPS integrates satellite infrared observations with in situ station data to produce rainfall estimates and has been validated across Africa, including East Africa (Dinku et al., 2018; Mahay et al., 2025; Mulungu & Mukama, 2023).

Temperature and soil moisture variables were derived from NASA's Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2), a global atmospheric reanalysis that integrates an Earth system model with data assimilation to provide internally consistent surface meteorology (Gelaro et al., 2017). MERRA-2 land surface hydrology and soil moisture estimates have been evaluated and show improved representation of terrestrial water dynamics (Reichle et al., 2017), with demonstrated correspondence to observed soil moisture patterns and seasonal variability. MERRA-2 temperature fields have been widely applied in regional climate analyses, including in East Africa, where they capture spatial and temporal temperature variability consistent with observed patterns (Abera et al., 2020).

We extracted monthly near-surface air temperature at 2 m (T2M) along with its monthly maximum and minimum values (T2M_MAX, T2M_MIN) as standard indicators of thermal conditions. These measures allow assessment of asymmetry between daytime and nighttime temperatures, summarized as diurnal temperature range (DTR = T2M_MAX − T2M_MIN) (Gelaro et al., 2017). Water availability below the surface was characterized using profile soil wetness (GWETPROF), which reflects modeled root-zone soil moisture within the land-atmosphere system and is widely used in land-hydrological assessments (Draper et al., 2018; Gelaro et al., 2017; Koster et al., 2016; Reichle et al., 2017).

To evaluate long-term change, we established a 30-year climatological reference period using the earliest available data (1981-2010) and quantified departures from expected seasonal conditions using baseline-standardized anomalies (z-scores), consistent with the standard use of 30-year climate normals in climatological analysis (Arguez & Vose, 2011). We summarized central tendency (annual means/totals), intra-annual variability (annual standard deviations of monthly values), and the frequency of unusually wet or dry months using a ±1.5 SD threshold (McKee et al., 1993). To our knowledge, this is the first study among the Hadzabe to directly integrate long-term gridded hydroclimatic data with foraging and dietary outcomes.

Tourism Engagement: We gathered official Tanzanian statistical data on international tourism, and tourism patterns in the Ngorongoro Conservation Region, which borders Lake Eyasi (Ministry of National Resources and Tourism, 2025; Ministry of Natural Resources and Tourism, 2023). Although no official data exists on tourism across the entire Hadzabe community, by comparing larger tourism patterns from 2015-2024 we can proxy how Hadzabe opportunities to engage in tourism may have expanded over time.

Dietary Diversity: Dietary diversity was assessed using presence-absence indicators of locally salient food categories derived from 24-hour recall data. Foods were classified into eight categories reflecting both subsistence and market-based sources: (1) tubers; (2) game meat; (3) honey; (4) wild fruits; (5) agricultural starches; (6) agricultural produce; (7) domesticated or minimally processed animal products (e.g., goat meat; chicken eggs; dried fish); and (8) processed foods. These categories were developed inductively based on food classifications used by participants during dietary recall interviews and are consistent with distinctions between wild and non-wild food sources used in comparable research (e.g., Reyes-Garcia et al., 2019).

For each participant, consumption of any item within a category was coded as present (1) or absent (0), generating a set of binary indicators for each recall. These indicators were then summed up to produce three dietary diversity measures. Firstly, a wild food diversity score (range: 0-4) summed the number of wild-sourced foods consumed (e.g., tubers, game meat, honey, wild fruits). Second, a non-wild food diversity score (range: 0-4) captured the number of agricultural and processed food categories consumed (e.g., agricultural starches, agricultural produce, domesticated/minimally processed animal products, processed foods). Finally, a total dietary diversity score (range: 0-8) was calculated as the sum of all food categories. This approach allows for the assessment of overall dietary diversity while also distinguishing between contributions from wild and non-wild foods, enabling evaluation of whether dietary change reflects substitution, expansion, or uneven shifts across domains.

We analyzed three cross-sectional samples of Hadzabe adults collected during the June-July dry seasons of 2015, 2019, and 2025 using consistent field protocols. Data were collected in the same broad residential regions across years, but from different individual participants (i.e., repeated cross-sections rather than paired longitudinal follow-up). Participants were classified by residential context as

living in either bush camps (≥1-day walking from routine market access) or village-adjacent camps (≤0.5-day walking to markets).

Community Partnership and Ethics: Research was conducted in partnership with community-based Hadzabe organizations within a community-based participatory research (CBPR) framework across 2015, 2019, and 2025 among n=202 Hadzabe participants (m=101, f=101). Community meetings were held prior to data collection in each residential area to describe study goals, procedures, data use, compensation, and to invite feedback. Oral consent was obtained from all participating adults (≥18 years). Interviews were conducted privately with trained researchers and Hadzabe collaborators fluent in Hadzane, Kiswahili, and English. All procedures were approved by XXX.

RESULTS

Dietary data from 2015, 2019, and 2025 were analyzed as repeated cross-sectional samples using presence-absence indicators for locally defined food categories and dietary diversity scores for wild, agricultural-processed, and total dietary diversity. Due to the non-normality of dietary data, non-parametric tests were used throughout. Differences in category-level proportions (count based) across study years were assessed using Fisher-Freeman-Halton tests, followed by Bonferroni-corrected pairwise comparisons. Differences in beverage volumes, and dietary diversity scores were assessed using Kruskal-Wallis tests with Bonferroni corrected Mann-Whitney U post-hoc comparisons. Sex- and residence-based differences were assessed using Fisher's exact tests for categorical variables and Mann-Whitney U tests for continuous or count-based variables. Hydroclimatic variables from 1981–2025 were summarized relative to a 1981–2010 baseline; linear regression was used to assess trends in annual central tendency, intra-annual variability, and counts of severe anomalies, with Durbin-Watson statistics used to evaluate autocorrelation. Demographic and tourism indicators were interpreted descriptively. All statistical analyses were performed in IBM SPSS v. 26.

Presence-absence data across 2015, 2019, and 2025 indicate clear changes in the composition and breadth of reported foods. The number of reported tubers, wild fruit, and honey species increased in 2025, while the number of reported wild game species declined over time. Agricultural produce diversity expanded substantially in 2025 following a decline in 2019. Domesticated animal products and commercially available dried fish (*dagaa*) also increased, with the greatest number of items reported in 2025. In contrast, agricultural staples remained limited to maize and rice across all years. Processed foods and beverages increased in diversity over time, with broader reporting of sweetened and commercially prepared items in 2025 (Table 1; item - and species-level changes are provided in Online Resource 1).

Wild plant consumption increased markedly in 2025. The proportion of individuals reporting tubers rose from 0.33 (2015) and 0.39 (2019) to 0.77 in 2025 ($p < 0.001$). Wild fruit consumption increased to 0.97 (vs. 0.74 in 2015 and 0.55 in 2019; $p < 0.001$), and honey more than doubled (0.51 vs. 0.18 and 0.10; $p <$

0.001). In contrast, game consumption declined from 2015 to 2019 and remained low in 2025 (0.60 vs. 0.35; $p < 0.001$) (see Table 1).

Agricultural and market foods also increased in 2025. Maize rose to 0.86 (vs. 0.55 in 2015 and 0.33 in 2019; $p < 0.001$) and produce increased nearly tenfold (0.37 vs. 0.03 and 0.02, $p < 0.001$). Domesticated animal-source foods and (commercially available) fish showed no significant overall differences, although *dagaa* (commercially dried fish) appeared more frequently in 2025 (Online Resource 1). Processed food consumption rose to 0.60 (vs. 0.20 and 0.18; $p < 0.001$), with emergence of sweetened beverages (0.28 vs. 0; $p < 0.001$) and increased alcohol reporting ($p = 0.016$) Additionally, 2025 has the largest mL intake of both sweetened beverages and alcohol (see Table 1).

Table 1
Proportion of participants reporting consumption (presence in 24-hr recalls) and mean number of species/items reported across major food categories 2015–2025

Tubers	**2025**	**2019**	**2015**	**Omnibus Test Statistics[+]**	**Pairwise Comparisons (Bonferroni Corrected sig = 0.0167)**
	0.77	**0.39**	**0.33**	**34.3*** **	**2015 v 2025: p < 0.001 2019 v 2025: p < 0.001**
No. Tuber Species	1.22	0.43	0.51	**45.65*** **	2015 v. 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
Game Meat	0.35	0.35	0.6	**12.06** **	2015 v 2019: **p = 0.006** 2015 v 2025: **p = 0.002**
No. Game Species	0.36	0.37	0.63	**12.39** **	2015 v 2019: **p = 0.007** 2015 v 2025: **p = 0.002**
Wild Honey	0.51	0.1	0.18	**32.10*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
No. Wild Honey Species	0.6	0.08	0.22	**42.20*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
Wild Fruits	0.97	0.55	0.74	**37.91*** **	2015 v 2025: **p < 0.001**

Tubers	**2025**	**2019**	**2015**	**Omnibus Test Statistics[+]**	**Pairwise Comparisons (Bonferroni Corrected sig = 0.0167)**
	0.77	**0.39**	**0.33**	**34.3*** **	**2015 v 2025: p < 0.001 2019 v 2025: p < 0.001**
					2019 v. 2025: **p < 0.001**
No. Wild Fruit Species	2.18	0.9	1.21	**33.24*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
Agricultural Staple Starches	0.86	0.33	0.56	**39.39*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001** 2019 v 2015: **p = 0.013**
Agricultural Produce	0.37	0.02	0.04	**39.60*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
No. Agricultural Produce Species	0.64	0.02	0.1	**40.98*** **	2015 v 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
Agricultural animal products and fish	0.14	0.04	0.1	3.51	No significant differences

Tubers	**2025**	**2019**	**2015**	**Omnibus Test Statistics[+]**	**Pairwise Comparisons (Bonferroni Corrected sig = 0.0167)**
	0.77	**0.39**	**0.33**	**34.3*** **	**2015 v 2025: p < 0.001 2019 v 2025: p < 0.001**
No. Domesticated animal and fish products	0.17	0.04	0.1	3.69	No significant differences
Processed Food	0.6	0.18	0.25	**31.89*** **	2015 v 2025: **p < 0.001** 2019 v. 2025: **p < 0.001**
No. Processed food products	0.78	0.18	0.25	**40.09*** **	2015 v. 2025: **p < 0.001** 2019 v 2025: **p < 0.001**
Alcohol (mean mL intake)	418.14	40.86	245.73	**10.93** **	2015 v. 2025: **p = 0.010** 2019 v. 2025: **p = 0.005**
Sweetened Beverages (mean mL intake)	214.74	0	0	**39.91*** **	2015 v. 2025: **p < 0.001** 2019 v 2025: **p < 0.001**

+ Fisher-Freeman-Halton tests were used for proportions (counts); Kruskal-Wallis H tests were used for volumes

* $p \leq 0.05$

** $p \leq 0.01$

*** p < 0.001

Dietary diversity varied significantly across study years in both wild and non-wild domains (Table 2). Wild dietary diversity (0–4) was highest in 2025 (Mean = 2.60), compared to 1.86 (2015) and 1.39 (2019) (H = 43.47, p < 0.001), with 2025 significantly higher than both prior years. Agricultural-processed dietary diversity (0–4) also increased sharply in 2025 (mean = 1.97 vs. 0.95 and 0.57; H = 59.28, p < 0.001). Total dietary diversity (0–8) followed the same pattern (2025: 4.58; 2015: 2.79; 2019: 1.96; H = 94.62, p < 0.001), with all pairwise comparisons significant and 2019 lowest overall (Table 2).

Table 2
Comparison of Dietary Diversity scores across 2015, 2019, and 2025

Mean Values	**2025**	**2019**	**2015**	**Statistical Differences (Kruskal-Wallis)**	**Post-Hoc Pairwise Comparisons (Bonferroni corrected sig = 0.0167)**
Wild DDV (0–4)	2.6	1.39	1.86	**43.47*** **	2019 v 2025: **p < 0.001** 2015 v 2025: **p < 0.001**
Agricultural-Processed DDV (0–4)	1.97	0.57	0.95	**59.28*** **	2019 v 2025: **p < 0.001** 2015 v 2025: **p < 0.001**
Total DDV (0–8)	4.58	1.96	2.79	**94.62*** **	2015 v 2019: **p = 0.004** 2019 v 2025: **p < 0.001** 2015 v 2025: **p < 0.001**

Women were less likely than men to report honey consumption overall, with differences present in 2015 (p = 0.006) and 2025 (p = 0.012) but not 2019. Sex differences in total dietary diversity were observed only in 2015 (men higher; U: 458.5, p = 0.018), with no differences in later years. No other consistent sex-based differences were observed.

Dietary intake varied by residential context. Across all years, bush camp residents were more likely to report honey and wild fruit consumption (both p < 0.001) and had higher wild dietary diversity (2.44 vs. 1.56; U: 2962.0, p < 0.001) and total dietary diversity (3.69 vs. 2.80; U:3651.5, p < 0.001). They also reported more produce consumption (p = 0.0014).

In 2015, bush camps showed higher honey and wild fruit consumption (both p < 0.001), lower agricultural starch and processed food intake (p = 0.002), and no alcohol use, with higher wild but lower agricultural-processed diversity. In 2019, bush camps again showed higher wild fruit consumption, while village-adjacent camps had higher agricultural-processed diversity (p = 0.042). In 2025, bush camps showed higher honey (p < 0.001) and produce (p = 0.014) consumption, greater alcohol use (p = 0.029), higher alcohol volume (536.1 vs. 168.0 mL; U: 474.5, p = 0.025), and higher wild (2.83 vs. 2.12; U:392.5, p = 0.002) and total dietary diversity (4.89 vs. 3.92; U: 389.0, p = 0.003).

Ecological Data

To contextualize environmental conditions during focal study years, monthly rainfall data from 1981–2025 were analyzed relative to a 30-year climatological historic baseline (1981–2010). Baseline monthly rainfall exhibited strong seasonality, and descriptive statistics for mean and standard deviation are reported in Supplemental Materials Comparable descriptive summaries for focal study years (2015, 2019, and 2025) and the year preceding the focal study (2014, 2018, and 2024). At the annual scale, rainfall did not exhibit a statistically significant linear trend from 1981–2025 (= 0.361 mm/year, F = 0.053, p = 0.818). Intra-annual variability also showed no significant temporal trend. Regression of annual standard deviation of monthly rainfall over year yielded a non-significant relationship (= -0.051, F = 0.062, p = 0.806; R^2 = 0.001; Durbin-Watson = 2.183).

To assess changes in rainfall extremes, monthly anomalies were standardized relative to the historic baseline (1981–2010). Months exceeding ± 1.5 standard deviations were classified as severely or extremely anomalous. Across the full record, both severe wet and severe dry months were rare. Linear regression of annual counts of severely wet months showed no significant trend over time (= -0.006, F = 0.237, p = 0.628; R^2 = 0.005; Durbin-Watson = 2.162). Similarly, annual counts of severely dry months exhibited no significant trend (= -0.003, F = 0.534, p = 0.469; R^2 = 0.012; Durbin-Watson = 1.947).

Contextualizing preceding and focal study years within the long-term distribution further illustrates climatic variability across the study period. In 2014 and 2015, annual rainfall totaled 584.67 mm (59th percentile) and 545.12 mm (45th percentile), respectively, with relatively low variability (41st and 32nd percentiles), indicating near-average conditions. In contrast, 2018 and 2019 were comparatively wetter and more variable, with rainfall totals of 778.43 mm (91st percentile) and 684.12 mm (84th percentile), and variability in the 95th and 77th percentiles, respectively; 2018 also included two severely wet months. More recent years show continued interannual fluctuation: 2024 recorded 640.84 mm of rainfall (75th percentile) with moderate variability (57th percentile) and one severely wet month, whereas 2025 recorded 500.24 mm (18th percentile) with relatively low variability (30th percentile). Together, these findings indicate that focal study periods capture short-term climatic variability, but do not reflect a consistent directional shift in rainfall magnitude or variability over time relative to the late 20th-century baseline.

Soil Moisture

To assess long-term changes in landscape water availability, monthly MERRA-2 profile soil moisture (GWETPROF) values were aggregated into annual mean soil moisture estimates for 1981–2025. Linear regression analysis indicated a statistically significant positive trend in annual mean soil moisture over time (B = 0.001 units/year, F = 11.18, p = 0.002), with year explaining approximately 20.6% of the variance in annual soil moisture (R^2 = 0.206). Durbin-Watson statistics (1.64) suggested no substantial autocorrelation in annual residuals. Across the 45-year record, this corresponds to an approximate increase of 0.045 units in mean soil moisture, consistent with observed differences between early and recent years. These findings indicate an upward trend in root-zone soil wetness over the study period

(7.4% higher, 0.58 vs. 0.54). Looking at increases in soil moisture in recent years (2011–2025) compared to the 30-year historic baseline (1981–2010); we see a modest 7.4% relative increase over time; which is an absolute jump from a baseline average of 0.54 to 0.58. To assess whether intra-annual variability in soil moisture changed over time, annual standard deviations of monthly soil moisture were regressed against year (1981–2025). This model did not yield a statistically significant trend ($F = 2.20$, $p = 0.127$, $R^2 = 0.053$).

To assess whether the occurrence of extreme soil moisture conditions changed, monthly soil moisture values were standardized relative to the 1981–2010 climatological historic baseline. Z-scores were calculated as the number of standard deviations each monthly observation deviated from the 1981–2010 baseline monthly mean, enabling comparison of anomalously wet or dry conditions across the full record (1981–2025). Months exceeding ± 1.5 standard deviations were classified as severely anomalous. Annual counts of severe soil moisture anomalies were calculated by summing monthly exceedances within each calendar year. Across the full record, severe wet soil moisture months ($n = 74$) were substantially more common than severe dry months ($n = 4$), indicating pronounced asymmetry in soil moisture anomalies. Linear regression of annual counts of severely wet soil moisture months over time indicated a statistically significant positive trend ($B = 0.082$ months/year, $F = 7.81$, $p = 0.008$), with year explaining approximately 15.4% of the variance in annual severe wet soil moisture counts ($R^2 = 0.154$). Durbin-Watson statistics indicated no substantial autocorrelation in annual residuals. These findings suggest that increases in mean soil moisture over time have been accompanied by a modest rise in the frequency of severely wet soil moisture months.

Contextualizing focal study years alongside their immediately preceding years highlights short-term variation within the broader range of observed conditions. In 2014 and 2015, mean soil moisture values were 0.5375 (39th percentile) and 0.5483 (57th percentile), respectively, with relatively low variability (25th and 39th percentiles), indicating near-average conditions. In contrast, 2018 and 2019 were characterized by higher soil moisture levels, with mean values of 0.6333 (98th percentile) and 0.5650 (70th percentile), and elevated variability (89th and 64th percentiles), suggesting comparatively wetter and more variable conditions. More recent years show continued interannual fluctuation: 2024 recorded high soil moisture (0.605; 91st percentile) and high variability (95th percentile), while 2025 remained relatively elevated in mean soil moisture (0.5925; 86th percentile) with moderate variability (66th percentile)

Temperature

To assess long-term changes in near-surface air temperature, monthly MERRA-2 air temperature at 2 meters (T2M) was aggregated into annual mean temperature estimates for 1981–2025. Linear regression of annual mean temperature against year did not yield a statistically significant trend ($F = 0.035$, $R^2 = 0.001$), with year explaining less than 0.1% of the variance in mean temperature. These findings indicate that mean near-surface air temperature remained statistically stable over the study period.

Linear regression analysis of annual mean maximum temperature (T2M_MAX) against year did not reveal a statistically significant trend ($F = 2.09$, $p = 0.155$, $R^2 = 0.046$). The estimated slope was slightly negative (= −0.013°C/year), indicating a small, non-significant decrease in daytime maximum temperature over the study period. Overall, maximum daytime temperatures remained statistically stable across 1981–2025. In contrast to mean and maximum temperatures, annual mean minimum temperature (T2M_MIN) exhibited a statistically significant positive trend over time. Linear regression analysis indicated that minimum temperature increased by approximately 0.017°C per year ($F = 14.39$, $p < 0.001$), with year explaining 25.1% of the variance in annual minimum temperature ($R^2 = 0.251$). Durbin-Watson statistics (1.88) indicated no substantial autocorrelation in annual residuals. Across the 45-year record, this corresponds to an approximate increase of 0.75–0.80°C in nighttime minimum temperatures. These findings indicate a statistically significant rise in modeled nighttime minimum temperatures over the study period.

To evaluate whether asymmetric warming occurred over time, annual diurnal temperature range (DTR), calculated as the difference between annual mean maximum and minimum temperatures, was regressed against year. This analysis yielded a statistically significant negative trend (= −0.030°C/year, $F = 13.71$, $p < 0.001$), with year explaining approximately 24.2% of the variance in DTR ($R^2 = 0.242$). Durbin-Watson statistics (1.56) indicated no substantial autocorrelation in annual residuals. Across the 45-year record, this corresponds to a reduction of approximately 1.3°C in diurnal temperature range, consistent with increases in nighttime minimum temperatures rather than changes in daytime maximum.

To contextualize environmental conditions during focal study years, annual mean, maximum, and minimum temperatures, along with diurnal temperature range (DTR), were examined relative to the long-term distribution (1981–2025). Focal years and their preceding years exhibit substantial interannual variability across temperature components rather than a consistent directional pattern. In 2014–2015, mean temperatures were relatively elevated (73rd-82nd percentiles), with moderately high maximum and minimum temperatures and relatively compressed diurnal ranges. In contrast, 2018 was notably cooler across multiple metrics (2nd percentile for both mean and maximum temperature), with reduced diurnal range, while minimum temperatures remained closer to average. Conditions in 2019 shifted toward warmer patterns, particularly in mean and minimum temperatures (75th and 93rd percentiles), though maximum temperature and diurnal range remained moderate to low. More recent years continue to reflect variability: 2024 combined relatively high mean and minimum temperatures (68th and 98th percentiles) with lower maximum temperature and reduced diurnal range, whereas 2025 showed more moderate mean and maximum temperatures, lower minimum temperature (23rd percentile), and a relatively higher diurnal range. Overall, these patterns indicate that focal study periods capture short-term variability across multiple dimensions of the temperature regime.

Tourism

Data from the Maliasili Statistical Bulletin (2022, 2024) show fluctuation and post-pandemic expansion in Tanzania's tourism sector over the past decade. International arrivals remained relatively high in both 2018 and 2019 prior to the pandemic collapse and rebounded sharply between 2021 and 2024. By 2024, Tanzania recorded 2.14 million international arrivals and USD 3.9 billion in tourism receipts. This substantially exceeded pre-pandemic levels (see Table 5).

International visitation to the Ngorongoro Conservation Area, which borders the Hadzabe community, increased from 391,030 arrives in 2017 to 445,283 in 2019. Following the pandemic slump (122,228 in 2020), tourism rates subsequently rebounded to 611,139 in 2024 – the largest number on record. Although the proportion of visitors participating in Hadzabe cultural tourism is unknown, these patterns indicate substantial expansion in regional tourism prior to 2025 dietary data collection.

Table 5
Tourism data for Tanzania and the Ngorongoro Conservation Area

(source: Maliasili Statistical Bulletin, 2022 and 2024)

Year	Tanzania Intl. Arrivals	Annual Change (%)	Tourism Receipts (USD mil)	Receipts Change (%)	Ngorongoro Intl. Arrivals	Ngorongoro Annual Change (%)
2014	1,140,156	4.0	2,006.32	11.0	-	-
2015	1,137,182	-0.3	1,901.95	13.8	-	-
2016	1,284,279	12.1	2,131.57	22.9	-	-
2017	1,327,143	3.2	2,258.96	8.6	391,030	-
2018	1,505,702	11.0	2,412.30	16.2	410,574	4.9
2019	1,527,230	1.4	2,604.46	3.5	445,283	8.5
2020	620,867	–59.3	714.59	–73.0	122,228	-72.5
2021	922,692	48.6	1,310.34	84.0	160,877	31.6
2022	1,454,920	57.7	2,527.77	93.3	390,837	142.9
2023	1,808,205	24.3	3,373.83	38.1	515,961	32.0
2024	2,141,894	18.5	3,903.06	15.7	611,139	18.5

DISCUSSION

Hadzabe dietary change from 2015–2025 is best characterized as an uneven transition marked by cross-domain broadening in 2025: wild plants and honey expanded alongside increased agricultural and processed foods, including sweetened beverages and alcohol, while game declined relative to earlier periods. This pattern indicates that wild foods are not changing as a single unit but reflect reconfiguration within the wild food domain rather than uniform erosion. Simultaneously, non-wild foods

expanded substantially, producing a mixed-food system in which market-linked foods increased without displacing wild plants and honey. These findings are consistent with cross-domain dietary broadening rather than linear substitution (Reyes-García et al., 2019; Donders & Barriocanal, 2020; Popkin et al., 2020).

Comparable patterns have been documented among the Baka in Central Africa, where agricultural staples increasingly contribute to caloric intake while wild foods remain important for protein, seasonal buffering, and cultural value (Gallois et al., 2020; Martin et al., 2020). Dietary diversity patterns further underscore the nonlinearity of change: 2019 represents a low-diversity year within an otherwise expanding system, highlighting interannual fluctuation rather than a steady trajectory of increase. This aligns with broader evidence that nutrition transitions vary across time, settlement context, and access to resources rather than following a uniform pathway (Amougou et al., 2022; Dufour & Piperata, 2023).

Residential context remained an important axis of dietary differentiation, but its relationship to market-linked foods shifted over time. Bush camps consistently showed high wild food intake and DDV, yet by 2025 also exhibited increased agricultural produce intake and alcohol consumption. This pattern suggests that market food intake is not structured solely by proximity to markets. Instead, intake may be increasingly shaped by cash access and mobility that decouples “geographic remoteness” from “market accessibility”; a pattern documented in other mixed-subsistence settings (Reyes-García et al., 2019; Donders & Barriocanal, 2020).

This pattern is not inherently “protective” or “harmful” but indicates changing risks and exposures. While diets remain grounded in wild foods, increased consumption of processed foods, sweetened beverages, and alcohol suggests exposure to the metabolic health risks of nutrition transition (Danaei et al., 2013; Dufour & Piperata, 2023; Popkin, 2004, 2021; Popkin et al., 2020). Connecting Hadzabe nutritional patterns to health outcomes will require future studies to explore how the pattern of mixed-subsistence dietary broadening impacts metabolic health. Across small-scale and forest-dependent populations, wild foods are widely recognized as critical components of dietary diversity and micronutrient intake and often function as buffers against periods of food insecurity, even as their availability becomes increasingly constrained (Dounias & Froment, 2011; Fungo et al., 2016).

A key challenge in identifying nutrition transition in mixed-subsistence systems is distinguishing longer-term food-environment change from interannual ecological variability that can shift wild food availability and foraging returns (Reyes-García et al., 2019; Gallois et al., 2021). We therefore used CHIRPS rainfall and MERRA-2 soil moisture and temperature indicators as standardized, multi-decadal data to evaluate whether the hydroclimatic indicators correspond to observed dietary shifts.

Hydroclimatic indicators showed limited correspondence with dietary change. Rainfall exhibited no long-term trend, while soil moisture increased and temperature patterns reflected rising nighttime temperatures alongside substantial interannual variability, an asymmetric warming pattern consistent with regional findings in East Africa (Collins, 2011; King’uyu et al., 2000; Thorne et al., 2016). Although 2025 coincided with relatively wet conditions in some metrics (particularly soil moisture), these signals

do not align consistently with observed dietary patterns. This lack of convergence suggests that coarse hydroclimatic indicators alone are insufficient to explain dietary change. Instead, they highlight the importance of access, mobility, and market-linked pathways that mediate how environmental conditions are experienced and translated into food consumption.

These findings also reflect scale mismatch: gridded hydroclimatic data does not capture the fine-grained ecological variability, phenology, and access constraints that structure daily foraging decisions and returns for small camps with averaging foraging radii under 10 km (Harris et al., 2024; Turner et al., 2003). As a result, dietary change is unlikely to reflect climatic conditions alone. Comparative work in low- and middle-income countries similarly demonstrates that the relationship between rainfall variability and nutrition is often inconsistent or mediated through complex pathways, such as agricultural productivity, vulnerability to infectious disease, and infrastructure (Mank et al., 2021; Niles et al., 2021; Ssentongo et al., 2020). Empirical studies further suggest that even when precipitation is associated with dietary diversity, effects may be lagged and context specific (Niles et al., 2021; Omiat & Shively, 2020). Instead, the primary contribution of the hydroclimatic analysis is interpretive: it provides an environmental backdrop and clarifies the limits of coarse ecological proxies for explaining dietary change in a highly patchy, access-mediated food environment (Bateson, 1976; Gallois et al., 2020; Turner et al., 2003).

Regional tourism trends partially align with observed dietary patterns across all study years. Tourism activity was already relatively high prior to 2019, despite 2019 representing the lowest-diversity dietary period in the study. However, the scale of post-pandemic tourism expansion was substantially greater than pre-pandemic levels, particularly within the Ngorongoro region. These shifts may have intensified opportunities for episodic cash access and market engagement within the broader regional food environment. Ethnographic research has demonstrated that Hadzabe cultural tourism provides an important entry point for cash access (Crittenden et al., 2017; Mollel, 2020; Yatsuka, 2015, 2018). Therefore, tourism is best understood as one likely mechanism reconfiguring dietary intake via increased access to agricultural and market-linked goods, particularly in the wake of a large post-COVID tourism rebound.

This study has several limitations that should be considered when interpreting the findings. First, dietary intake was assessed using 24-hour recalls, which provide high-resolution snapshots of consumption but do not capture day-to-day variation in food intake. In foraging systems where some foods are highly variable (Marlowe and Berbesque 2009), short-term fluctuations in resource availability, sharing, and mobility can produce variation that is not fully captured in single-day recall measures. Relatedly, 24-hour recalls are subject to recall bias, including underreporting, omission of items, and misremembering (Sedgwick, 2012). This may be particularly challenging in a foraging context, where some wild foods are consumed opportunistically in the bush prior to redistribution at home (O'Connell et al., 2024). The use of the multi-pass method, locally trained research collaborators, and culturally salient prompts likely improved recall completeness (Gibson et al., 2017). Importantly, consistent methods (and the same local research collaborators) were employed across study periods. Additionally, dietary data were analyzed

using presence-absence indicators of domain diversity rather than quantitative intake. As such, increases in dietary diversity should not be interpreted as equivalent to improvements in nutritional status or nutritional health; these factors should be explored in future studies.

Hydroclimatic data derived from CHIRPS and MERRA-2 operate at spatial and temporal scales that do not fully correspond to the fine-grained ecological heterogeneity that structured daily foraging decisions. The limited correspondence observed between ecological data and dietary change likely reflects both scale mismatch and highlight a key methodological lesson: understanding how environmental variability shapes diet requires approaches that operate at the scale of lived experience. Future research should prioritize integrating ethnoecological methods that document how communities perceive, classify, and identify environmental change, particularly local variation in resource distribution, phenology, and constrained access (Bateson, 1976; Pancorbo-Olivera et al., 2024; Wolverton et al., 2023). Pairing such approaches with dietary data would allow more precise alignment between ecological measurement and food acquisition, improving the ability to identify when and how environmental conditions meaningfully influence diet in highly patchy, access-mediated systems.

CONCLUSION

Taken together, these findings show that contemporary Hadzabe dietary change from 2015–2025 is not a linear erosion of wild subsistence, but a reconfiguration of a flexible food system. The 2025 data illustrate clear cross-domain dietary broadening: increased wild plant and honey consumption occurred alongside substantial expansion of agricultural and processed foods, including sweetened beverages and alcohol, while game declined relative to earlier periods. Rather than moving uniformly away from wild foods, different domains shifted in distinct directions, producing a mixed-subsistence system that reflects both continuity and change.

Simultaneously, hydroclimatic and tourism indicators provided only partial correspondence with observed dietary patterns. Although modeled soil moisture increased, nighttime temperatures rose, and tourism expanded substantially following the pandemic, these coarse indicators did not map consistently onto fine-grained dietary outcomes across all study periods. This mismatch highlights an important methodological insight: broad ecological and economic indicators may help contextualize changing food environments, but they incompletely capture how environmental and economic change are mediated through access, mobility, settlement patterns, and daily provisioning decisions. Tourism represents one potential pathway through episodic cash access and shifting settlement dynamics, but it does not appear to operate in a uniform way across time. More research is needed to explore how tourism operates in the community on a fine-grained level.

More broadly, the Hadzabe case supports approaches to nutrition transition that conceptualize transition as heterogeneous food-environment reconfiguration rather than linear substitution. It also demonstrates both the value and limitations of pairing dietary data with coarse ecological and economic proxies. Future research should build on this approach by integrating ethnoecological and access-focused

methodologies capable of capturing environmental variability and food availability at the scale of lived experience, where dietary decisions are made.

Declarations

Funding:

This research was supported by two Wenner Gren Foundation grants

(#10994 and #9780).

Competing Interests: The authors declare no conflict of interest.

Ethics Statement: All procedures involving human participants were approved by the

Institutional Review Board at the lead university and by the Tanzanian

Commission for Science and Technology (COSTECH), as well as local district

authorities in Tanzania. All methods were reviewed and approved by the Hadzabe

community.

Author Contribution

MCK and ANC conceptualized the study. MCK conducted data collection and analysis and wrote the first draft of the manuscript. IAM and ESE contributed to study design, conducted data collection, contributed to data interpretation, and reviewed manuscript. ANC obtained university human research subjects approval, obtained all Tanzanian research permits and permission, contributed to data analysis, and reviewed and edited the manuscript.

Acknowledgement

The authors would like to thank the Hadzabe community for their continued collaboration and participation in our research.

Data Availability

Data are not publicly available due to the sensitive nature of Indigenous community data but are available from the corresponding author under appropriate conditions and with community permissions.

References

1. Abera, T. A., Heiskanen, J., Maeda, E. E., & Pellikka, P. K. E. (2020). Land Surface Temperature Trend and Its Drivers in East Africa. *Journal of Geophysical Research: Atmospheres*, *125*(23), e2020JD033446. https://doi.org/10.1029/2020JD033446
2. Amougou, N., Pasquet, P., Bernard, J. Y., Ponty, A., Fotso, M., Said-Mohamed, R., & Cohen, E. (2022). Determinants of energy intake in Central African populations experiencing nutrition transition. *British Journal of Nutrition*, *128*(2), 263–272. https://doi.org/10.1017/S0007114521003159
3. Apicella, C. L., Crittenden, A. N., & Tobolsky, V. A. (2017). Hunter-gatherer males are more risk-seeking than females, even in late childhood. *Evolution and Human Behavior*, *38*(5), 592–603. https://doi.org/10.1016/j.evolhumbehav.2017.01.003
4. Arguez, A., & Vose, R. (2011). The Definition of the Standard WMO Climate Normal: The Key to Deriving Alternative Climate Normals The Key to Deriving Alternative Climate Normals. *Bulletin of the American Meteorological Society*, *92*(6). https://www.jstor.org/stable/26218540?seq=1
5. Bateson, G., & with Internet Archive. (1976). *Steps to an ecology of mind*. Ballantine Books. http://archive.org/details/stepstoecologyof00bate
6. Blurton-Jones, N. (2016). *Demography and Evolutionary Ecology of Hadza Hunter-Gatherers*. Cambridge University Press.
7. Broegaard, R. B., Rasmussen, L. V., Dawson, N., Mertz, O., Vongvisouk, T., & Grogan, K. (2017). Wild food collection and nutrition under commercial agriculture expansion in agriculture-forest landscapes. *Forest Policy and Economics, Forest, Food, and Livelihoods*, *84*, 92–101. https://doi.org/10.1016/j.forpol.2016.12.012
8. Caro, T., Salerno, J. D., Mwalyoyo, J., Fitzherbert, E., & Mulder, B., M (2017). The Consequences of Internal Migration in Sub-Saharan Africa: A Case Study. *BioScience*, *67*(7), 664–671. https://doi.org/10.1093/biosci/bix041
9. Collins, J. M. (2011). *Temperature Variability over Africa*. https://doi.org/10.1175/2011JCLI3753.1
10. Conway, J. M., Ingwersen, L. A., & Moshfegh, A. J. (2004). Accuracy of dietary recall using the USDA five-step multiple-pass method in men: An observational validation study. *Journal of the American Dietetic Association*, *104*(4), 595–603. https://doi.org/10.1016/j.jada.2004.01.007
11. Conway, J. M., Ingwersen, L. A., Vinyard, B. T., & Moshfegh, A. J. (2003). Effectiveness of the US Department of Agriculture 5-step multiple-pass method in assessing food intake in obese and nonobese women12. *The American Journal of Clinical Nutrition*, *77*(5), 1171–1178. https://doi.org/10.1093/ajcn/77.5.1171
12. Crittenden, A. (2016). To Share or Not to Share? Social Processes of Learning to Share Food Among Hadza Hunter-Gatherer Children | SpringerLink. *Social Learning and Innovation in Contemporary Hunter-Gatherers: Evolutionary and Ethnographic Perspectives*, 61–70.
13. Crittenden, A. (2019). Who Owns Poop? And other ethical dilemmas facing an anthropologist who works at the interface of biological research and indigenous rights. *The Secret Lives of Anthropologists: Lessons from the Field*. Routledge.

14. Crittenden, A., & Schnorr, S. L. (2017). Current views on hunter-gatherer nutrition and the evolution of the human diet. *American Journal of Physical Anthropology*, *162*(S63), e23148. https://doi.org/10.1002/ajpa.23148
15. Crittenden, A., Sorrentino, J., Moonie, S. A., Peterson, M., Mabulla, A., & Ungar, P. S. (2017). Oral health in transition: The Hadza foragers of Tanzania. *PLOS ONE*, *12*(3), e0172197. https://doi.org/10.1371/journal.pone.0172197
16. Danaei, G., Singh, G. M., Paciorek, C. J., Lin, J. K., Cowan, M. J., Finucane, M. M., Farzadfar, F., Stevens, G. A., Riley, L. M., Lu, Y., Rao, M., Ezzati, M., & Chronic Diseases Collaborating Group. (2013). & on behalf of the Global Burden of Metabolic Risk Factors of. The Global Cardiovascular Risk Transition. *Circulation*, *127*(14), 1493–1502. https://doi.org/10.1161/CIRCULATIONAHA.113.001470
17. Dinku, T., Funk, C., Peterson, P., Maidment, R., Tadesse, T., Gadain, H., & Ceccato, P. (2018). Validation of the CHIRPS satellite rainfall estimates over eastern Africa. *Quarterly Journal of the Royal Meteorological Society*, *144*(S1), 292–312. https://doi.org/10.1002/qj.3244
18. Donders, I., & Barriocanal, C. (2020). The Influence of Markets on the Nutrition Transition of Hunter-Gatherers: Lessons from the Western Amazon. *Environmental Research and Public Health*, *17*(17), 1–17.
19. Dounias, E., & Froment, A. (2011). From foraging to farming among present-day forest hunter-gatherer. *International Forestry Review*, *13*(3), 294–304.
20. Draper, C. S., Reichle, R. H., & Koster, R. D. (2018). *Assessment of MERRA-2 Land Surface Energy Flux Estimates*. https://doi.org/10.1175/JCLI-D-17-0121.1
21. Dufour, D. L., & Piperata, B. A. (2023). Nutritional Anthropology. *A Companion to Biological Anthropology* (pp. 244–261). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119828075.ch15
22. Fungo, R., Muyonga, J., Kabahenda, M., Kaaya, A., Okia, C. A., Donn, P., Mathurin, T., Tchingsabe, O., Tiegehungo, J. C., Loo, J., & Snook, L. (2016). Contribution of forest foods to dietary intake and their association with household food insecurity: A cross-sectional study in women from rural Cameroon. *Public Health Nutrition*, *19*(17), 3185–3196. https://doi.org/10.1017/S1368980016001324
23. Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations—A new environmental record for monitoring extremes. *Scientific Data*, *2*(1), 150066. https://doi.org/10.1038/sdata.2015.66
24. Gallois, S., Heger, T., van Andel, T., Sonké, B., & Henry, A. G. (2020). From Bush Mangoes to Bouillon Cubes: Wild Plants and Diet among the Baka, Forager-Horticulturalists from Southeast Cameroon. *Economic Botany*, *74*(1), 46–58. https://doi.org/10.1007/s12231-020-09489-x
25. Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A., Gu, W., & Zhao, B. (2017). The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, *30*(Iss 13), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

26. Gibbons, A. (2018). Hadza on the brink. *Science*, *360*(6390), 700–704. https://doi.org/10.1126/science.360.6390.700
27. Gibson, R. S., Charrondiere, U. R., & Bell, W. (2017). Measurement Errors in Dietary Assessment Using Self-Reported 24-Hour Recalls in Low-Income Countries and Strategies for Their Prevention. *Advances in Nutrition*, *8*(6), 980–991. https://doi.org/10.3945/an.117.016980
28. Harris, J., Anyawire, M., Mabulla, A., & Wood, B. (2024). Hadza Landscape Burning. *Human Nature*, *35*, 197–224.
29. Hawkes, K., O´Connell, J. F., & Blurton Jones, N. G. (1991). Hunting income patterns among the Hadza: Big game, common goods, foraging goals and the evolution of the human diet. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *334*(1270), 243–251. https://doi.org/10.1098/rstb.1991.0113
30. Hawkes, K., O'Connell, J., & Blurton Jones, N. (1989). Hardworking Hadza grandmothers. In V. Standen, & R. Foley (Eds.), *Comparative Socioecology: The Behavioral Ecology of Humans and Other Mammals* (Vol. 8, pp. 341–366). Blackwell Scientific Publishing.
31. Hawkes, K., O'Connell, J. F., & Blurton Jones, N. G. (1997). Hadza Women's Time Allocation, Offspring Provisioning, and the Evolution of Long Postmenopausal Life Spans. *Current Anthropology*, *38*(4), 551–577. https://doi.org/10.1086/204646
32. Hawkes, K., O'Connell, J. F., & Blurton Jones, N. G. (2001). Hadza meat sharing. *Evolution and Human Behavior*, *22*(2), 113–142. https://doi.org/10.1016/S1090-5138(00)00066-0
33. Hawkes, K., O'Connell, J. F., & Blurton Jones, N. G. (2014). More Lessons from the Hadza about Men's Work. *Human Nature*, *25*(4), 596–619. https://doi.org/10.1007/s12110-014-9212-5
34. Huff, A. R. (2014). Weathering the Long Wounded Year: Livelihoods, nutrition, and changing political ecologies in the Mikea Forest Region, Madagascar. *Journal of Political Ecology*, *21*(1). Article 1. https://doi.org/10.2458/v21i1.21126
35. Joachim, L., & Zahor, Z. (2022). Hadzabe's Transformation and Livelihood Dynamics: Livelihood Sustainability in the Changing Environment of Yaeda Valley. *Tanzania Journal for Population Studies and Development*, *29*(1), Article 1. https://journals.udsm.ac.tz/index.php/tjpsd/article/view/5093
36. Karanja, A., Ickowitz, A., Stadlmayr, B., & McMullin, S. (2022). Understanding drivers of food choice in low- and middle-income countries: A systematic mapping study. *Global Food Security*, *32*, 100615. https://doi.org/10.1016/j.gfs.2022.100615
37. King'uyu, S., Ogallo, L., & Anyamba, E. (2000). Recent Trends of Minimum and Maximum Surface Temperatures over Eastern Africa. *Journal of Climate*, *13*(16), 2876–2886.
38. Koster, R. D., McCarty, W., Coy, L., Gelaro, R., Huang, A., Merkova, D., Smith, E. B., Sienkiewicz, M., & Wargan, K. (2016). *MERRA-2 Input Observations: Summary and Assessment* (GSFC-E-DAA-TN37524). https://ntrs.nasa.gov/citations/20160014544
39. Kramer, K. L., & Greaves, R. D. (2017). Why Pumé Foragers Retain a Hunting and Gathering Way of Life. In V. Reyes-García & A. Pyhälä (Eds.), *Hunter-gatherers in a Changing World* (pp. 109–126). Springer International Publishing. https://doi.org/10.1007/978-3-319-42271-8_7

40. Leatherman, T., Hoke, M., & Goodman, A. (2016). Local nutrition in global context: Critical biocultural perspectives on the nutrition transition in Mexico. In M. Zuckerman, & D. Martin (Eds.), *New Directions in Biocultural Anthropology* (pp. 49–65). John Wiley & Sons, Ltd.
41. Mabulla, A. Z. P. (2007). Hunting and Foraging in the Eyasi Basin, Northern Tanzania: Past, Present and Future Prospects. *African Archaeological Review*, *24*(1), 15–33. https://doi.org/10.1007/s10437-007-9013-x
42. Mabulla, I. (2012). *Impacts of Climate Change and Other Factors on Hadza Hunter-Foragers of Northern Tanzania*. University of Dar es Salaam.
43. Mahay, F., Valimba, P., Tumbo, M., Izdori, F., & Maketa, L. (2025). Impacts of Climate Variability on Hydrological Response and Water Resources: Case of Little Ruaha Catchment -Tanzania Using Ground and CHIRPS Data. *Tanzania Journal of Engineering and Technology*, *44*(4), 27–38. https://doi.org/10.65085/2619-8789.1044
44. Mank, I., Belesova, K., Bliefernicht, J., Traoré, I., Wilkinson, P., Danquah, I., & Sauerborn, R. (2021). The Impact of Rainfall Variability on Diets and Undernutrition of Young Children in Rural Burkina Faso. *Frontiers in Public Health*, *9*. https://doi.org/10.3389/fpubh.2021.693281
45. Marlowe, F. (2002). Why the Hadza are still hunter-gatherers. In S. Kent (Ed.), *Ethnicity, Hunter-Gatherers, and the Other: Association or Assimilation in Africa* (pp. 247–275). Smithsonian Institution.
46. Marlowe, F. (2010). *The Hadza: Hunter-gatherers of Tanzania*. University of California Press.
47. Marlowe, F., & Berbesque, J. (2009). Tubers as fallback foods and their impact on Hadza hunter-gatherers. *American Journal of Biological Anthropology*, *140*(4), 751–758.
48. Martin, E. A., Brull, G. R., Funk, S. M., Luiselli, L., Okale, R., & Fa, J. E. (2020). Wild meat hunting and use by sedentarised Baka Pygmies in southeastern Cameroon. *PeerJ*, *8*, e9906. https://doi.org/10.7717/peerj.9906
49. McKee, T., Doesken, N., & Kleist, J. (1993). The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology*. American Meteorological Society.
50. Ministry of National Resources and Tourism. (2025). In E. Kohi, K. Mwadua, P. Mwiru, A. Kwitema, J. Msimbano, & B. Osewe (Eds.), *Maliasili Statistical Bulletin*. Ministry of Natural Resources and Tourism.
51. Ministry of Natural Resources and Tourism. (2023). *Maliasili Statistical Bulletin*. The United Republic of Tanzania.
52. Mollel, T. R. (2020). *AN INVESTIGATION OF THE IMPACT OF CHANGE IN NATURAL RESOURCE USE IN HADZA LIVELIHOOD A case of Eyasi Basin* (SSRN Scholarly Paper No. 3732100). https://doi.org/10.2139/ssrn.3732100
53. Mulungu, D. M. M., & Mukama, E. (2023). Evaluation and modelling of accuracy of satellite-based CHIRPS rainfall data in Ruvu subbasin, Tanzania. *Modeling Earth Systems and Environment*, *9*(1), 1287–1300. https://doi.org/10.1007/s40808-022-01555-8

54. Murray, S., Schoeninger, M., Bunn, H., Pickering, T., & Marlett, J. (2001). Nutritional Composition of Some Wild Plant Foods and Honey Used by Hadza Foragers of Tanzania. *Journal of Food Composition and Analysis*, *14*, 3–13.
55. Niles, M., Emery, B., Wiltshire, S., Brown, M., Fisher, B., & Ricketts, T. (2021). Climate impacts associated with reduced diet diversity in children across nineteen countries. *Environmental Research Letters*, *16*, 015010.
56. O'Connell, J., Hawkes, K., & Jones, N. B. (2024). Hadza Men's Follows, 1985–1986: Data and Implications for Ideas About Ancestral Male Foraging Effort in Human Evolution. *PaleoAnthropology*, *2024*(1), 112–138.
57. O'Connell, J., Hawkes, K., & Jones, N. B. (2025). Targeting the Hunting Hypothesis: Review of Evidence From the Hadza. *Evolutionary Anthropology*, *34*(2), e70002. https://doi.org/10.1002/evan.70002
58. Omiat, G., & Shively, G. (2020). Rainfall and child weight in Uganda. *Economics & Human Biology*, *38*, 100877. https://doi.org/10.1016/j.ehb.2020.100877
59. Pancorbo-Olivera, M., Parra-Rondinel, F., Torres-Guevara, J., Cruz-Soriano, A., & Casas, A. (2024). Gathering, agriculture, and exchange: An ethnoecological approach to the study of food patterns and feedstuff sources in communities of the Central Andes, Peru. *Journal of Ethnobiology and Ethnomedicine*, *20*(69). 10.1186/s13002-024-00705-9. https://link.springer.com/article/
60. Piperata, B. A., Scaggs, S. A., Dufour, D. L., & Adams, I. K. (2023). Measuring food insecurity: An introduction to tools for human biologists and ecologists. *American Journal of Human Biology*, *35*(2), e23821. https://doi.org/10.1002/ajhb.23821
61. Pollom, T. (2022). *Hunter-Gatherers in Context: Hadzabe People and Early Nutrition Transition* [Ph.D., University of Nevada, Las Vegas]. https://www.proquest.com/docview/2823400578/abstract/2EFF500127D442F6PQ/1
62. Pollom, T., Cross, C. L., Herlosky, K. N., Ford, E., & Crittenden, A. (2021). Effects of a mixed-subsistence diet on the growth of Hadza children. *American Journal of Human Biology*, *33*(1), e23455. https://doi.org/10.1002/ajhb.23455
63. Pollom, T., Herlosky, K. N., Mabulla, I. A., & Crittenden, A. (2020). Changes in Juvenile Foraging Behavior among the Hadza of Tanzania during Early Transition to a Mixed-Subsistence Economy. *Human Nature*, *31*(2), 123–140. https://doi.org/10.1007/s12110-020-09364-7
64. Popkin, B. (2004). Nutrition Transition: An Overview of World Patterns of Change | Nutrition Reviews. *Nutrition Reviews*, *62*(Supplemental 2), S140–S143.
65. Popkin, B. (2021). Measuring the nutrition transition and its dynamics. *Public Health Nutrition*, *24*(2), 318–320. https://doi.org/10.1017/S136898002000470X
66. Popkin, B., Corvalan, C., & Grummer-Strawn, L. M. (2020). Dynamics of the double burden of malnutrition and the changing nutrition reality—The Lancet. *The Lancet*, *395*(10217), 65–74.
67. Reichle, R., Draper, C., Liu, Q., Girotto, M., Mahanama, S., Koster, R., & Lannoy, G. (2017). *Assessment of MERRA-2 Land Surface Hydrology Estimates*. https://doi.org/10.1175/JCLI-D-16-0720.1

68. Reyes-García, V., Powell, B., Díaz-Reviriego, I., Fernández-Llamazares, Á., Gallois, S., & Gueze, M. (2019). Dietary transitions among three contemporary hunter-gatherers across the tropics. *Food Security*, *11*(1), 109–122. https://doi.org/10.1007/s12571-018-0882-4

69. Safari, J. G., Nkua, A. J., & Masanyiwa, Z. S. (2021). Household food security among Hadza hunter-gatherers in Mkalama district, Tanzania. *Agriculture & Food Security*, *10*(1), 20. https://doi.org/10.1186/s40066-021-00293-x

70. Schnorr, S. L., Candela, M., Rampelli, S., Centanni, M., Consolandi, C., Basaglia, G., Turroni, S., Biagi, E., Peano, C., Severgnini, M., Fiori, J., Gotti, R., De Bellis, G., Luiselli, D., Brigidi, P., Mabulla, A., Marlowe, F., Henry, A., & Crittenden, A. (2014). Gut microbiome of the Hadza hunter-gatherers. *Nature Communications*, *5*(1), 3654. https://doi.org/10.1038/ncomms4654

71. Schoeninger, M. J., Bunn, H. T., Murray, S. S., & Marlett, J. A. (2001). Composition of Tubers Used by Hadza Foragers of Tanzania. *Journal of Food Composition and Analysis*, *14*(1), 15–25. https://doi.org/10.1006/jfca.2000.0961

72. Sedgwick, P. (2012). *What is recall bias?* https://doi.org/10.1136/bmj.e3519

73. Ssentongo, P., Ba, D., Fronterre, C., & Chinchilli, V. (2020). Village-level climate and weather variability, mediated by village-level crop yield, is associated with linear growth in children in Uganda. *BMJ Global Health*, *5*, e002696.

74. Thorne, P. W., Menne, M. J., Williams, C. N., Rennie, J. J., Lawrimore, J. H., Vose, R. S., Peterson, T. C., Durre, I., Davy, R., Esau, I., Klein-Tank, A. M. G., & Merlone, A. (2016). Reassessing changes in diurnal temperature range: A new data set and characterization of data biases. *Journal of Geophysical Research: Atmospheres*, *121*(10), 5115–5137. https://doi.org/10.1002/2015JD024583

75. Turner, B. L., Kasperson, R., Matson, P., McCarthy, J., Corell, R., Christensen, L., Eckley, N., Kasperson, J., Luers, A., Martello, M., Polsky, C., Pulsipher, A., & Schiller, A. (2003). A framework for vulnerability analysis in sustainability science. *Proceedings of the National Academy of Sciences of the United States of America*, *100*(14), 8074–8079. https://doi.org/10.1073/pnas.1231335100

76. Vincent, A. S. (1985). Plant foods in savanna environments: A preliminary report of tubers eaten by the Hadza of northern Tanzania. *World Archaeology*, *17*(2), 131–148. https://doi.org/10.1080/00438243.1985.9979958

77. Wolverton, S., Chambers, K., & Veteto, J. (2023). Climate Change and Ethnobiology. *Journal of Ethnobiology*, *34*(3), 273–275.

78. Wood, B. M., Millar, R. S., Wright, N., Baumgartner, J., Holmquist, H., & Kiffner, C. (2021). Hunter-Gatherers in context: Mammal community composition in a northern Tanzania landscape used by Hadza foragers and Datoga pastoralists. *PLOS ONE*, *16*(5), e0251076. https://doi.org/10.1371/journal.pone.0251076

79. Wood, B. M., & Marlowe, F. (2013). Household and Kin Provisioning by Hadza Men. *Human Nature*, *24*, 280–317.

80. Woodburn, J. (1968). Stability and Flexibility in Hadza Residential Groupings. *Man the Hunter* (1st ed., pp. 103–110). Routledge.

81. Wutich, A., & Brewis, A. (2014). Food, Water, and Scarcity: Toward a Broader Anthropology of Resource Insecurity. *Current Anthropology*, *55*(4), 444–468. https://doi.org/10.1086/677311
82. Yatsuka, H. (2015). Reconsidering the Indigenous Peoples in the African Context from the Perspective of current livelihood and its Historic Changes: the case of the Sandawe and the Hadza in Tanzania. *African Study Monographs*, *36*(1), 27–48.
83. Yatsuka, H. (2018). Sustainable Hunting as Commodity: The Case of Tanzania's Hadza Hunter-gatherers. *Globe Journal*, *11*.
84. Zeitler, L., Downs, S., & Powell, B. (2024). Adapting food environment frameworks to recognize a wild-cultivated continuum. *Frontiers in Nutrition*, *11*. https://doi.org/10.3389/fnut.2024.1343021

Figures

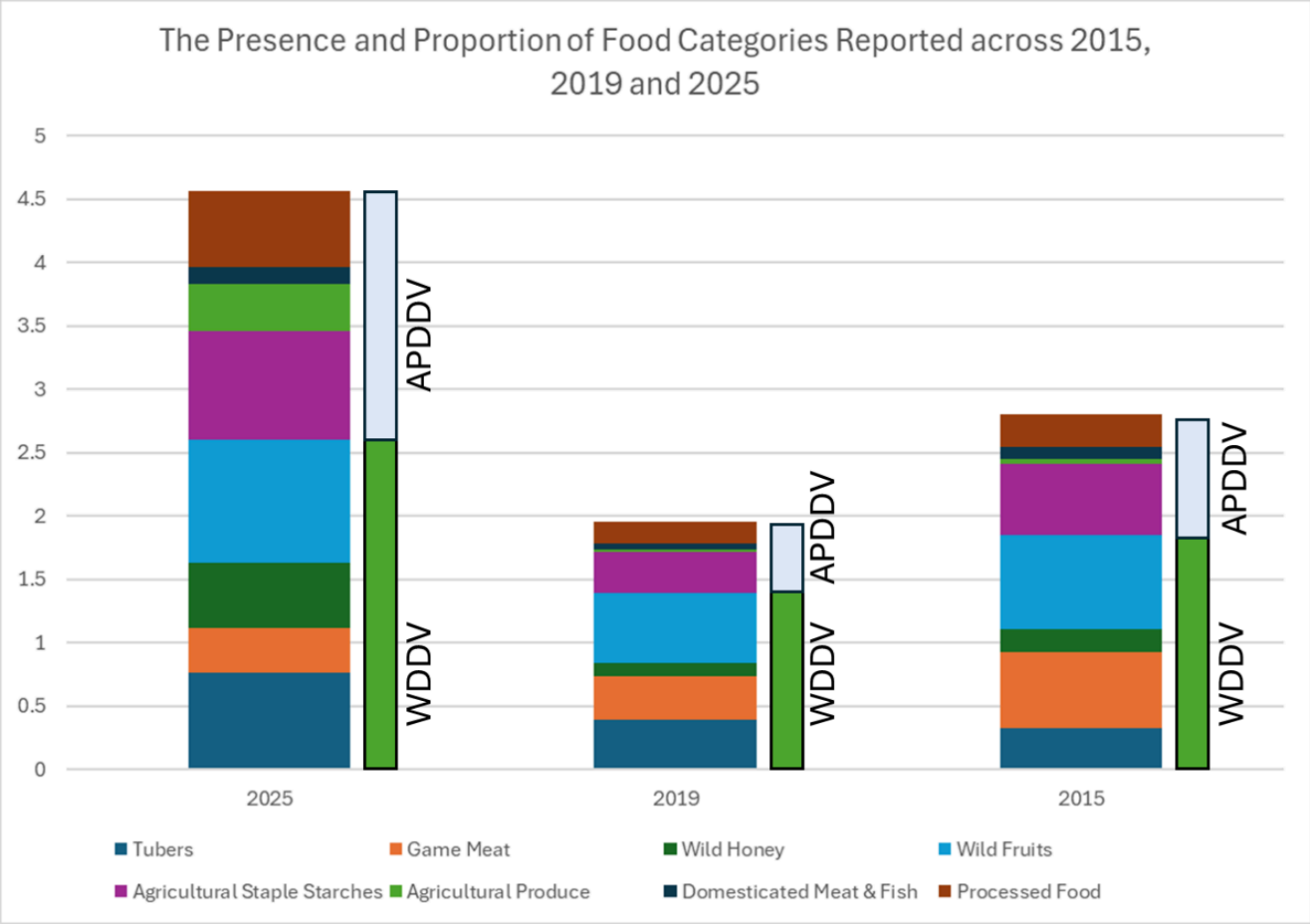


Figure 1

Categorical comparison of food intake across 2015, 2019, and 2025

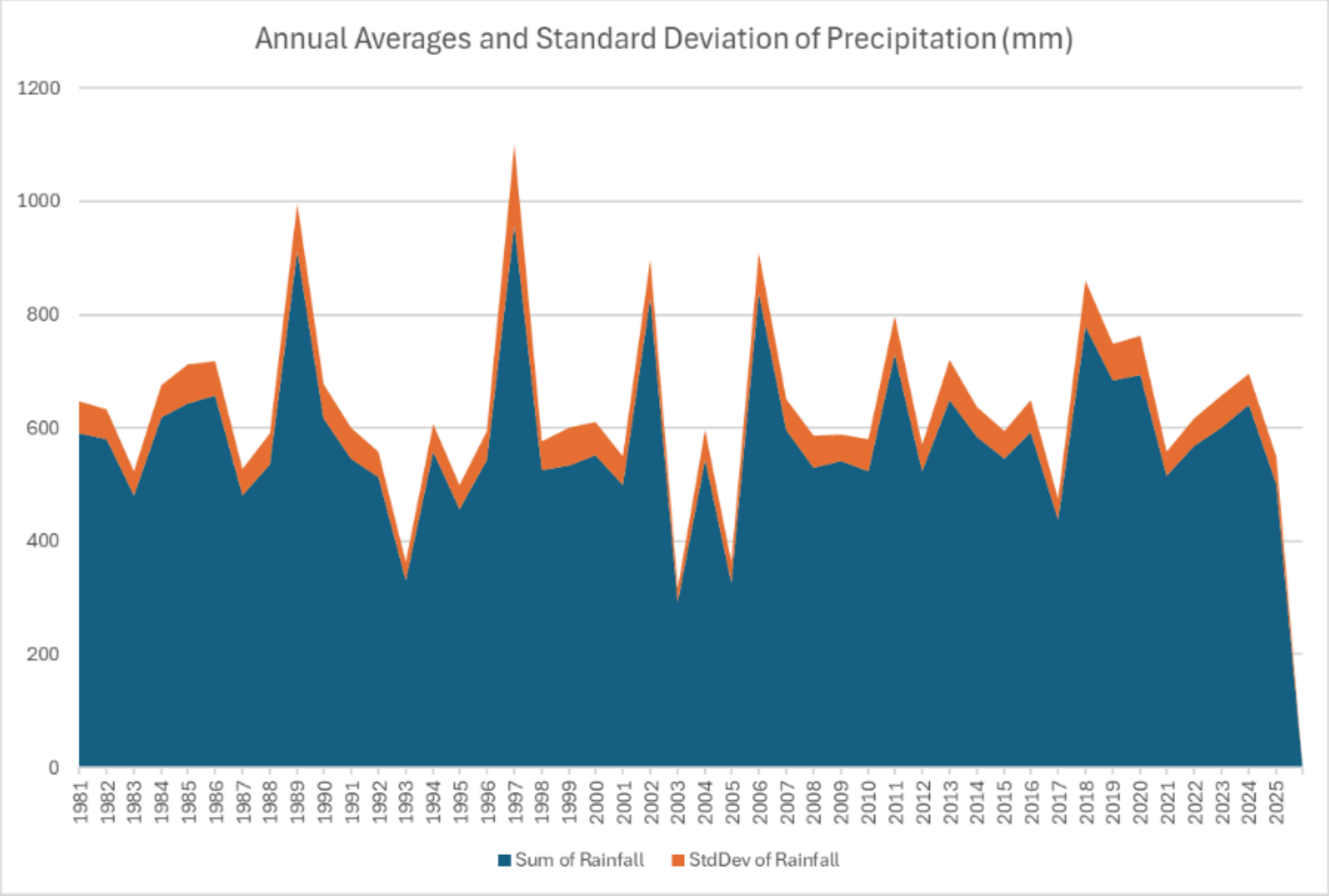


Figure 2

Annual averages and standard deviations of precipitation (mm) from CHIRPS data for Mang'ola, Tanzania

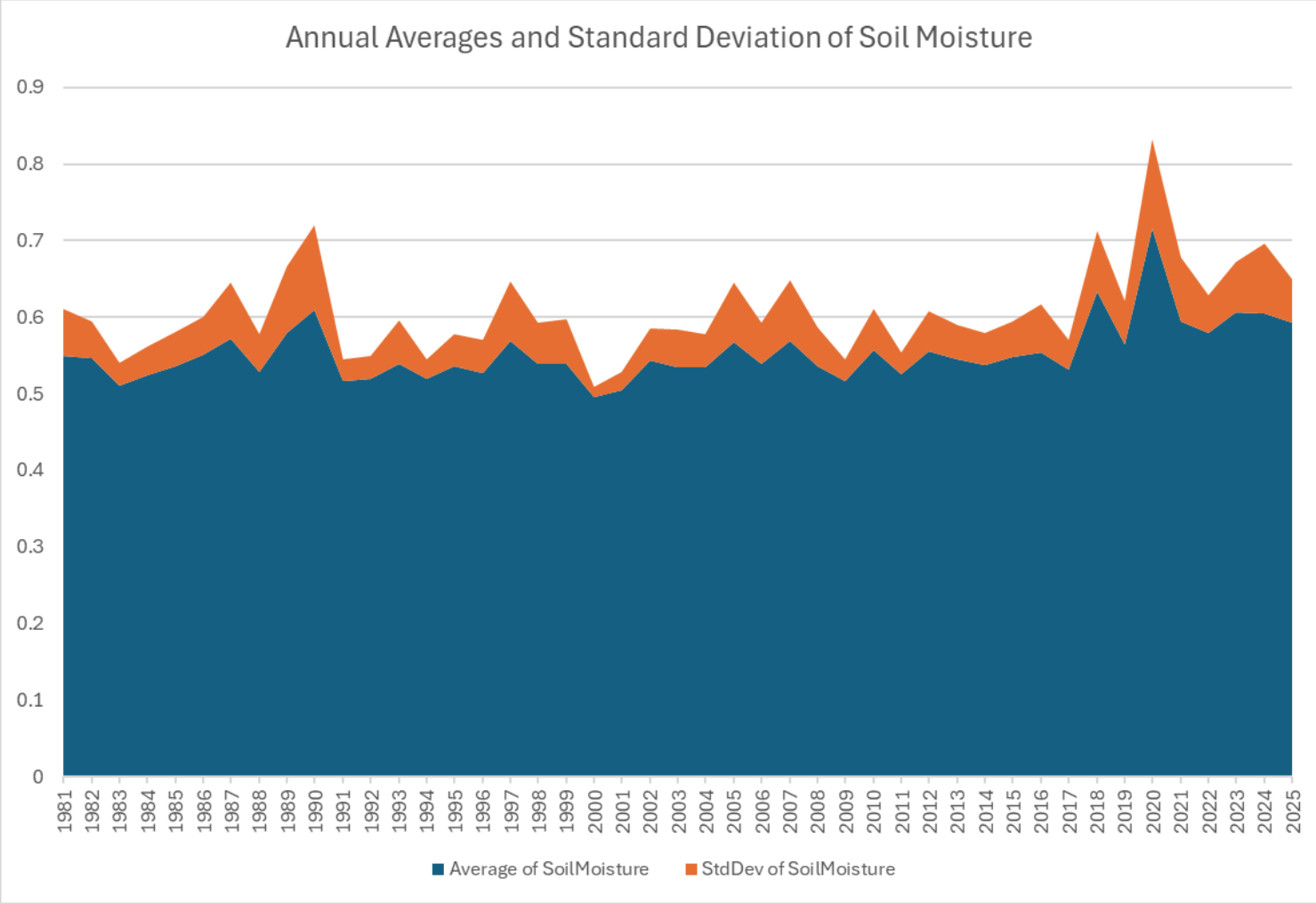


Figure 3

Annual averages and standard deviations of Soil Moisture from MERRA-2 data for Mang'ola, Tanzania

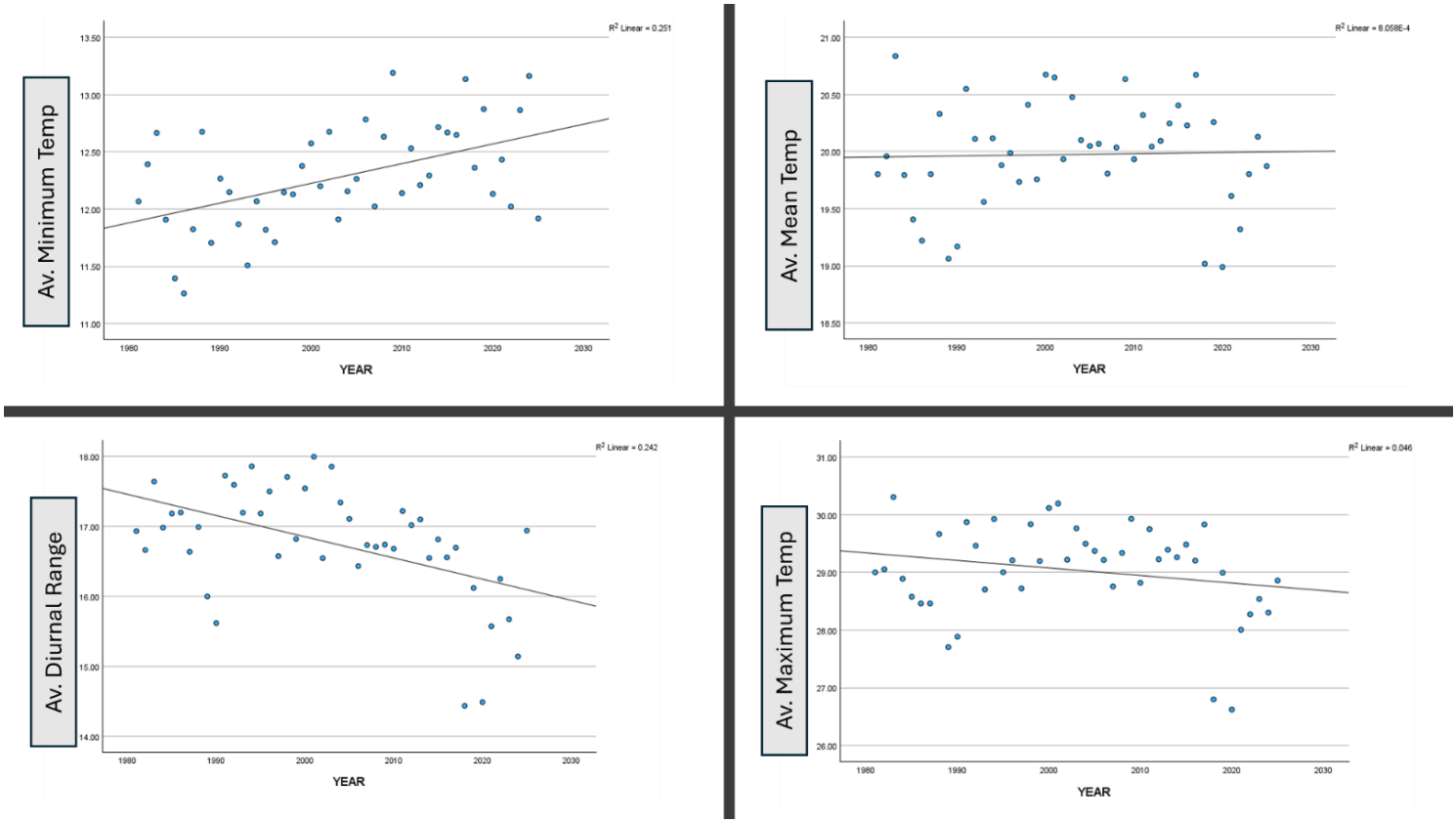


Figure 4

Annual Averages, Maximum (daytime), Minimum (nighttime), and Diurnal Range Temperature (difference between max and min) data from MERRA-2 for Mang'ola Tanzania

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- HumEcoOnlineResource1.xlsx
- HumEcoOnlineResource2.xlsx