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Hydro-climatic anomalies and livelihoods associated with thinness among children and adolescents in Mount Meru, Tanzania

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Abstract

Background: School-aged children and adolescents face significant nutritional challenges in sub-Saharan Africa yet remain understudied compared to under-five populations. Climate variability increasingly threatens food security in rural communities, but evidence on climate-nutrition relationships beyond early childhood is limited. We investigated associations between hydro-climatic anomalies, livelihood strategies, demographic characteristics, and thinness among school-aged children and adolescents on the slopes and surrounding plains of Mount Meru, northern Tanzania.

Methods: We analysed five waves of anthropometric data from 26,009 records of children and adolescents aged 6-18 years attending 18 public primary schools in the Mount Meru ecosystem between 2010 and 2015. Thinness was defined as BMI-for-age Z-score < -2 using the World Health Organisation (WHO) 2007 growth references. Bayesian logistic mixed-effects models were used with school-level and temporal random effects to examine associations of thinness with sex, age, dominant livelihood (farming, agropastoralism, pastoralism), and standardized anomalies in precipitation, evapotranspiration, and land-surface temperature.

Results: Overall thinness prevalence ranged from 61.2% in 2010 to 72.7% in 2015. Girls had lower odds of undernutrition than boys (odds ratio [OR]: 0.58, 95% credible interval [CrI]: 0.54-0.61), but age-sex interactions revealed complex developmental patterns. Girls showed peak vulnerability at age 12 years followed by sharp decline, while boys demonstrated more sustained risk through mid-adolescence. Children and adolescents from pastoralist communities had substantially higher undernutrition odds compared to farming communities (OR: 2.21, 95%CrI: 1.31-3.50). Above-normal precipitation was protective (OR: 0.34, 95% CrI: 0.20-0.54), while elevated evapotranspiration increased the odds of thinness (OR: 2.18, 95%CrI: 1.41-3.24).

Conclusions: The odds of thinness among school-age children and adolescents vary substantially by livelihood strategy and respond dynamically to hydro-climatic anomalies. Age- and sex-specific vulnerability patterns reveal critical windows requiring targeted interventions. Evapotranspiration emerged as a particularly informative climate indicator for nutritional surveillance. These findings support integrating climate monitoring into school-based nutrition programs and developing livelihood-specific adaptation strategies for climate-vulnerable communities.

Keywords: Thinness; school-aged children and adolescents; hydro-climatic anomalies; livelihoods; climate change; nutrition surveillance; Tanzania.

Background

Undernutrition remains one of the most pressing public health challenges of the twenty-first century. Despite global progress in reducing hunger, sub-Saharan Africa continues to shoulder a disproportionate burden, with an estimated 22% of the population undernourished in 2022, compared to 9% globally [1, 2]. Undernutrition encompasses multiple forms, including stunting, wasting, underweight, thinness, and micronutrient deficiencies [3] associated with impaired growth, reduced cognitive development, lower school performance, and increased susceptibility to infectious diseases [4, 5]. Its impacts extend across the life course: nutritional deprivation in childhood and adolescence contributes to long-term risks of non-communicable diseases (NCDs) such as diabetes and cardiovascular disease, as well as reduced human capital and economic productivity. Addressing undernutrition is central to the United Nations (UN) Zero Hunger Sustainable Development Goal (SDG) 2 [6]. Yet persistent inequalities challenge the equity principle underpinning the SDGs, expressed in the commitment to leave no one behind.

In Tanzania, despite gains in maternal and child health, high levels of undernutrition persist [7]. While investments in health systems have contributed to declining infant and child mortality [8], access to nutrient-rich foods remains limited, especially in rural areas reliant on subsistence farming [9]. Recent studies indicate that more than 40% of children and women are underweight, with stunting and recurrent illness from inadequate diets continuing at concerning levels [9, 10].

School-aged children and adolescents also face significant nutritional challenges, although much of the research and programming has focused on children under five. A national survey in 2019, involving 44,120 primary school adolescents, found around one-third (32%) of Tanzanian children were stunted [11]. Adolescence represents a critical second window of growth and development after early childhood, characterised by rapid physical and cognitive maturation, increased energy and nutrient requirements, and heightened social transitions [12]. Nutritional deficits during this stage are associated with impaired school performance, delayed psychosocial development, increased risk of adverse pregnancy outcomes, and greater vulnerability to NCDs in adulthood [13]. Despite this, the adolescent population remains comparatively neglected in nutrition research, surveillance, and intervention strategies, particularly in sub-Saharan Africa [14].

Climate variability and extreme events affect nutrition through multiple pathways [15]. The first is agricultural production: droughts, erratic rainfall, or unseasonal cold spells can reduce crop yields, diminish dietary diversity, and raise food prices [16]. The second is food access: climate-induced disruptions to food supply chains and price volatility can reduce household purchasing power and dietary quality, particularly among low-income rural populations [15]. The third is disease burden: extreme weather can exacerbate diarrhoeal diseases, vector-borne infections, and other illnesses that impair nutrient absorption and increase energy expenditure [17, 18]. These mechanisms often interact, compounding vulnerabilities in food-insecure populations. In Tanzania, several studies have documented associations between climate and nutrition in children. Drought has been linked to increased stunting [19], cold spells to higher risk of undernutrition [20] and seasonal food insecurity to wasting and low birthweight [21]. Such evidence highlights the plausibility of climate as a driver of child growth outcomes. However, research to date has overwhelmingly prioritised early childhood, leaving a critical knowledge gap regarding older children and adolescents. Given their distinct physiological demands, developmental transitions, and social roles within households, understanding how school-aged children and adolescents are affected by climate anomalies is essential. Additionally, the role of household livelihood strategies in shaping nutritional vulnerability to climate events remains an underexplored area of research. In line with the sustainable livelihoods' literature [22, 23], we understand livelihoods as the capabilities, assets (including material and social resources), and activities that households mobilise to secure food and income. In rural Tanzania, these livelihoods are primarily organised around smallholder farmers, pastoralists and agropastoralists, with specific combinations of crop production, livestock keeping, and informal labour that vary by geography and ecosystem [24]. Households that rely on rainfed agriculture are particularly vulnerable to drought and irregular rainfall, while pastoralist communities face nutritional stress when grazing resources diminish [25]. Livelihoods influence both exposure to climate and the capacity to buffer their effects through coping strategies, food purchasing power, or access to diversified diets [26]. Yet the intersection of livelihoods, climate variability, and adolescent nutrition remains poorly understood. Existing knowledge is primarily drawn from national surveys or cross-sectional studies that, while valuable, provide limited granularity on local dynamics. Such evidence gaps constrain the design of effective interventions to mitigate climate-related nutritional risks and to strengthen food security and resilience in rural settings.

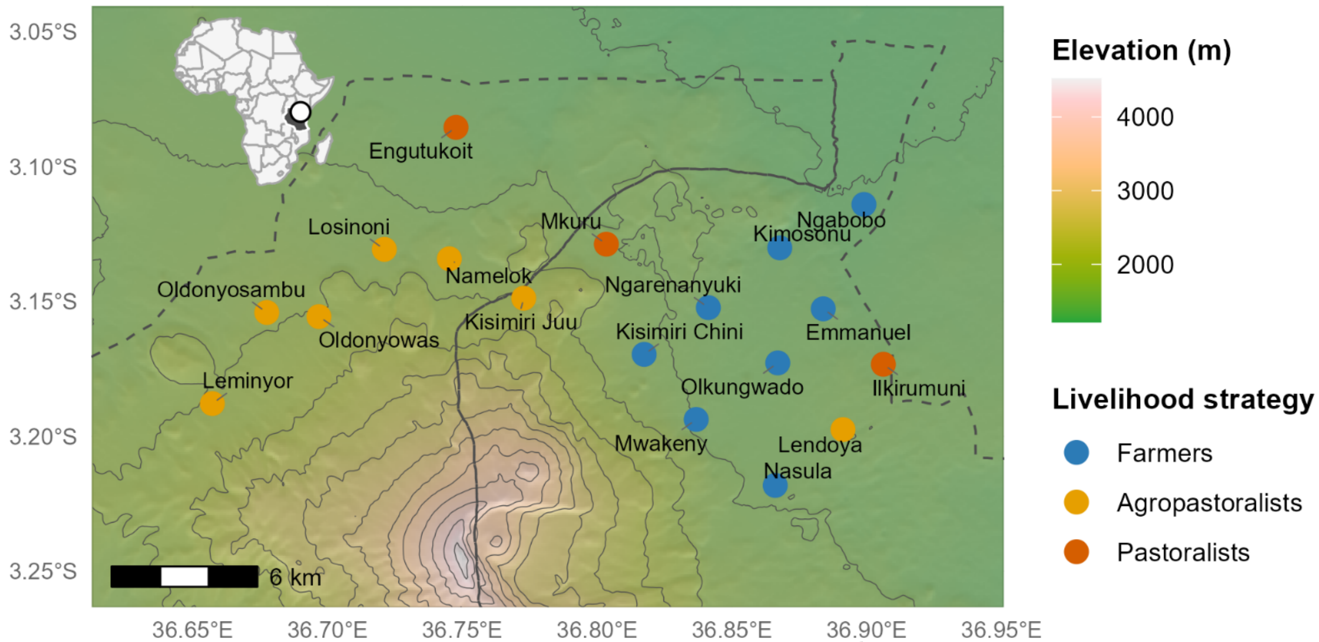
In this study, we address these gaps by investigating the spatial and temporal variation in undernutrition among primary school children and adolescents in the Mount Meru ecosystem of northern Tanzania. Specifically, we use thinness, as the primary indicator of undernutrition, which reflects acute nutritional insufficiency associated with recent food deprivation or illness [27] and we define children as boys and girls aged 6-9 years, and adolescents as those aged 10-18 years, consistent with the WHO definition of adolescence [13]. The Mount Meru ecosystem represents an ecologically diverse region, encompassing highland slopes and lowland plains, is characterised by heterogeneous climate patterns and livelihood strategies that shape food security and nutrition. Using existing biometric data, we examined the associations between children and adolescent thinness and hydro-climatic anomalies, defined as departures from long-term baseline conditions in precipitation, evapotranspiration, and land-surface temperature, alongside household livelihood strategies and demographic characteristics. To our knowledge, this is the first study to investigate how hydro-climatic anomalies relate to thinness among children and adolescents in rural northern Tanzania, after adjusting for local livelihood strategies and demographic characteristics.

Methods

Study design and setting

This was a repeated cross-sectional secondary analysis of data collected between 2010 and 2015 in 18 public primary schools on Mount Meru (4,566 m a.s.l.) slopes and surrounding plains. This is a high-biodiversity area bordering Arusha National Park in north-eastern Tanzania. The region encompasses distinct sub-ecosystems that differ in precipitation, soil quality, and land use, which in turn shape local livelihoods and diets. Fertile highland zones are densely populated, with 210-250 people per km^2, while the drier lowland plains are more sparsely inhabited and dominated by rangelands [28].

Households rely on ecosystem services for their subsistence, with three main livelihood strategies: farming, agropastoralism, and pastoralism. Farmers and agropastoralists typically occupy wetter or irrigated areas that allow multi-cropping and more diversified agroecosystems, while pastoralists inhabit the drier savannah stretching from Mount Meru towards the Kenyan border. Livelihood diversification and altitude contribute to varying levels of resilience to environmental shocks. The combined population of the study villages was approximately 36,860 at the time of the 2012 national census [29]. These villages were the target of public health activities implemented during 2010-2015, which included nutritional monitoring in schools and the present study builds on those data to investigate the relationship between socio-demographic characteristics, climate anomalies, and undernutrition. Figure 1 illustrates the geographic location of the 18 primary schools within the Arumeru District on the slopes of Mount Meru. The study sites are distributed across areas characterized by different dominant livelihood strategies (pastoralist, agropastoralist, and farming), reflecting the diverse ecological and topographic settings of the Meru ecosystem.



Inset: Location within Africa and Tanzania

Figure 1 - Geographic distribution of the schools in Mount Meru. Schools are colour-coded by dominant livelihood strategies. The background features terrain elevation and contour lines; dashed grey lines delineate administrative boundaries.

Data sources

This study is a secondary analysis of data collected during public health interventions aiming to improve food security. The interventions were co-implemented by Oikos East Africa, a locally registered Tanzanian NGO, in collaboration with Arumeru District Authorities and the parastatal agency Tanzania Food and Nutrition Centre (TFNC; https://www.tfnc.go.tz), which designed and monitored the first data-collection campaign. A nurse from Mount Meru Hospital (Arusha) assisted the TFNC team during the first campaign and trained the NGO team and schoolteachers on biometric data collection. Height and weight measurements were collected for all children and adolescents attending school on the survey days. Weight was measured using a calibrated mechanical scale (Seca, maximum capacity 150 kg) to the nearest 0.1 kg, while height was recorded to the nearest 0.1 cm using a wooden stadiometer [30]. The simplicity of the equipment allowed teachers to lead the data collection after receiving appropriate training. The training included visual aids that served as reminders for proper technique, emphasizing the correct positioning of the child against the stadiometer. For height measurement, children were required to stand barefoot and upright with their heels, calves, buttocks, scapulae, and head touching the stadiometer. They were instructed to stand upright, with arms hanging freely and gaze directed forward, ensuring that the Frankfurt plane was horizontal. The headpiece was then gently lowered onto the child's head. A Community Development Officer assisted with the data collection to ensure standardization and supported the recording in logbooks. Age was taken from records from birth certificates deposited at the school during enrolment; otherwise, especially for migrant children, it was obtained from school registers and complemented with teacher/parent information. Additional variables included village of residence, school grade, and sex.

Inclusion and exclusion criteria

The five waves of data collection included 26,289 records obtained from children and adolescents attending the 18 public primary schools on the slopes of Mount Meru. Cases with no information on weight or height, and cases with missing or misreported age were excluded (overall 144 records). Children and adolescents (n=136) identified as overweight or obese over the study period were also excluded, as these conditions represent distinct forms of malnutrition and cannot be considered part of the nutritionally adequate reference category [5, 31]. Overall, 1.08% of records were excluded, resulting in a final analytical sample of 26,009 measurements (13,664 girls and 12,345 boys), aged 6-18 years.

Study variables

Outcome variable

The primary outcome was the prevalence of thinness, defined as a body mass index (BMI)-for-age Z-score (BAZ) < -2 according to the WHO 2007 Growth Reference for children and adolescents aged 5-19 years [32], and validated in line with recommendations from the Food and Nutrition Technical Assistance (FANTA) Guide to Anthropometry [33]. BMI was calculated from weight and height measured using standardized procedures, with exact age determined at the time of measurement; sex-specific WHO LMS (Lambda for the skew, Mu for the median, and Sigma for the generalized coefficient of variation) parameters were applied to compute BAZ. WHO categories of moderate (BAZ between -3 and < -2) and severe thinness (BAZ < -3) were derived, but because the main aim of this study was to estimate the overall odds of thinness rather than severity gradients, a single binary indicator, i.e., thinness (BAZ < -2) versus normal weight, was created.

Exposure variables

Each school was assigned a dominant livelihood category: farmers, agropastoralists, pastoralists, based on local administrative information reflecting the primary livelihood system of the village where each school was located, based on field assessments by staff with long-term presence in the area. In this ecosystem, livelihood systems are strongly shaped by annual precipitation. Areas receiving less than 400 mm per year are predominantly pastoral, as rainfed cropping is not viable below this threshold. Where annual precipitation typically exceeds 400-500 mm, maize-based cropping systems become feasible. This classification captured differences in exposure and adaptive capacity related to rain-fed agriculture, mixed crop livestock systems, and pastoralism within the Mount Meru ecosystem.

Additionally, for each school and survey year, environmental and climatic exposures were summarized within a 5-km Euclidean buffer centred on the school coordinates, used as a proxy for the school catchment. The 5-km radius was chosen to follow evidence on average travel distance to school in Tanzania [34].

Specifically, elevation (m) was extracted from the Amazon Web Services (AWS) Terrain Tiles via the R package *elevatr* (tile set derived from the Shuttle Radar Topography Mission [SRTM] and the Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER]). Grids were mosaicked and area-averaged within each 5-km buffer.

To provide climatic context for children's growth histories, annual series for 2000-2015 were compiled and each variable was expressed as a school-specific standardised anomaly relative to the 2000-2009 baseline. Sources and pre-processing, which was performed through the platform of Google Earth Engine were as follows:

- Precipitation (mm/yr) was derived from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) pentad precipitation (0.05°) [35] for 2000-2015. Pentad accumulations were summed to annual totals at the pixel level and then area-averaged within a 5-km buffer around each school to obtain annual precipitation (mm/yr) representative of the school catchment.
- Evapotranspiration (mm/yr) was obtained from Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS), specifically the NASA FLDAS: NOAH01/C/GL/M (v001) dataset [36]. Monthly fields of actual evapotranspiration ($kg/m^2/s$) at 0.1° resolution served as a measure of land-atmosphere water fluxes. For each school (2000-2015), monthly data were area-averaged within a 5-km buffer and converted to annual totals (mm/yr) by multiplying by the number of seconds in each month and summing across months (equivalently, annual mean rate x seconds in the year). Evapotranspiration here represents the realised land-atmosphere water flux, integrating both atmospheric demand and water availability, and is informative for soil moisture, crop water stress, and local food systems.
- Land-surface temperature (°C) was extracted from Moderate Resolution Imaging Spectroradiometer (MODIS) (Terra) 8-day land-surface temperature (~1 km). The pixels were screened using the product's quality assurance/quality control (QA/QC) mask, excluding cloud-contaminated or low-quality observations and were converted to °C, averaged to annual means at the pixel level, and then area-averaged within a 5-km buffer around each school.

The hydro-climatic variables (precipitation, evapotranspiration and land-surface temperature) were processed to compute standardised anomalies (z-scores) within each school's 5-km buffer relative to the 2000-2009 long-term mean, as in previous studies by Thiede (2014) [37] and Thiede and Strube (2020) [38]. For each climate variable v at school k and year t the standardised anomalies were computed as follows:

$$z_{v,k,t} = \frac{X_{v,k,t} - m_{v,k}^{(2000\text{-}2009)}}{SD_{v,k}^{(2000\text{-}2009)}}$$

where $X_{v,k,t}$ is the annual school-specific value, $m_{v,k}^{(2000\text{-}2009)}$ and $SD_{v,k}^{(2000\text{-}2009)}$ are the school-specific mean and standard deviation (SD) over the 2000-2009 baseline. A one-unit increase in $X_{v,k,t}$ thus corresponds to one SD above the school's long-term mean.

Data analysis

A Bayesian logistic mixed-effects model [39] was used to assess how thinness among children and adolescents of rural communities of Mount Meru was influenced by demographic characteristics as well as by livelihoods, environmental and hydro-climatic anomalies. Although the data span multiple years, child/adolescent-level linkage was not possible due to inconsistent identifiers; hence, each year was treated as an independent cross-section and included a random effect for school plus a smooth temporal component for year. In detail, we assumed that each child or adolescent i in school k and year t has an undernutrition status y_{ikt} drawn from a Bernoulli distribution with probability p_{ikt}. Then, the logit link was specified as:

$$\begin{aligned} \text{logit}(p_{ikt}) = {} & \alpha + S_k + \sum_{m=2}^{3} \beta_{1m} \text{Livelihood}_{m,ikt} + \beta_2 \text{Evapotraspiration}_{kt} \\ & + \beta_3 \text{Precipitation}_{kt} + \beta_4 \text{Land surface temperature}_{kt} \\ & + \beta_5 \text{Elevation}_{kt} + \beta_6 \text{Sex}_{ikt} + f(\text{Age}_{ikt}) + g(\text{Age}_{ikt}) \times \text{Girl}_{ijk} + h(t) \end{aligned}$$

were is a global intercept, S_k is a school-level random effect, which account for unobserved heterogeneity between schools that may influence the odds of underweight and modelled using Gaussian white noise prior (a sum-to-zero constraint was applied to ensure identifiability of the year-specific effects, expressing them as deviations from the global mean odds of underweight), $_{1m}$ is the regression coefficients for livelihood (where *m*=2 agropastoralist and m=3 pastoralist; farmers as reference), $\beta_2, \ldots, \beta_5$ are the regression coefficients for the climatic anomalies and elevation and β_6 is the regression coefficient for sex (boys as reference). The term $f(\mathrm{Age}_{ikt})$ models the non-linear effect of age using a flexible first-order random walk (RW1) prior [39], representing the general age trajectory for all individuals, adjusted for all covariates. The additional RW1 term $g(\mathrm{Age}_{ikt}) \times \mathrm{Girl}_{ijk}$ captures the sex-specific deviation for girls, resulting in distinct age trajectories for boys and girls. Finally, $h(t)$ represents a smooth temporal effect across years modelled as an RW1 with a sum-to-zero constraint to ensure identifiability. Thus, although a unique child/adolescent identifier was not available across the years, and each year's sample was treated independently, the smooth process on t allowed borrowing of information across adjacent years. Penalized complexity priors [40] were placed on the precision parameters of these RW1 components to discourage overly complex shapes. Specifically, we penalised by specifying that the SD is larger than 1 with a probability of 1%. Weakly informative priors were assigned to the intercept and regression parameters, using a zero-centered Gaussian distribution with variance 100.

Analyses were performed using the R package (version 4.4.2). The model was implemented using the Integrated Nested Laplace Approximation (INLA) through the package INLA [41]. Model diagnostics such as alternative modelling structures were evaluated based on the Watanabe Akaike information criterion (WAIC) [42].

Additional analyses

Additional analyses were performed to study the robustness of the results. To assess multicollinearity among fixed-effect covariates in the INLA logistic regression model, the Variance Inflation Factor (VIF) was computed using a frequentist generalized linear model with a binomial logit link. The VIF analysis revealed moderate multicollinearity between evapotranspiration anomaly (VIF = 6.06) and precipitation anomaly (VIF = 3.27). Other covariates showed minimal multicollinearity (VIF < 3.24). To evaluate the impact of precipitation anomalies, a reduced model was refitted excluding precipitation anomalies, resulting in a higher WAIC (29937.29) compared to the full model (29910.13, Δ = 27.16). This suggested that precipitation anomalies contributed unique predictive information, likely reflecting its ecological relevance to livelihoods at Mount Meru. The full model was retained, as the Bayesian hierarchical framework, through partial pooling and regularizing priors, mitigates the impact of moderate multicollinearity on posterior inference [43, 44].

To check the robustness of the INLA model, the assumptions (priors) used for the fixed and random effects were varied. In detail, for the fixed effects minimally informative priors were tested , given by zero-cantered Gaussian distribution with variance of 10. Regarding the random effects' priors, the original model used a standard setting, while alternative models tested stricter assumptions (penalizing large deviations more strongly) and more flexible ones (allowing greater variability). The WAIC showed minimal change (range: 29909.88-29910.91), and the effects of the covariates remained consistent across models. This confirms that the findings are reliable regardless of the chosen assumptions.

Results

The final sample included 26,009 measurements (13,664 girls and 12,345 boys), aged 6-18 years, mean age 10.8 (SD 2.6) years. The number of schools surveyed varied across waves due to operational and funding constraints; across the five waves, 18 unique schools participated in total, though not all schools were included in every wave. There was no wave in 2014. Table 1 presents the baseline characteristics of children and adolescents in each wave. The prevalence of thinness among children and adolescents was high, increasing upward across the years. Overall thinness prevalence ranged from 61.2% in 2010 to 72.7% in 2015.

Table 1. Socio-demographic characteristics of the children and adolescents by survey wave.

Variables	Wave 1	Wave 2	Wave 3	Wave 4	Wave 5

	(Year 2010)	(Year 2011)	(Year 2012)	(Year 2013)	(Year 2015)
Number of schools surveyed	17	17	17	17	7
Number of children	6810	6969	5423	5294	1513
Nutritional status (%)*					
Normal weight	2646 (38.8)	2431 (34.9)	1672 (30.8)	1542 (29.1)	413 (27.3)
Moderately thin	2300 (33.8)	2330 (33.4)	1785 (32.9)	1714 (32.4)	459 (30.3)
Severely thin	1864 (27.4)	2208 (31.7)	1966 (36.3)	2038 (38.5)	641 (42.4)
Age mean in years (SD)	11.0 (2.8)	10.8 (2.7)	10.8 (2.5)	10.6 (2.5)	10.9 (2.5)
Gender (%)					
Male	3349 (49.2)	3283 (47.1)	2527 (46.6)	2499 (47.2)	687 (45.4)
Female	3461 (50.8)	3686 (52.9)	2896 (53.4)	2795 (52.8)	826 (54.6)
Livelihood (%)					
Farmers	2611 (38.3)	2654 (38.1)	2120 (39.1)	2066 (39.0)	557 (36.8)
Agropastoralist	3680 (54.1)	3777 (54.2)	2956 (54.5)	2896 (54.7)	752 (49.7)
Pastoralist	519 (7.6)	538 (7.7)	347 (6.4)	332 (6.3)	204 (13.5)

* Moderate and severe thinness were combined into a single binary outcome (thin vs. normal weight) for inferential analyses.

Figure 2 displays the prevalence of normal weight and thinness across pastoralist, agropastoral, and farmer livelihoods from 2010 to 2015, with pastoralist communities appearing more vulnerable to thinness, as evidenced by the proportion of thinness increasing from 78.4% in 2010 to 85.3% in 2015.

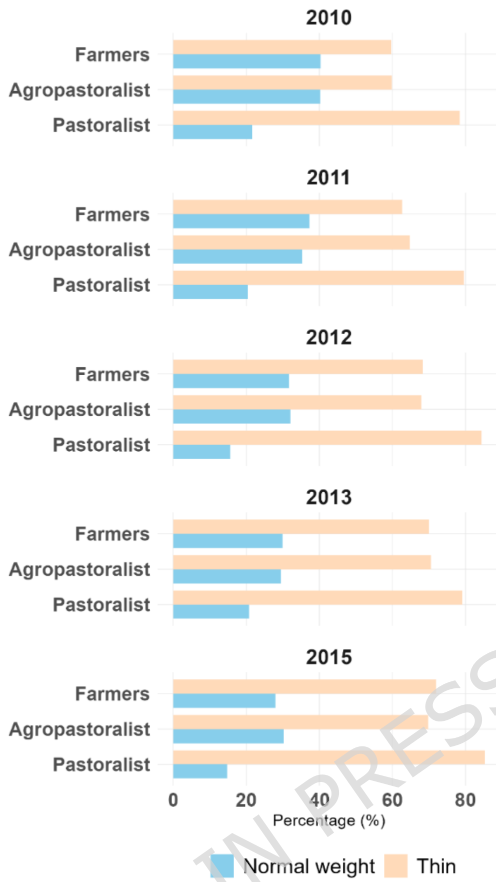


Figure 2. Prevalence of thinness among children and adolescents by year and livelihood.

Three hydro-climatic anomalies were included in the model (i.e., precipitation, evapotranspiration and land-surface temperature) and Figure 3 displays the observed values for each climatic variable across schools and years, showing substantial annual and spatial variability. Tiles display annual absolute precipitation, evapotranspiration and daytime land-surface temperature, while overlaid points indicate school-specific standardized anomalies (relative to each school's 2000-2009 baseline).

Figure 3. Annual absolute values and standardized anomalies for precipitation, evapotranspiration and daytime land-surface temperature, by school and year (2010–2015). Schools are ordered by latitude (North to South).

The posterior estimates for the adjusted Odds Ratios (ORs) from the Bayesian logistic regression model along with their corresponding 95% credible intervals (95%Crl), estimating the strength and direction of the association between thinness and demographic characteristics, livelihood and climatic variables, are presented in Table 2. Among schoolchildren and adolescents of the Mount Meru region, girls had substantially lower odds of thinness compared to boys (OR: 0.58, 95%CrI: 0.54-0.61). Children and adolescents from pastoralist communities had the highest odds of thinness compared to those from farming households (OR: 2.21, 95%CrI: 1.31-3.50), whereas children and adolescents in agropastoralist households showed a moderate increase in odds, though with wider credible intervals (OR: 1.58, 95%CrI: 0.82-2.74).

Among the hydro-climatic variables, evapotranspiration anomalies were strongly and positively associated with thinness (OR: 2.18, 95%CrI: 1.41-3.24), indicating that higher-than-average environmental water stress is associated with poor nutritional outcomes. In contrast, precipitation anomalies were inversely associated with thinness (OR: 0.34, 95%CrI: 0.20-0.54), suggesting that above-average rainfall may help mitigate food insecurity and reduce the odds of thinness. Land-surface temperature and elevation showed no conclusive association with thinness, as their 95%CrIs included the null value of 1.0 (Table 2).

Table 2 - Odds Ratio (OR; posterior mean) and 95% credible intervals (95%CrI) for the fixed effect parameters.

Covariate	**OR**	**95%Crl**
Sex		
Boys (reference)	1	
Girls	0.58	0.54-0.61
Livelihood		
Farmers (reference)	1	
Agropastoralist	1.58	0.82-2.74
Pastoralist	2.21	1.31-3.50
Evapotranspiration anomaly	2.18	1.41-3.24
Precipitation anomaly	0.34	0.20-0.54
Land-surface temperature anomaly	1.11	1.00-1.24
Elevation	0.77	0.56-1.02

Beyond the overall sex effect, the interaction between sex and age revealed important heterogeneity across developmental stages: boys and girls showed broadly similar odds of thinness in early childhood, with trajectories diverging markedly during adolescence. While the random smooth effect for age indicated that younger children had lower-than-average probabilities of thinness, with odds increasing sharply during early adolescence before plateauing, the sex and age specific interactions revealed that this “average” pattern was masking divergent trajectories for boys and girls. Figure 4 displays the posterior predictions of thinness on the probability scale, obtained by applying the inverse logit transformation to the model’s log-odds posterior estimates. Although 95%CrIs overlap in several age groups, the trajectories diverge during adolescence: girls show a sharp increase in thinness probability peaking around age 12 years before declining, whereas boys present a more gradual and sustained increase extending into mid-adolescence. Between-school variability was modest: the school-level random intercept had a variance of 0.11 (95%CrI: 0.06-0.25), implying an intraclass correlation coefficient of approximately 0.03 (95%CrI: 0.02-0.07) on the logit scale, meaning that about 3% of the residual variability was attributable to differences between schools.

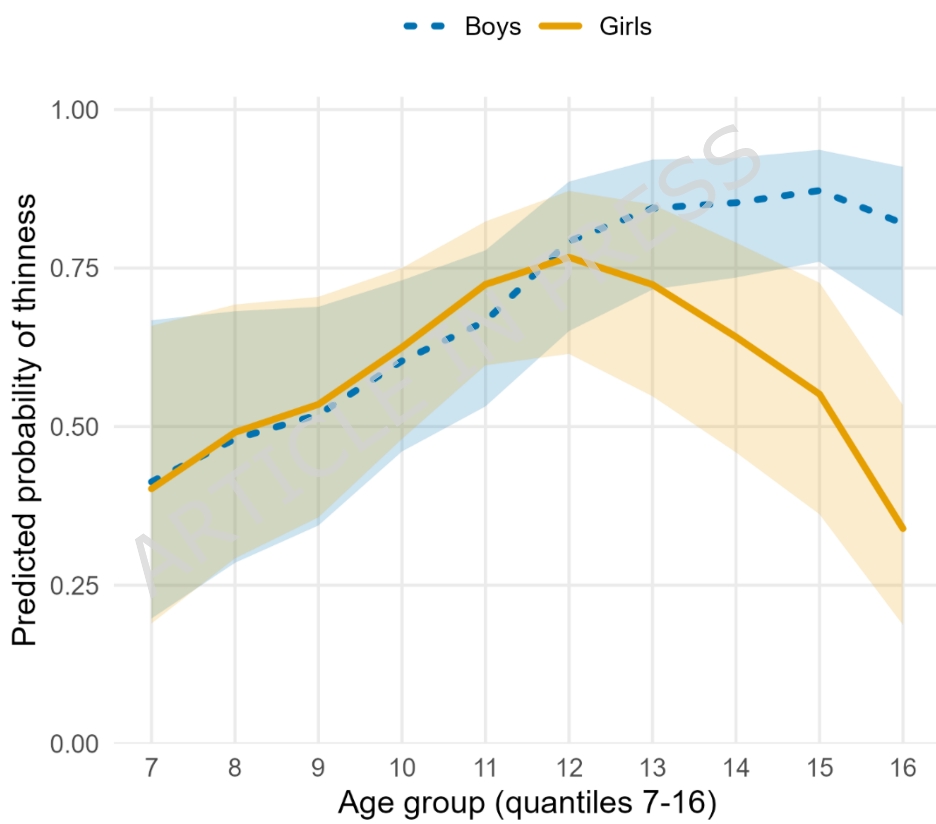


Figure 4. Predicted probability of thinness by age and sex. Curves represent posterior means of the predicted probabilities and shaded areas indicate 95% credible intervals.

Year-specific ORs relative to the grand-mean (OR = 1), revealed an upward trend in thinness odds over the study period, as displayed in Figure 5. Despite the smaller sample in 2015, which is reflected in wider 95%CrIs, the RW1 prior stabilised the estimates: OR = 0.43 (95%CrI: 0.32-0.58) in 2010, 0.83

(95%CrI: 0.65-1.05) in 2011, 1.23 (95%CrI: 0.98-1.55) in 2012, 1.05 (95%CrI: 0.89-1.22) in 2013, and 2.28 (95%CrI: 1.44-3.47) in 2015 (no survey took place in 2014).

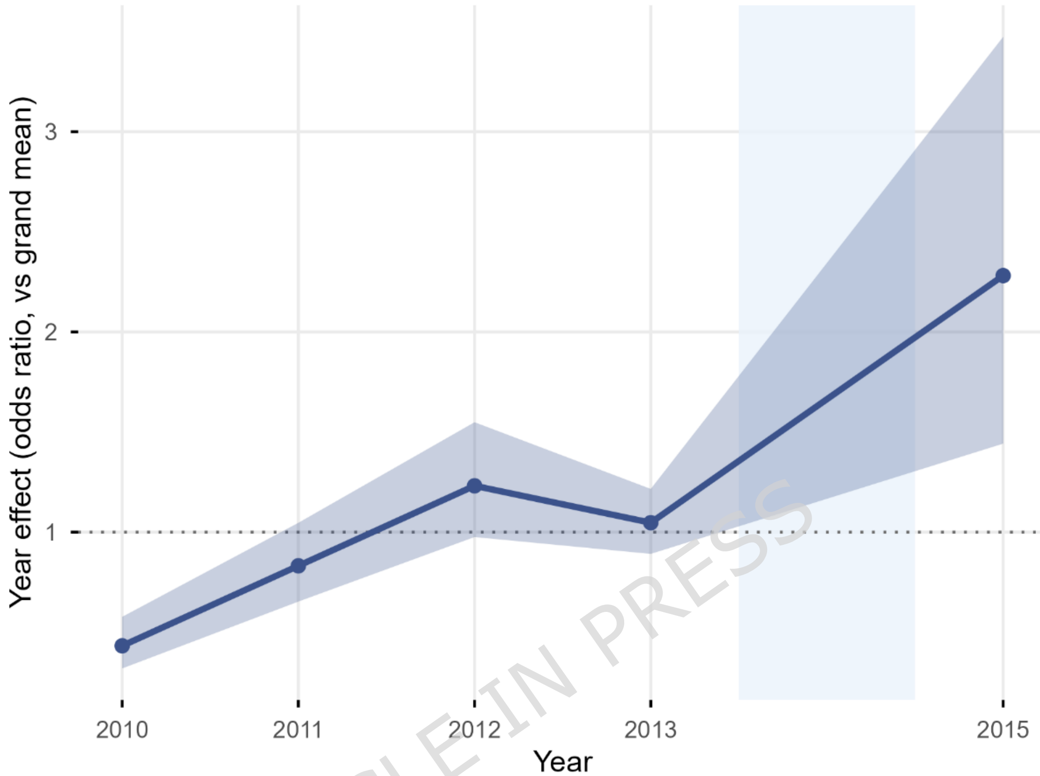


Figure 5. Year-to-year random effect on the odds of thinness. Points show posterior mean odds ratios (OR) and ribbons show 95% credible intervals. No survey took place in 2014 (grey band).

Discussion

This study examines the associations between thinness in school-age children and adolescents and livelihood strategies and hydro-climatic anomalies in a rural East African setting, by analysing five waves of biometric data (between 2010 and 2015) from 18 schools in the Mount Meru ecosystem, northern Tanzania. To the best of our knowledge, this is the first study to investigate the intersection of climate anomalies with school-age children and adolescent nutrition, accounting for differences in livelihood strategies. We found a high overall prevalence of thinness, with between 65-72% of school-aged children across all years with a BMI z-score under two SD for age. Greater adjusted odds of thinness were seen among pastoralists and following evapotranspiration climate anomalies. The relation between thinness and sex was complex, with similar odds of thinness up to approximately age 12 years, and significantly higher odds in boys at higher age.

The prevalence of thinness among school-aged children and adolescents from the Mount Meru area was far greater than that described in national or regional estimates. The WHO estimated a nine percent prevalence of thinness in children and adolescents in Tanzania in 2022 [45]. Limited data from across sub-Saharan Africa found up to one third of this age-group to be affected [46, 47]. This evidence underlines that national data may mask ample sub-national variation in malnutrition, and the importance for public health interventions of granular data.

Our findings on the heightened vulnerability of pastoralist communities resonate with existing literature on climate-induced nutritional insecurity in Tanzanian pastoral groups, while extending the evidence to the Mount Meru ecosystem. Safari et al. (2022) [48] reported high food insecurity (55%) among Maasai in Ngorongoro due to drought and conservation restrictions, aligning with the positive association between evapotranspiration anomalies and undernutrition, though our study with temporal random effects quantifies a trend of thinness not emphasized in their survey. Our results on the vulnerability of pastoralist communities are also consistent with Lawson et al. (2014) [49], who documented disadvantaged child health among Maasai pastoralists, including higher underweight rates (20%) due to food insecurity and limited-service access. Similarly to Lawson et al. (2014) [49], this study highlights ethnic disparities in northern Tanzania. However, this analysis quantifies the role of hydro-climatic anomalies extending Lawson's cross-sectional findings by linking thinness to climate variability, rather than chronic stunting alone.

These findings reveal a complex interplay between age and sex in shaping probability of thinness among schoolchildren and adolescents in the Mount Meru region. Overall, girls had substantially lower odds of undernutrition than boys, but the incorporation of the interaction term between sex and age highlighted important heterogeneity across developmental stages. In early childhood, boys and girls showed broadly similar probabilities of thinness, with overlapping credible intervals. However, the trajectories begin to diverge in early adolescence: girls exhibited a sharp rise in thinness probability peaking around the age of 12 years, while boys showed a more gradual but sustained increase extending into mid-adolescence (13-15 years). This critical window of vulnerability in girls corresponds to the period immediately preceding menarche, when nutritional demands peak due to the pubertal growth spurt [50]. In Tanzania specifically, a large study of 8,012 adolescent schoolgirls aged 11-18 years, more than 60% of whom resided in rural areas, estimated a mean age at menarche of approximately 12.9 years [51]. This indicates that the vulnerability window defined in our analysis captures the critical pre-menarcheal period, which typically coincides with the adolescent growth spurt [52]. The demand for iron is particularly acute, given the combined effects of expanded blood volume and impending menstrual losses [53]. These heightened biological needs may intersect with gendered household food allocation and cultural norms that disadvantage girls in many East African contexts [54, 55] amplifying their vulnerability during this critical phase. By contrast, boys showed a more gradual and sustained increase in thinness probability, consistent with their typically later and more prolonged growth trajectory [52]. Boys generally experience their peak growth velocity later than girls (around ages 13-15 years) and maintain elevated nutritional requirements throughout this extended developmental period [52, 56]. Unlike girls, whose vulnerability appears transient and concentrated in early adolescence, boys face an extended period of elevated risk that persists into mid-teen years. The subsequent decline in thinness probability among girls after age 12 suggests that the disadvantage is time-limited and may resolve as pubertal growth demands lessen and nutritional needs stabilize. This recovery could also reflect household or social role shifts during later adolescence that alter resource allocation. The contrasting sustained vulnerability in boys underlines their need for longer-term nutritional support. Together, these findings reinforce the importance of developmental timing in designing interventions. Nutritional strategies for girls should prioritize the short, high-risk window before menarche, while for boys, interventions need to extend across mid- to late adolescence. Evidence from sub-Saharan Africa has repeatedly underscored the limitations of "one-size-fits-all" approaches [57]. These results strengthen the case for developmentally timed, sex-specific nutritional programs, particularly in climate-vulnerable rural communities where food insecurity and resource competition exacerbate adolescent undernutrition risks.

Additionally, these findings point out significant associations between hydro-climatic anomalies and thinness, consistent with emerging evidence linking climate variability to child nutrition outcomes in sub-Saharan Africa. The protective effect of above-normal precipitation aligns with previous studies documenting associations between rainfall and child growth outcomes. For instance, Shively et al. (2015) [58] found that increased rainfall improved child height-for-age z-scores in Nepal, while Thiede (2014) [37] demonstrated that precipitation anomalies significantly predicted stunting rates across sub-Saharan Africa. Our results extend this evidence to the school-aged children and adolescent population in Tanzania, showing that years with higher-than-average precipitation reduce significantly thinness odds. This precipitation-nutrition relationship likely operates through multiple pathways documented in agricultural and food security literature. Enhanced precipitation improves crop yields and livestock productivity, leading to increased household food availability and dietary diversity [59]. In the Mount Meru context, where communities rely heavily on rainfed agriculture and pastoralism, adequate precipitation supports both crop production in highland areas and pasture quality for livestock in lowland zones. Additionally, improved water availability can enhance school feeding programs that draw on local agricultural production, stabilizing nutritional support for children and adolescents during critical developmental periods [56, 60].

The strong positive association between evapotranspiration anomalies and thinness provides novel evidence for the utility of this integrated hydro-climatic indicator in nutrition surveillance. Unlike precipitation or temperature alone, actual evapotranspiration captures the balance between atmospheric water demand and surface water availability, making it particularly relevant for assessing agricultural water stress [61]. These findings align with recent studies highlighting evapotranspiration as a more sensitive indicator of drought impacts on food systems than traditional meteorological indices [62]. In water-limited ecosystems like Mount Meru, anomalously high evapotranspiration signals rapid soil moisture depletion and vegetation water stress, directly impacting crop yields and livestock forage availability [63].

Although the association between land-surface temperature anomalies and thinness was uncertain (95%CrI including 1.0), the positive direction of the estimate is consistent with existing evidence on heat stress impacts on food systems and human health. Elevated temperatures can reduce crop yields through heat stress and accelerated crop development cycles [64], while also increasing human energy expenditure and water requirements [65]. The uncertainty in this estimate likely reflects shared variance with evapotranspiration and precipitation, and future studies with larger samples may be better powered to disentangle these correlated hydro-climatic exposures.

Considered together, our climate findings support a coherent theoretical framework where water availability (captured by precipitation) and water stress (captured by evapotranspiration) represent the primary hydro-climatic drivers of nutritional vulnerability in semi-arid East African settings. This pattern aligns with broader evidence from climate-health studies in sub-Saharan Africa, where water-related variables often show stronger associations with health outcomes than temperature alone [66, 67].

Several limitations merit consideration in interpreting these findings. The use of annual aggregations, while necessary for linking climate exposures to growth outcomes, may attenuate effects tied to critical seasonal timing of precipitation and temperature extremes [68]. The bimodal precipitation pattern in northern Tanzania means that the timing and distribution of precipitation within the year significantly influence agricultural productivity and food security [69]. Future studies incorporating seasonal climate metrics may reveal stronger or more nuanced associations.

Additionally, while the 5-km buffer zones provide reasonable catchment proxies based on established evidence of school travel distances in Tanzania [34], some children may originate from more distant areas, potentially introducing exposure misclassification. The moderate multicollinearity between evapotranspiration and precipitation reflects the inherent interdependence of these hydro-climatic processes, though the sensitivity analyses confirm that both variables contribute unique predictive information. Data collection took place over a six-year period, during which an ongoing development project was implemented in the study area. While it is possible that interventions introduced as part of this project may have influenced the nutritional status of students, we believe their effect within this time frame was likely limited. Additionally, it was not possible to account for broader secular trends in nutritional status over time, which may have affected the observed patterns.

This study offers several key strengths that enhance its contribution to the literature on nutrition and climate variability in sub-Saharan Africa. First, the use of high-resolution, locally collected anthropometric data from development projects (2010-2015) enables a detailed examination of thinness among school-age children and adolescents in the Mount Meru ecosystem. Unlike national surveys such as the Demographic and Health Surveys, which often underrepresent remote rural communities due to low population density, seasonal migration patterns, and limited infrastructure, this dataset captures localized nutritional dynamics in a diverse ecological and socio-economic setting. This approach demonstrates the value of secondary analysis of ad hoc data for uncovering context-specific patterns of undernutrition that are often obscured in broader datasets.

Second, this study addresses a critical gap in nutrition research by focusing on school-age children and adolescents, a population historically understudied compared to children under five, which have been deeper studied [37, 38, 70, 71]. By identifying age- and sex-specific vulnerability windows, such as the peak in thinness probability for girls at ages 10-12 years and the sustained risk for boys into mid- and late-adolescence, this study points out the need for developmentally tailored nutritional interventions rather than uniform strategies. These findings are particularly relevant given the heightened nutritional demands during adolescence and the long-term implications for health and human capital.

Third, the integration of hydro-climatic anomalies (precipitation, evapotranspiration, and land-surface temperature) with livelihood strategies provides a novel framework for understanding the interplay of environmental and socio-economic drivers of undernutrition. Notably, the use of evapotranspiration as an integrated indicator of water stress emerges as a particularly sensitive predictor of nutritional outcomes, offering a promising tool for climate-informed nutritional surveillance in semi-arid regions like Mount Meru. This approach extends beyond traditional meteorological indicators, enhancing the granularity of climate-nutrition research.

Finally, the study's findings offer actionable insights for public health and climate adaptation strategies. By highlighting the elevated vulnerability of pastoralist communities and the critical role of hydro-climatic factors, particularly the strong association between elevated evapotranspiration and increased odds of thinness, these results support the development of targeted interventions. These include enforcing school feeding programs as per national policy in Tanzania, promoting affordable and more diverse and nutritious school menu from locally grown cereals, indigenous green leafy vegetables and legumes [72, 73], raise awareness of the risks of extreme thinness among teachers and parents, promote school gardens where feasible, and livelihood-specific adaptation measures, such as integrating evapotranspiration monitoring into early warning systems to mitigate nutritional risks in climate-vulnerable communities.

Conclusions

This study advances the understanding of how hydro-climatic variability and livelihood strategies are linked to thinness among school-age children and adolescents in the Mount Meru ecosystem. To our knowledge, this is among the few studies to quantify how climate variability, captured through anomalies in evapotranspiration, precipitation and land-surface temperature, relates to undernutrition beyond early childhood, extending evidence to the often-neglected school-age and adolescent groups. These findings fill an important knowledge gap between under-five nutrition research and the growing focus on adolescent health, while underscoring the need for interventions sensitive to both environmental and socio-cultural determinants.

By revealing age- and sex-specific vulnerabilities, heightened risks in pastoralist communities, and the pivotal role of hydro-climatic anomalies, particularly evapotranspiration, as drivers of nutritional outcomes, these findings advocate for targeted, climate-informed interventions. Integrating indicators like evapotranspiration into nutritional surveillance systems can enhance early warning and response, supporting school feeding programs and livelihood-specific adaptation measures. These efforts are critical for achieving SDG 2 (Zero Hunger) in climate-vulnerable regions. Future research should explore seasonal climate effects and validate these findings across East Africa to strengthen food security and resilience for underserved populations.

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Declarations

Authors' contributions

SC: conceptualization, methodology, writing, review and editing; NM: methodology, writing, review and editing; AM: methodology, writing, review and editing; MS: conceptualization, methodology, writing, review and editing; MP: conceptualization, methodology, formal analysis, writing, review and editing.

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Data availability

The data that support the findings of this study are not publicly available due to confidentiality restrictions. Anonymized datasets are however available from the corresponding author upon reasonable request.

Ethics approval and consent to participate

This study is based on secondary analysis of biometric data and publicly available data (climate data). The biometric data was collected by government authorities as part of public health activities. The first wave and teacher's training was conducted by the parastatal agency Tanzania Food and Nutrition Centre of the Ministry of Health with the mandate to plan, initiate, and coordinate food and nutrition programs, conduct research, and provide expert advice to the government on nutrition issues, and a local NGO, Oikos East Africa. Biometric data was not collected for research purposes, but to inform a public health intervention on food security.

In accordance with national regulations governing health research in Tanzania, routine data collected by government authorities for public-health programming, and subsequently provided in anonymized form for analysis, are exempt from formal ethical review because they do not constitute human-subjects research [nimr.or.tz].

For this study, the research team received a fully de-identified dataset from district health authorities who in turn had received them from the schools. All personal identifiers were removed prior to transfer, and no attempt was made to re-identify any individual. The dataset contained only information obtained through government-mandated public-health activities and therefore fell outside the categories of research requiring ethical clearance as stipulated in the NIMR Guidelines on Ethics for Health Research in Tanzania [74], which specify that secondary analysis of anonymized, non-research public-health data does not require review by the National Health Research Ethics Committee [nimr.or.tz]. These characteristics align precisely with Sections 24.1.7 and 24.2, which classify such activities as non-research and therefore exempt from formal ethical review, including review by the National Health Research Ethics Committee (NatHREC).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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