Micronutrient constraints on seasonal human mobility

A computational investigation of residential strategy under resource scarcity

Version 1.2 • 24 November 2026 • Phases I–X and publication-preparation study

Abstract

Human seasonal physiology and ecological flexibility are well documented, but the role of selected micronutrients in residential strategy optimisation warrants examination. We compare permanent residence, fixed-base access to complementary habitats, and seasonal relocation using a monthly linear programme. In 144 matched synthetic settings, adding twelve micronutrient floors to four nutritional targets changed five unique winners at a 0.5 percentage-point tolerance, including four migration-to-residence reversals. All occurred under combined stress in one abstract habitat pair. Independent reformulation reproduced 3,840 annual strategy evaluations to numerical precision. A subsequent 100-setting sensitivity study, with 21 additional energy-only comparisons, tested the mechanism against measured-source wild-tuber energy/protein inputs and joint parameter variation. Strict annual mean reversals occurred in 16/36 scarcity-grid settings, 13/21 measured-pair settings and 13/32 jointly varied settings. The mechanism survives several perturbations, but depends on assumed resource caps; the model does not estimate real mobility or nutritional adequacy. The contribution is a reproducible conditional counterexample, not evidence of a new evolutionary mechanism.

Research status

Exploratory theoretical study; not peer reviewed. This consolidated report supersedes the v1.0 conclusions and integrates the v1.1 publication supplement. The original research files and audit remain unchanged. Empirical food availability calibration, full composition verification, demonstrated novelty and independent specialist review remain outstanding. This is a candidate for specialist review before dissemination, not a validated empirical discovery.

Keywords: human behavioural ecology; seasonal mobility; micronutrients; linear programming; resource scarcity; nutritional niche.

AI-assisted analysis and report preparation. No external scientific reviewer or institutional affiliation is claimed.

Research question and prior science

Question: Under what modelled conditions does including micronutrient availability change the predicted preference between permanent residence, ecological boundary residence and seasonal migration? The broader questions of natural habitat and biological seasons motivate the experiment but are not directly tested by it.

Evidence domain	What existing science establishes
Seasonal biology [1–3]	Seasonal gene expression, sleep and endocrine patterns. An autonomous annual clock and obligatory migration instinct remain unproven.
Terrestrial physiology [4–6]	Humans show terrestrial locomotor and cooling adaptations; adjusted water turnover is lower than in other apes. Wet-grip evidence is mixed and cannot identify an ancestral habitat.
Aquatic resource use [7–9]	Early hominin aquatic food exploitation at East Turkana (~1.95 Ma); marine food use by early humans at Pinnacle Point (~164 ka). These do not establish an estuary origin.
Mobility [10–12,27]	Residential mobility is associated with resources, climate, density and storage. Aquatic dependence is not equivalent to coastline proximity or caloric share.
Nutritional ecology [18–20,24–25]	Iodine varies with food webs and local water chemistry; UVB varies seasonally. Floodplain nutritional niches and inland aquatic iodine have prior literature.

Originality

Dietary linear programming predates this investigation [22–23]. Brown et al. explored floodplain nutritional niches [24]; the FORGE model incorporates seasonal hunting and gathering [26]; later work examines micronutrient-driven evolutionary adaptation [28]. The present contribution is a specific matched comparison of residential strategies with and without selected micronutrient floors. The prior searches were targeted, not exhaustive; no priority claim is made.

From habitat hypotheses to a controlled experiment

Phase	Work and final disposition
I–III	156 candidate traits, 14 habitat archetypes, 9 comparative species, 8 hypotheses. Scoping, not a verified comparative phylogenetic test.
IV–V	672 monthly habitat cases; 45 climate scenarios; 432 resource strategy evaluations; 2,000 sensitivity draws. Illustrative energy and travel trade-offs.
VI	80 convenience records; 17 food–nutrient values; 25 winter contribution cases. Descriptive replication, not causal inference.
VII	44 requirement entries; 20 food proxies; 16 modelled targets; 6,720 monthly cases; 216 schedules; 168 iodine thresholds. Nutrient matrices and caps incomplete.
VIII	1,260 annual optimisations; 15,120 monthly outputs. Simplified iodine reserves and UVB; no calibrated physiology.
IX–X	144 matched settings; 6,912 distinct monthly LP calls; 3,840 annual evaluations. Replay, independently reformulated LP, corrections and assumption audit.
Publication preparation	100 additional matched settings; 21 energy-only comparisons; 17,424 LP calls. Measured-source tuber inputs and joint sensitivity; resource caps remain hypothetical.

Relevant earlier findings

A hypothetical 3,000 km annual round trip at 42 kcal/km costs 126,000 kcal. The earlier England–Lisbon climate scenario saves 38,996 kcal of assumed cold surcharge, equivalent to a one-way break-even of approximately 464 km. The cold coefficient is unvalidated; this is not a real migration forecast.

The archived 80-record D-PLACE convenience sample yields Spearman $\rho = -0.517$ for fishing dependence versus residential movement (-0.447 excluding sedentary cases). Median annual movement is 49.9 km in the 50–100% fishing-dependence category versus 318.6 km in the 0–20% category. Variable definitions were checked [11–12]; individual source records were not independently re-transcribed. Geographic clustering, density, storage and selection preclude causal conclusions.

Matched nutritional optimisation

Let x denote non-negative daily food quantities (100 g units), M a 16 × 20 nutrient matrix, t positive reference targets, c additive nutrient credits, G the food-group membership matrix and L monthly caps. Each month maximises q subject to:

$$Mx + c \geq qt;\ Gx \leq L;\ 0 \leq q \leq 1;\ x \geq 0.$$

Provisional energy, animal-retinol, zinc, iodine and protein-energy ceilings are retained. The four-target control enables energy, protein, fat and fibre floors; the expanded model adds twelve vitamin/mineral floors. The score is limiting-reference-target coverage, not health, fitness or survival. Energy is a soft floor scaled by q, not a hard sufficiency constraint. Reference targets are modern dietary standards [13–17].

Strategy	Model representation
A — Permanent	Best of two stationary bases, each with its own monthly food caps.
B — Boundary	Best fixed base with 25% complementary resource-cap blend; extra 2 km/day walking (84 kcal/day).
C — Seasonal	Two six-month stays, 12 departure timings; 25, 100 or 300 km one way. Travel cost 42 kcal/km, assumed 20 km/day and 50% food access loss on travel days.

Monthly scores are weighted by calendar days. An alternative objective selects the schedule with the best worst-month score. Strategies within 0.005 of the maximum are tied; a strict reversal requires different unique winners between target sets.

Original design

Six abstract habitat pairs × two profiles (adult male and early lactation) × four environmental conditions × three distances = 144 matched settings. Conditions: baseline; 60 µg/day iodine from water; 70% food access; combined stress (70% caps, root energy 22 kcal/100 g, protein 0.4 g, fat 0.1 g, no UV credit, water iodine 6.4 µg/day). Neither the pairings nor the monthly resource caps represent measured geographical routes.

Full matrices, nutrient targets, constraints, scripts and software details are supplied in the companion archives.

Verification and principal results

All five archived computational scripts were rerun in Phase X; 42 compared CSV tables, including unchanged inputs, matched exactly. Independent reformulation using HiGHS interior-point optimisation reproduced all 3,840 annual evaluations (maximum mean-score discrepancy 2.2×10^{-15}; worst-month discrepancy 2.8×10^{-14}). This verifies numerical implementation, not empirical validity or independent replication by another researcher.

Metric	Result
Winner sets changed	111/144 (101 overlapping changes, 5 disjoint changes without two unique winners, 5 strict reversals).
Strict reversals	4 migration → residence; 1 boundary → residence; all in wooded savannah/lakeshore combined stress.
Threshold sensitivity	16 at numerical tolerance, 5 at 0.5 points, 4 at 1 point, 1 at 2 points.
Worst-month objective	10 strict reversals at 0.5 points; none at 2 points.
Boundary residence	No unique winner with all 16 targets at 0.5 points.

Illustrative contrast: 100 km one way, adult male

Target set	A: permanent	B: boundary	C: migration
Four targets	96.274%	96.886%	98.597%
Sixteen targets	55.697%	53.152%	53.473%

Migration exceeds A by 2.323 percentage points with four targets. A exceeds migration by 2.224 points with sixteen. These are model scores, not the percentages of an adequate diet actually obtained.

Initial falsification tests

Removing either scarcity or low root energy eliminated the five strict reversals in the six affected settings; restoring UV credit or increasing water iodine retained five, removing the iodine floor retained four. Changing walking costs from 30 to 70 kcal/km gave five and four, respectively. These one-factor tests motivated the wider publication-preparation sweep.

Wild tuber composition and parameter justification

Schoeninger et al. (2001) measured Hadza wild-tuber composition [29]. We converted reported dry peeled energy and protein to fresh peeled weight using the measured moisture fraction: fresh concentration = dry concentration × (1 − moisture fraction). No additional edible-fraction correction was applied.

Sample	Moisture	Energy*	Protein*
Vigna frutescens 2	83.4%	24.24	0.73
Vigna frutescens 3	75.1%	40.84	0.82
Vigna frutescens 4	76.5%	22.80	0.99
Vigna frutescens 5	75.8%	14.76	1.50
Vigna mean estimate	77.7%	32.56	1.00
Eminia	79.9%	40.00	1.39
Ipomoea	85.9%	42.02	0.32

* kcal and g per 100 g fresh peeled mass, respectively. Source [29], Tables 3–4. Sample 1 lacks moisture; sample 5 aggregates duplicate preparations; the species mean is derived from reported means, not an independent observation.

The original 22 kcal/100 g assumption lies within this converted range. The denominator is peeled resource mass rather than swallowed mass; the model's food caps are not calibrated to that distinction. Fat is set to zero in the measured substitutions because it was not measured; other nutrient values remain inherited proxies. No claim of a complete measured wild-food matrix follows.

Other evidence-informed parameters

The 2,500 kcal adult baseline is near the Hadza male mean of 2,649 ± 395 kcal/day [30]. Western Kenyan water iodine ranged 0.2–304.1 µg/L (median 3.2) [19]; seafood composition varies between and within species [18]. Published residential travel geometric means of approximately 158–174 km/year contextualise our distances [10]. These data justify exploring ranges, not assigning values to specific ancestral populations.

Conditional boundaries and sensitivity

The publication study retained the Phase IX caps and targets, and tested 100 matched settings (14,400 LP calls) plus 21 energy-only comparisons (3,024 calls). A 32-point Latin hypercube jointly varied 12 parameters (seed 926); all LP primal residuals were checked below 0.0001. The tested designs are not independent observations or probabilities.

Design	Settings	Mean strict	Worst strict
Food access × energy grid	36	16	18
Measured energy/protein pairs	21	13	14
Joint Latin hypercube	32	13	10
Archived reference cases	6	5	6
Root fibre/micronutrient scaling	5	5	5

Threshold grid: strict annual mean migration-to-residence reversal

Access	10	22	30	40	60	90
50%	Yes	Yes	Yes	Yes	Yes	Yes
60%	Yes	Yes	Yes	Yes	Yes	Yes
70%	Yes	Yes	Yes	Yes	—	—
80%	—	—	—	—	—	—
90%	—	—	—	—	—	—
100%	—	—	—	—	—	—

Root energy (kcal/100 g) in columns; access relative to inherited caps. Adult male, 100 km one way, 25% boundary blend, 42 kcal/km, no UV credit, water iodine 6.4 µg/day. Grid holds root protein and fat fixed; not coherent measured foods.

At 22 kcal, the observed transition is bracketed between 70% and 80% of baseline access; this is not a real-world scarcity threshold. The measured-pair settings reversed in 7/7 cases at 60% access, 6/7 at 70%, 0/7 at 90%. Root fibre/micronutrient scaling from zero to twice the original proxy did not remove the switch in the selected scenario. Energy-only control gave the same strict reversal classifications across all 21 measured-pair settings. The mean grid, measured and joint strict reversals were all C → A; worst-month reversals often involved B instead.

Assumptions audit and corrections

The Phase X register contains 1,195 entries, of which 755 are explicitly hypothetical and 187 are unverified catalogue entries or hypotheses. The 15-item correction register and 28-source audit remain in the archive. The publication supplement adds a parameter justification register but does not close all outstanding items.

Assumption or issue	Final disposition
Phase VII energy ceiling and averaging	Corrected ceiling to 105% of adjusted requirement and day-weighted annual scores; all 216 schedules rerun. 15 positive gains remain.
Vitamin D winter	O'Neill et al. [20] report five UK months below their study threshold, not six; public-health definitions may differ.
Food composition	Of 320 original cells, only 11 had specific source anchors. New tuber conversions and selected seafood/water measurements improve justification, not full calibration. Bulk CoFID not acquired.
Reference targets and safety	Modern intake references, not survival thresholds; only 16 of 44 catalogued requirements modelled. Potential vitamin-A unit differences, uncalibrated upper bounds and incomplete bioavailability.
Resource caps and migration	Seasonal caps, 25% blend, travel-day loss and added walking remain hypothetical. Possible double-counting of baseline activity.
Physiology and reproduction	Simplified UV/iodine credits and reserve models; constant early-lactation profile not a reproductive model. No hard energy balance or realised fertility.
Independent observations	Hadza survey [31] reported 2.5 places annually on average (136 respondents), with social and resource drivers. Context only, not predictive validation.

Model documentation is consistent with the intent of TRACE [32], but does not satisfy every empirical validation step. No new external audit is claimed for this consolidation. Original climate transcriptions and ethnographic rows remain incompletely checked.

Interpretation, originality and research closure

Defensible contribution

Adding selected micronutrient floors can reverse the preferred annual residential strategy in this defined model, particularly under resource scarcity. The reversal persists for several measured-source root energy/protein inputs, alternative objectives and jointly varied parameters. It is not confined to the exact 22 kcal value or to iodine alone. This is a counterexample to the proposition that energy-based rankings must remain unchanged when nutrient constraints are added.

Adversarial assessment

Challenge	Consequence
Evolutionary inference	Present traits have multiple functions; no unique ancestral habitat or migration programme follows.
Anthropological analogy	Modern foragers are not unqualified ancestral proxies. Social motives, access rights and land restrictions matter.
Ecological calibration	Unknown resource availability, seasonal correlations, sustainable yield and collection time are critical blockers.
Nutritional validity	Incomplete composition, absorption and nutrient scope; modern reference targets are not minimum needs.
Statistical interpretation	Shared-input design counts do not establish prevalence, confidence intervals or population effects; not preregistered.
Behavioural objective	Max-min nutritional optimisation is a mathematical criterion, not a validated human decision rule.

Final answers

Humans exhibit biological seasonal responses; obligatory southward migration is not demonstrated. Aquatic margins may offer complementary foods, but neither estuaries nor any other unique natural habitat is established. Nutritional constraints can change mathematical mobility predictions; the historical importance remains unknown.

Publication position

Suitable as an exploratory theoretical manuscript for specialist assessment, not a validated empirical discovery. Full calibration, comprehensive literature novelty review and external peer review remain necessary for stronger claims. Phases I–X and the targeted preparation exercise are closed; additional empirical work would be a separate project. No personal health or migration advice follows.

Source register (1 of 2)

Selected central sources from the archived literature audit and publication-preparation study. Links retained for verification; this is not an exhaustive systematic review.

[1] Tendler et al 2021 Hormone seasonality in medical records suggests circannual endocrine circuits. pubmed.ncbi.nlm.nih.gov/33531344/

[2] Yetish et al 2015 Natural sleep and its seasonal variations in three pre-industrial societies. pubmed.ncbi.nlm.nih.gov/26480842/

[3] Day-night and seasonal variation of human gene expression across tissues 2023. pubmed.ncbi.nlm.nih.gov/36745672/

[4] Pontzer et al 2021 Evolution of water conservation in humans. pubmed.ncbi.nlm.nih.gov/33675699/

[5] Kareklas et al 2013 Water-induced finger wrinkles improve handling of wet objects. pmc.ncbi.nlm.nih.gov/articles/PMC3639753/

[6] Haseleu et al 2014 Water-induced finger wrinkles do not affect touch acuity or dexterity. pubmed.ncbi.nlm.nih.gov/24416318/

[7] Braun et al 2010 Early hominin diet at East Turkana. pubmed.ncbi.nlm.nih.gov/20534571/

[8] Marean et al 2007 Early human use of marine resources and pigment in South Africa. doi.org/10.1038/nature06204/

[9] Ragsdale et al 2023 A weakly structured stem for human origins in Africa. doi.org/10.1038/s41586-023-06055-y

[10] Hamilton et al 2016 ecological and evolutionary energetics of hunter-gatherer residential mobility. doi.org/10.1002/evan.21485

[11] D-PLACE fishing B003. d-place.org/parameters/B003

[12] D-PLACE annual movement B014. d-place.org/parameters/B014

[13] UK COMA 1991 dietary reference values. assets.publishing.service.gov.uk/media/5bab98f7ed915d2bb2f56367/Dietary_Reference_Value…

[14] British Nutrition Foundation adult men reference values. www.nutrition.org.uk/nutrition-for/men/nutrition-recommendations-for-men/

[15] NIH ODS iodine fact sheet. ods.od.nih.gov/factsheets/Iodine-HealthProfessional/

[16] NIH ODS vitamin D fact sheet. ods.od.nih.gov/factsheets/Vitamind-HealthProfessional/

Source register (2 of 2)

Selected central sources from the archived literature audit and publication-preparation study. Links retained for verification; this is not an exhaustive systematic review.

[17] NIH ODS calcium fact sheet. ods.od.nih.gov/factsheets/calcium-HealthProfessional/

[18] Sprague et al 2022 Iodine content of wild and farmed seafood. doi.org/10.3390/nu14010195

[19] Iodine status in western Kenya 2019/2020. pubmed.ncbi.nlm.nih.gov/31190125/

[20] O'Neill et al 2016 Seasonal changes in vitamin D-effective UVB availability. doi.org/10.3390/nu8090533

[21] Jones et al 2014 25(OH)D2 half-life is shorter than 25(OH)D3 half-life. doi.org/10.1210/jc.2014-1714

[22] Belovsky 1987 Hunter-gatherer foraging a linear programming approach. www.sciencedirect.com/science/article/pii/027841658790016X

[23] 1988 An optimal foraging-based model of hunter-gatherer population dynamics. www.sciencedirect.com/science/article/pii/0278416588900025

[24] Brown et al 2013 Site distribution at the edge of the Palaeolithic world. doi.org/10.1371/journal.pone.0081476

[25] Fishing for iodine what aquatic foraging by bonobos tells us about human evolution 2019. doi.org/10.1186/s40850-019-0043-z

[26] Global hunter-gatherer population densities constrained by seasonality of diet 2021. doi.org/10.1038/s41559-021-01548-3

[27] Hamilton et al 2024 Food storage mobility and density-dependence. www.sciencedirect.com/science/article/pii/S2352409X24000695

[28] Rees Castellano and Andres 2025 Global impact of micronutrients in modern human evolution. doi.org/10.1016/j.ajhg.2025.08.005

[29] Schoeninger et al. (2001). Composition of tubers used by Hadza foragers of Tanzania.. doi.org/10.1006/jfca.2000.0961

[30] Pontzer et al. (2012). Hunter-gatherer energetics and human obesity.. doi.org/10.1371/journal.pone.0040503

[31] Sayre et al. (2023). Lifestyle and patterns of physical activity in Hadza foragers.. doi.org/10.1002/ajpa.24846

[32] Grimm et al. (2014). Towards better modelling and decision support: documenting model development, testing, and analysis using TRACE.. doi.org/10.1016/j.ecolmodel.2014.01.018

Reproducibility and data availability

Companion bundle contains the original Phase I–X archive, the publication-preparation archive and this consolidated report. Reproduce the added sensitivity experiments by extracting the supplement and running sweep.py and energy_only.py with Python, NumPy, pandas and SciPy. See each README for exact procedures, software and input provenance. No independent researcher replication is claimed.