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Mineral Nutrition of Samburu Adolescents:

A Comparative Study of Pastoralist Communities in Kenya

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Running title (48 characters): Mineral Nutrition of Samburu Adolescents

Abstract

Objectives: This study aimed to characterize mineral nutrition (copper, magnesium, selenium, and zinc) in Samburu pastoralist youth, in the context of differential cultural transitions due to uneven changes in educational access, herding intensity, polygyny, and access to wild, domesticated, and market-sourced foods.

Materials and Methods: Whole dried blood spots were collected in a total of 161 youth (highlands, $n = 97$; lowlands, $n = 64$) to assess concentrations of: cadmium, copper, lead, magnesium, mercury, selenium, and zinc. Concentrations were determined through Inductively Coupled Mass Spectrometry. Dietary intakes were assessed by 24-hour recall method and calculation of probability of inadequate intakes. WHO protocols were applied to collect anthropometric measures in the youth.

Results: Nearly half of the adolescents (47.8%) fell below the reference range for zinc status, and 88.2% had low zinc-to-copper ratios. High probability of nutrient inadequacies were evident for protein, fat, vitamins A, B_{12}, C, and E. In generalized linear modeling, lowland residence was negatively associated with zinc status and the zinc-to-copper ratio, and positively correlated with selenium and copper status. Other significant correlates were: dairy livestock ownership; wife number of the youth's mother; meat consumption; vegetable consumption; protein intake; infectious disease morbidities; BMI; and hemoglobin concentrations.

Discussion: In recent decades, Samburu pastoralists of northern Kenya have experienced marked dietary changes in the context of market integration, extreme drought, diminishing pasture availability, and violent civil conflict. Some children (particularly boys) successfully supplement their diets by foraging for wild foods, while others (particularly actively herding girls) may be more vulnerable.

Keywords (3-5): mineral nutrition, adolescents, pastoralism, environment, polygyny

INTRODUCTION

Adolescence is a vital period of human life history when rapid growth and developmental trajectories are especially sensitive to socially and environmentally mediated exposures (Bogin, 1999). Northern Kenyan pastoralist youth may be vulnerable to malnutrition in view of recent transitions from mobile livestock rearing to mixed livelihoods including cultivation, increased sedentarization, and greater emphasis on market foods (Fratkin, 1991; Fratkin, Roth, and Nathan, 2004; Little and Leslie, 1999; Shell-Duncan and Obiero 2000). However, studies of the transition to market foods in South American foraging communities have been mixed, with some positive results (Urlacher et al., 2016). These contrasting findings point to the need for further study. For pastoralist youth, daily activities in the changing pastoral livelihood sector shape the types of food they access and are thus of potential importance for nuanced understandings of the human biological impact of secular trends in northern Kenya.

Animal source foods represent a critical source of bioavailable minerals but are often inaccessible to low-resource populations globally (Iannotti 2018). In Samburu pastoralists, access to pasture has diminished due to drought, conflict and changing land tenure (Lesorogol and Boone 2016). Moreover, the past three decades has seen an increased frequency in the strategy of families selling goats and sheep to purchase market foods (Holtzman, 2009). We previously demonstrated that among highland Samburu pastoralists, milk consumption has declined dramatically in recent years (Iannotti and Lesorogol, 2014a), and the prevalence of undernutrition as indicated by low body mass index Z (BMIz) values was high: 57.6% for 12-14 year olds and 54.6% for 15-17 year olds (Iannotti and Lesorogol 2014b; Pike et al. 2016; Pike et al. 2018). Here, we focus on the mineral nutrition in Samburu adolescents living in two highly differentiated communities (highland, lowland) reflecting different livelihood strategies in changing pastoralist economies (Straight 1997, 2007). Specifically, an increasing emphasis on market foods characterizes both the lowland and highland regions, but the allocation of young people's labor and emphasis on education continues to differentiate these two communities in ways important to mineral nutrition, with more herding in the lowlands and more educational attainment in the highlands.

Mineral nutrition has multiple determinants beginning at the cellular level and extending to social and physical environmental contexts. In human biology, mineral status impacts multiple systems and pathways manifesting in growth during childhood and adolescence, immune function, reproductive health, and neurodevelopmental outcomes, among others (Gropper et al. 2012). Additionally, in this analysis, we highlight a range of key cultural, behavioral, physiological, and environmental factors linked to mineral status. Mineral availability for human nutrition may also be driven by ecological stochiometry or flows through ecosystems, recently disrupted by the effects of climate change (Myer et al. 2014; Sterner and Elser 2002). This is especially the case with soil selenium which influences plant and animal selenium status. The environmental conditions of elevated CO_2 and temperature, drought, waterlogging, and other stressors impact food production and nutrient concentrations in plants (Soares et al. 2019). Here, we draw on a theoretical framework including proximal to distal factors underlying malnutrition, posited in its original form over three decades ago (UNICEF 1990), and integrate it with an ethnographically informed biological anthropological approach. We examine the potential synergies between human-landscape interactions and cultural norms as proximal and distal factors that manifest as nutritional outcomes.

The original study was designed to comparatively examine health and psychosocial effects of resource availability and violence exposure in the daily lives of pastoralist adolescent girls and boys aged 10-19 years. Sites were selected based on dramatic contrasts in the environment and practice of pastoralism, intercommunity violence risk, and accessibility to market and social service infrastructure. Samburu lowland communities are hotter and drier, rely more on semi-nomadic or transhumant pastoralism, and exhibit higher rates of polygyny, compared to the highlands. Access to education, healthcare, and markets is greater in the highlands vs lowlands. Here we aimed to describe differences in mineral status between youth living in highlands compared to lowlands. Secondarily, we characterized factors derived from the theoretical framework in association with mineral status: dietary and nutrient intakes including with respect to wild sourced foods; differences in daily movements; health status of the youth; wealth represented in livestock ownership; and the cultural practice of polygyny.

METHODS

Samburu County is located in the Rift Valley of north-central Kenya, an arid and semi-arid-land (ASAL) region whose roughly 220,000 inhabitants are among the 10 million Kenyans most affected by recurrent extreme drought (Bollig and Lesorogol 2016). The Samburu are semi-nomadic pastoralists who herd goats, sheep, cattle, and camels and in wetter, highland, areas engage in some cultivation. In Samburu families, each wife builds and maintains her own house (the ‘house’ level in our study), exercising control over milk and her cooking pot. The father controls the sale of livestock and manages the entire family herd (the ‘family’ level in our study) as well as the labor of wives and children. Sons eventually inherit the livestock over which their mothers are accorded use rights. In response to environmental extremes; more circumscribed pasture availability; chronic food and water insecurity; and social inequality, Samburu households have sought to diversify income earning strategies. Trade and wage-labor strategies have increased for decades (Lesorogol 2008; Straight 2007).

Observations occurred from June to July 2017 after a 2016 methods pilot. Two Samburu sites, one highland and one lowland, were selected so as to compare the influence of environmental and socio-economic conditions on adolescent health. The highland site is characterized by lower per capita livestock holdings, higher rates of intentional monogamy, and better infrastructure. The lowland site in contrast, has higher per capita livestock holdings, higher polygyny rates, and less infrastructure. Youth were recruited using the WHO definition of adolescence, based on the following eligibility criteria: estimated ages of 10-19 years in an age-, gender-, and wealth-balanced distribution; residence in the highland or lowland site; and in good health. Exclusion criteria included: pregnancy for girls; severe malnutrition (weight-for-height Z score<-3); and age outside the 10-19 years range. There were no refusals to participate in the study.

The sample size was pre-determined based on the original study designs and population for each site (highlands, n = 97; lowlands, n = 64). The lowland site has a lower population density. Power calculations (α = 0.05 and β = 0.80) using mineral means and SD were conducted to determine the necessary sample size for detecting significant differences. Estimates varied by mineral indicating a range of sample size necessary: n = 10 (copper) to n = 170 (selenium) to n = 286 (zinc). The study was approved by the Western Michigan University Human Subjects Institutional Review Board and permission to conduct research was granted by Kenya’s National Commission for Science, Technology and Innovation.

Additional details on study site and sample recruitment may be found in *Supplementary Section A.*

Biomarkers
Our primary outcome of interest in this study was the status of essential minerals in the Samburu youth – copper, magnesium, selenium and zinc. While the DBS method enabled us to study some minerals and metals in the challenging field environment without cold chain or storage capabilities, it did not allow for inclusion of some important limiting nutrients such as iron and iodine. Toxic metals were also analyzed and published elsewhere (Ashley-Martin et al. in press). We include them here to examine for potential interactions. As divalent cations, zinc and copper interact in metabolic pathways and may impact oxidative stress when the ratio is low. We therefore examined the zinc-to-copper ratio in the adolescents along with other minerals.

For the DBS protocol, whole blood by lancet finger prick was first collected on Whatman 903 filter paper. Risk of contamination of filter paper was mitigated through handwashing and handling protocols as well as proper punching instumentation. Samples were then dried for four hours in a cool place and transferred to field clinic refrigerators in less than 24 hours, where they were packaged in groups of ~5 with humidity sponges. The cold chain was unbroken from field to lab by means of a hand-carried YETI cooler with frozen YETI ice when in transit. A stopover in Europe permitted refrigeration, replacement of humidity sponges, and newly frozen YETI ice for the Europe-to-U.S. leg. Humidity sponges were replaced again when transferred to refrigerator in U.S., then cold-shipped to the Biodemography Lab at the University of Washington's Center for Studies in Demography and Ecology (CSDE) where they were tested for CRP and anti-EBV antibody (Detailed methods are described in Supplementary Section). Time from refrigerator storage to -20 freezer at University of Washington was 17-35 days (earliest to latest samples).

The DBS samples were then shipped to ZRT Laboratory (Beaverton, OR) where they were analyzed for the minerals and metals. Two 6-mm punches and 0.55 mL of extraction solution were used for the analysis. Samples were extracted in 96-well fritted filter blocks using dilute ammonium hydroxide, L-cysteine, ethylenediaminetetraacetic acid (EDTA), triton-X, and internal standard. An amount of 0.55 mL of extraction solution was added plus internal standards (germanium, indium, and iridium), and then the block was shaken and centrifuged to produce the extract to be analyzed. The blood spots were run on Inductively Coupled Mass Spectrometry (Perkin Elmer NexION 300D ICP-MS with Dynamic Reaction Cell Technology) in kinetic gas mode using helium, and employing a micro-flow pump and nebulizer to make effective use of the small sample volume. Element masses were selected based on abundance and potential interferences. Prior validation work was conducted to determine intra- and inter-assay precision. Intra-assay precision was based on 20 sample replicates, and the CV was <8.3% for all analytes. Inter-assay precision for both low and high samples for each analyte was tested during 12 sample runs over 1 month, keeping samples at room temperature to replicate conditions of collection and transport in areas without refrigeration. The CV for inter-assay precision was <15.1% for all analytes.

Healthy reference ranges were established by ZRT Laboratory drawing the evidence base: zinc (mg/L) 5.04-8.46; copper (mg/L) 0.59-1.03; magnesium (mg/L) 27-49; selenium (ug/L) 116-314; cadmium (ug/L) <1.04; zinc:copper raio 6.6-10.8. Although reference ranges were not available for the Samburu population, element testing is highly standardized through proficiency programs including official proficiency programs such as CAP Blood Lead (BL) and Trace Metals Whole Blood (TMWB). Samples below the limit of detection were assigned values of LOD/√2 (NHANES).

Hemoglobin concentrations were measured using Hemocue Hb201+. Morbidities, considered as exposures, were assessed by asking an individual if she/he was currently experiencing any symptoms of illness, and second, what symptoms she/he may have experienced in the previous 24 hours. WHO hemoglobin cut-offs were used to define anemia: children ages 5-11 year, <11.5 g/dL; children ages 12-14 yrs, < 12.0 g/dL; nonpregnant girls 15 yr or older, <12.0 g/dL; and boys 15 yr or older, <13.0 g/dL.

Anthropometry and Body Composition
Anthropometric indicators of growth and body composition were examined as confounders related to youth's mineral status. Training was administered with the enumerator team over a two day period in 2015, and over a two period again in 2017 to refresh skills for the collection of anthropometric measures of height, weight, and skinfold thicknesses using WHO protocols and Lohman procedures (Lohman, Roche, and Martorell 1988; WHO 2006). Validation exercises against a gold standard enumerator were undertaken in a small sub-group of adolescents. Two enumerators recorded measures of height using a stadiometer (seca GmbH & Co. KG, Hamburg, Germany); two measures were taken and if the measures differed by 0.5 cm a third was taken to average with the closest measure. Similarly, weight was measured two times on a Seca model 213 electronic digital scale (Seca GmbH & Co. KG, Hamburg, Germany) to the nearest 0.1 kg, and if measures difference by 0.5 kg, a third measure was recorded. Measures were later converted to BMI and Z scores (HAZ and BMIz) using WHO Reference 2007. Skinfolds measures on triceps, subscapular, and supra iliac were taken on Lange skinfold calipers following procedures from (Lohman, Roche, and Martorell 1988). We later converted the skinfold thicknesses to muscle and fat areas using the following formulas:

$$\text{Area} = \pi/4 * (\text{circumference}/\pi)^2$$
$$\text{Muscle area} = [\text{circumference} - (\pi * \text{skinfold thickness})]^2/4\pi$$
$$\text{Fat area} = \text{area} - \text{muscle area}$$

Dietary intakes and probability of inadequacy approach
Dietary intakes were assessed using an adaptation of the 24-hour recall method. The youth were asked to recall whether they consumed tea in the morning yesterday and whether the tea had milk or sugar. Next, they were asked to recall if they consumed another item for breakfast, the quantity, and who gave them the food. This sequence of questioning was repeated for lunch and dinner, with prompting to recall if they had accessed any wild foods. One plate was converted to 0.5 kg and 1 cup to 0.5 liter. When more than one food was reported by plate units, estimated proportions were made based on usual diets in Samburu.

Quantified dietary intakes were then used to calculate total intakes of energy, macronutrients and micronutrients by the youth and probability of inadequacies for the various nutrients, described below. First, the energy and nutrient concentrations per 100 g for the food items reported consumed in this Samburu population were determined using the USDA food composition database (USDA 2019). The USDA database contains one of the most comprehensive set of foods globally including those from Kenya. Next, the total intakes of energy, macronutrients (carbohydrates, protein, and fat), and micronutrients (vitamins A, B_{12}, C, E, folate, calcium, magnesium, selenium, zinc) were estimated based on total reported intake in the 24-hour reporting period by the youth and the USDA concentration values. These nutrient intakes were characterized based on availability in the USDA database, potential influence on mineral status, and plausible role as limiting nutrients in this context. We then applied the full probability approach to compare nutrient intake levels relative to normative standards of adequacy (Gibson 2005). This allows us to consider the entire intake distribution rather than a single threshold cut-point. We selected nutrients using the following criteria: normally distributed; assessed in the blood biomarkers for this study; and those previously identified as deficient in low-resource settings. Dietary Reference Intakes were used based on age and sex of the children (National Academies 2019).

We also assessed youth morbidities by inquiring about the current symptoms youth were experiencing as well as those experienced in the previous 24 hours. In regression modeling, we examined the total number of different morbidities experienced, as well as varying cut-points (e.g. 1 vs 2 or more different morbidities).

Socio-economic factors

We also examined socio-economic factors as potential confounders associated with area of residence and mineral status outcomes of the youth. Livestock wealth was assessed through tropical livestock units (TLU), weighting different categories of livestock according to the current exchange values in the community (Ensminger 1992; Jahnke 1982). One TLU was equivalent to: 0.7 camel; 1 cattle; 10 sheep; 11 goats. We examined both *total TLUs* (for the entire family) to provide an estimate of overall wealth, and *per house TLU* (total TLU/number of wives) to estimate livestock wealth for the youth's house only. In order to measure youth access to milk, we also calculated *dairy-only TLUs per house* (dairy TLUs for participant house/mother's milk herd), and the *per capita dairy TLU* (dairy TLU per house/number of individuals in house). Because of non-normal distributions, we transformed the *per house TLU* and *per capita dairy TLU* using natural logarithm and into quartiles to examine in the regression models.

We assessed level of education by asking if the adolescent was currently in school, how many total years of formal education received, and highest level reached. Number of siblings and birth order was also accounted for in analyses although not hypothesized to be associated with mineral status. Finally, we investigated the influence of living in polygynous families on nutrition by assessing differences within and across the house and family levels. We tested differences between adolescents whose mother was the first wife versus second or higher, and if the adolescent belonged to a polygynous or nonpolygynous family.

Statistical analyses

Descriptive statistics were used to examine sample characteristics. Kernel density estimation plots and the Shapiro-Wilk test assessed the normality of the mineral concentration distributions. Univariate analyses were then applied to test for signficant associations between area of residence and key variables including those at the individual level (e.g. age, sex, nutrition and dietary intakes, health status) and house or family level (e.g. polygyny, mother wife number, expenditures, livestock ownership, and demographic characteristics).

Generalized Linear Modeling (GLM) was applied to test the significance of area of residence in association with the four essential mineral outcomes – copper, magnesium, selenium, and zinc. The zinc-to-copper ratio was also included to examine interactions in these nutrients that might impact oxidative stress emerging from the two divalent cations (Valko, Morris, & Cronin 2005). We applied GLM to account for any nonlinearity in the error terms of the response variables. Other covariates were added based on the theoretical framework in a stepwise process. Covariates were retained in the model if the β coefficient was significant or trending signficant (P < 0.10).

Regression diagnostics were applied to examine collinearity (using variance inflation factor and covariate correlations greater than 0.7) and goodness of fit using adjusted R^2 and Akaikes Information Criteria (AIC) and Bayesian Information Criterion (BIC) to identify models explaining the greatest degree of variation with the fewest number of covariates. Age, sex of the child, and total energy intakes were included in all models as confounding factors (Willet 1999). We assesed effect sizes using the β coefficients of the GLM models as well as a standardized difference in means using Cohen's D (Cohen 1988). All data analyses were performed in STATA software (version 16.0; StataCorp, College Station, TX).

RESULTS

A total of 164 eligible adolescents were recruited for the study, with fewer identified from the lowlands. Three individuals were later excluded: one due to pregnancy and two due to parental fears of finger pricks. Thus, the remaining study sample was: highlands (n = 97); and lowlands (n = 64). Lowland youths showed a mean higher age than highland youths (**Table 1**). Education also significantly differed by area of residence, with less than one half of the youth from the lowlands currently in school and a mean number of years in school below that seen in the highland youth. Lowland girls had the lowest rate of school attendance (38.2%) compared to lowland boys (60.0%), highland girls (89.8%), and highland boys (89.6%). No difference was seen in the proportion of youth whose mothers were first wife, second, or third and above. Livestock ownership was greater in the lowlands with significant differences across all livestock categories and TLU. *Per capita dairy* TLU for the youth household unit was substantially greater in the lowlands, over six-fold times the number seen in the highlands.

The mean and/or median values for the essential minerals examined - copper, magnesium, selenium, and zinc – fell within the ZRT laboratory reference ranges (**Table 2**). However, nearly one-half of the youth fell below the reference range for zinc, with significant differences apparent by area of residence: highlands vs. lowlands (P = 0.03). A high percentage of the adolescents had zinc-to-copper ratios below the reference range, with no significant differences by area of residence. Only 8 adolescents, all from the highlands, showed lower selenium concentrations than the reference range. In unadjusted analyses not accounting for age differences, all anthropometric indicators were greater in the lowlands with the exception of arm muscle area. Hemoglobin concentrations were significantly higher in the highlands than lowlands, particularly in highland girls (13.0 ± 1.4 g/dL) compared to lowland girls (11.3 ± 2.0 g/dL)(P<001). Among the adolescents with exact age reporting (n = 83), there was a 28.9% prevalence of anemia and signficantly different prevalence by residence (P = 0.01), with the highlands at 23.3% and the lowlands at 50.0%.

Milk consumption (84.1%) was high, largely coming from "mixed tea" (tea with milk). Consumption of other animal source foods, however, was low: 15.3% of the youth reported any meat consumption in the previous 24 hours. There were significant differences in meat consumption by sex, with a higher proprotion of boys (24.4%) consuming any meat compared to girls (7.2%)(P=0.003). Reporting for the past month, 11.8% of boys (and no girls) reported consuming wild meat, hunted or scavenged by themselves, their brothers, or warriors. Youths reported that most food, including meat and milk, came from their mothers, but other providers included other older relatives, siblings, and neighbors (**Table 3**). Protein as a proportion of total kcal was low, 12.8 % (SD 5.1), as was fat, 15.2 % (SD16.0) relative to carbohydrate intakes 71.8% (SD 20.4). Vegetable consumption was also low, with only 27.0% reporting any cabbage, kale, or other vegetables in the previous 24 hours. Nutrient inadequacies were widely prevalent in the youth affecting greater than half for many nutrients (**Table 4**). Vitamins A, B_{12}, and C, calcium, and selenium showed notably high intake inadequacies.

Regression models revealed that several factors mapping to individual, house, family, and regional levels of the framework were associated with mineral status in the youth (**Table 5**). *Area of residence* was significantly associated with all mineral outcomes except magnesium, showing high effect sizes in the mean differences as represented in the Cohen's D metric: 2.72 (copper); 6.96 (selenium); 3.32 (zinc); and zinc:copper ratio (1.99). Copper and selenium positively associated with living in the lowlands; and zinc and the zinc-to-copper ratio was negatively related to lowland residence. At the level of the individual, there was a high degree of inter-mineral and metal correlations, including: cadmium positively associated with copper and magnesium; lead for selenium; and mercury for magnesium and zinc-to-copper ratio; and selenium across all mineral outcomes. Higher proportion of protein intakes was positively associated with zinc status. Other nutrient intakes associated with mineral outcomes were vitamins A, C, and folate. BMI was negatively associated with copper and zinc-to-copper ratio, and hemoglobin concentration showed a strong positive association with magnesium and selenium. Reporting of two or more morbidities in the previous 24 hours was negatively associated with magnesium and zinc.

At the house and family levels, livestock ownership and polygyny both showed associations with mineral status. Positive associations were found for *per capita dairy TLU* with zinc*, per house TLU* with magnesium, and total number of dairy sheep and goats with selenium. Youth whose mother was wife number two or greater showed a negative association with copper and zinc status. We also tested for differences in mineral nutrition within polygynous households, and for polygynous versus nonpolygynous families. No significant differences were apparent for polygynous households compared to non-polygynous households across the minerals. However, there was a trend for high zinc status in youth whose mothers were first polygynous or non-polygynous wives, compared to youth of mothers who were wife number two or greater.

DISCUSSION

This study is the first to characterize the mineral status of Kenyan pastoralist youth. Mineral status and nutrition more broadly may reflect cultural norms, environmental conditions, food system dynamics and human behaviors largely mediated through dietary patterns and biological pathways. Our findings confirmed the importance of regional differences in labor and dietary changes affecting pastoralist young people, though directionality of associations with area of residence were inconsistent. Highland youth showed better zinc status, while those in the lowlands had greater selenium concentrations. These differences emanated from livestock ownship, family structure, and likely environmental conditions, and could have varied with labor and education patterns by sex of the child. Across all adolescents, there was clear evidence for malnutrition risks, evidenced by inadequate nutrient intakes, poor zinc status, low BMI, and rates of anemia. This study also revealed differences in how foods were acquired, including from schools, neighbors, warriors, a variety of family members, as well as self-provisioning of wild foods consistent with cultural and gender norms. These nuances in changing livelihood patterns may explain differences in nutritional outcomes that require additional study. There is a need to deepen the evidence base for pastoralist well-being and, specifically, to mitigate the health and developmental consequences associated with mineral nutrition in adolescents.

Minerals, the environment, and adolescent movement across the landscape

Area of residence was significant for three of the four minerals studied - copper, selenium, and zinc - after adjusting for several potential confounding factors. Standardized effect sizes were also shown to be large for these differences in mineral status by area of residence. Selenium and zinc play critical roles in antioxidant defense, thyroid metabolism, growth, immune and reproductive functions (Thomson 2013). While we recognize that disentangling the precise pathways may be challenging, findings suggested a potential role for ecosystem dynamics in the availability and flow of minerals. Pastoralists live and work in close proximity to animals and their landscapes to a greater extent than many populations, offering an interesting opportunity to study minerals at this interface.

Plants and animals raised in ecosystems depleted of minerals will similarly manifest these deficiencies. A recent study in Western Kenya showed variability in the nutritive value of pasture vegetation for ruminant feed; iron and selenium were greater in highlands and during wet seasons (Onyango et al. 2019). This contradicts our findings for higher selenium values in the youth of lowlands, but is consistent for our zinc findings. Another study compared plasma selenium concentrations among pregnant women in two countries with high (Phillipines) and low (Malawi) soil selenium levels (Gibson et al. 2011). Plasma selenium was significantly lower in Malawi and associated with consumption of animal source foods. In Ghana, findings showed serum copper, selenium, and zinc concentrations were higher in adults living in rural areas compared to urban (Asare and Nani 2010). Although beyond the scope of this study, our findings suggest a need for further investigation into the mineral content of soils and plants that feed livestock and ultimately humans, across lowlands and highlands. Differences in the youth may also likely be driven by other environmental factors such as level of rainfall or seasonality, as well as vector-borne disease, e.g., malaria, related to altitude. Climate-changed induced effects on elevated CO_2 particularly has been shown to reduce zinc and iron across C_3 grasses (wheat, rice), C_3 legumes (field peas, soybeans) and C_4 grasses (maize, sorghum)(Myers 2014).

Two factors are of particular importance for our study as they affect the human-environment interface and the foods young people access: herding compared to education focus; and the 2016-2017 drought affecting Samburu County that preceded data collection. Based on 2016 pilot data during the drought (Straight and Hilton, in prep.), children in both regions reported food insecurity (71% skipped meals) and thirst (80% lacked suficient drinking water). Moreover, highland children of both sexes spent more time in school while lowland children spent more time herding, covering farther daily distances. These differences were significant based on pedometer and focal follows data in the pilot. Highland girls spent the least time herding, while lowland girls spent the least time in school (Straight and Hilton, in prep.). This is consistent with educational attainment in the total sample (Table 1), with 90% school attendance for highland girls and boys, 60% school attendance for lowland boys, and 38% attendance for lowland girls. Since children typically access wild fruits while herding, soil composition and nutrient content of particular fruits would be likely to have an impact on mineral nutrition. Lastly, boys, but not girls, reported consuming wild meat (e.g., small-bodied birds and mammals) in the past month that they hunted for themselves or that older brothers shared with them. Hunting small animals is a typical behavior for Samburu boys in both the highlands and lowlands. Hunting is rarer for girls, although girls in some lowland families might occasionally do so (Straight, unpublished data).

Also relevant to the human-environmental relationship, lowland participants – both girls and boys – were herding animals in more remote areas at higher elevations during the 2016-2017 drought, often going into the Matthews Mountain Range adjacent to their communities (Straight and Hilton 2017). The Matthews is characterized by gneisses, with some areas rich in ferromagnesian minerals, and well-drained, rocky, humus soils (Touber 1989). Whereas youth – mostly boys – from the highland sites take their animals to areas likely more environmentally degraded due to greater accessibility from surrounding communities and the increased population density relative to the lowlands. Resulting differences in vegetation consumed by livestock – whether due to soil mineral content or other envrionmental conditions - may partly explain mineral differences for these lowland youth compared to those in the highland site, and warrants further study.

Mother's House and Family: Socio-economic drivers

At the house and family level, our findings show consistent associations between mineral status and livestock wealth, and the practice of polygyny. These factors were likely linked to access to certain foods such as milk, meat, fruits, and vegetables. Additionally, gender patterns emerged, as noted above, in the kinds of foods reportedly consumed and how they were acquired. Iannotti & Lesorogol (2014b) previously demonstrated that livestock ownership among highland Samburu pastoralists is positively associated with dietary diversity and nutrient adequacy for vitamins A, B_{12}, and zinc while income predicts dietary diversity and vitamin C adequacy. Galvin et al. (2015) have shown greater dietary diversity and nutrient intakes with better access to markets. We found higher intake levels for some nutrients in the highland youth compared to those in the lowlands, but not for all nutrients (**Table 3**). Some differences could be explained by higher rates of school attendance in the highlands, where market foods are eaten that include some vegetables. Lowland girls have the least access to school-sourced foods in our sample. In contrast, boys reported most of the wild foods (meat, fruits, honey) and reported more meat intake overall. Girls, in contrast, reported somewhat more milk intake. This suggests gender differences in how youth acquire food that warrants further study. Some previous studies in Latin America have shown poorer health and nutrition-related outcomes associated with living close to markets or in urban compared to rural areas (Palacios et al. 2021), while other studies have found improved nutrition-related outcomes (Urlacher et al., 2016). A study of Tsimane children showed those living close (< 2 hours walk) to markets had higher helminth infections relative to those living at a mid-distance (2-5 hr walk) from markets (Tanner et al. 2014). Poor environmental conditions for hygiene and sanitation experienced in urban areas may explain these relationships.

Additional differences may be explained by greater livestock production, dairy in particular. Camel ownership and camel milk are almost exclusively in the lowlands, which could have an impact on lowland mineral nutrition. Fratkin (1991) noted, that for the nearby Ariaal pastoralists, camel milk consumption provides a key supplemental food item for pastoralists in the harsh arid landscapes of northern Kenya. We also found some evidence for own food production, dairy livestock ownership particularly, as a potential explanation for positive associations with mineral status.

The effects of polygyny on child health is equivocal in the evidence-base and not always consistent with evolutionary theory (Sellen 1999). Studies reveal a complex set of conditions can underly and drive the relationship between polygyny and child health (Lawson et al. 2015; Reiger and Wagner 2016). To our knowledge, no other studies have examined mineral nutrition in pastoralist youth in association with polygyny though child nutrition more broadly has been investigated. One review from Sub-Saharan Africa found that linear growth as indicated by height-for-age Z scores was greater in children from monogamous compared to polygynous mothers (Wagner and Rieger 2014). Also consistent with our findings for increasing wife number associated with poorer mineral status, Wagner and Rieger (2014) found an inverse relationship between growth and mother hierarchy within polygynous households. Different groups, including pastoralist communities, have been studied in Tanzania with varying findings. One showed that environmental vulnerability (rainfall) and marginalization (access to education) confound the relationship between polygyny, food security, and child health (Lawson et al. 2015). In these communities, polygynous households had greater wealth in terms of livestock and land and increased food security compared to non-polygynous households. Two other studies in Tanzania, however, found that after consideration of household wealth, children from polygynous households were at greater risk for growth faltering (Hadley 2004; Sellen 1999).

While our analyses did not find significant differences in mineral status in polygynous compared to non-polygynous households, our analyses did show a negative association between increasing wife number and adolescent mineral status in copper and zinc. This relationship held for within polygynous household differences in high zinc status for youth from first wives compared to those whose mothers are wife two or higher. Regression modeling indicated that the wife number of the mother was associated with consumption of any meat by the youth and relatedly, the proportion of protein in the total energy intakes (**Table 5**). In Samburu society, first wives generally enjoy higher status in the family and community compared to subsequent wives. Although each wife is allocated livestock with an expectation that she will have adequate means of support, first wives may have advantages due to the greater time length they have had in growing herds and establishing supportive social networks. First wives may also benefit from the support from their adult children. In cases of resource scarcity, first wives might therefore be better positioned to sustain their children's diet and welfare compared to later wives. Generally, adolescents eat meals at their mother's house, though they may eat away from home occasionally, and boys appear to be supplementing their meat through some hunting of wild birds and small animals, such as dik dik and gazelles. Our findings suggest reduced quality food access with increasing wife number leads to to diminished mineral status, which could be explained by some of these intra-family dynamics.

Mineral, dietary, and health interactions

We found evidence that markers of adolescent health and diet were associated with mineral concentrations. Anemia was widely prevalent, particularly in the lowlands affecting one-half of the adolescents, with lowland girls the most at risk for anemia. Our finding for positive correlations between hemoglobin concentration and mineral status is consistent with known anemia etiologies (de Benoist et al. 2008). Infectious disease morbidities showed negative relationships with zinc and magnesium status, again aligned with the evidence base for zinc's role in immune functioning (Black et al. 2013). Dietary intake findings corroborated our previous study in another community of Samburu showing low BMIz, declining milk consumption, and high probabilities of nutrient inadequacies in critical nutrients such as vitamin A, B_{12}, and C (Iannotti and Lesorogol 2014a, b).

Although few studies have examined biomarkers of nutrient status in pastoralist youth or even communities more broadly, our findings were largely consistent with the evidence base. One study in Ethiopia examined mineral status of school children ages 10-14 years (Amare et al. 2012). Although serum levels were investigated as compared to the whole blood concentrations used in our study, they also found a comparable percentage of zinc deficiency (47%), but higher percentage of selenium deficiency (62%). Another study in Central Mozambique carried out in girls only aged 14-19 years assessed diet using 24-hour recall and examined both nutrient intake levels and several biomarkers of nutrient status (Korkalo et al. 2015). The study found a 32.7% prevalence of low serum zinc, and anemia prevalence of 42.4%. Total intakes for several micronutrients were below those of the Samburu adolescents, but proportion of energy intake from different macronutrients were in almost parallel with findings from our study.

Limitations

The project was originally designed to study the effects of daily activities and risks, violence, and other risk factors on adolescent psychosocial stress in Samburu and thus, not *a priori* designed to examine nutrition and mineral status. Sample size may not have been sufficient to detect differences in region or other factors influencing nutrition in the adolescents. There were significant differences in age of the adolescents between highlands and lowlands, though we adjusted for child age in all models and showed no confounding effect. We were also limited by use of DBS in the breadth of minerals and metals investigated for this study. Iron and iodine, both commonly deficient minerals in low-resource populations, would have provided added insights here especially in view of the high anemia prevalence found. Although the laboratory analyzing the mineral concentrations established reference ranges drawing from populations around the world, they were not available for the Samburu population. Element testing is highly standardized when conducted on the same instrumentation, so this should not diminish the validity of the findings. Dietary intakes were measured using 24-hour recall, generally considered the gold standard in nutrition epidemiology (Willett 1999). However, because the recall was conducted at only one time point in a relatively small sample, we may not have entirely captured usual intakes or any seasonality effects. This is particularly true for capturing the consumption of wild foods.

Conclusion

This study uniquely characterized the mineral status of pastoralist youth, an important but largely neglected population in the literature. Descriptively, we found substantial differences in how lowland youths spend their time compared to highland youths in ways that impact the amount and type of market-, livestock-based, and wild foods they access. We also found gender differences that reinforce cultural norms, including greater access to meat through hunting for boys. These descriptive analyses have direct implications for adolescent pastoralist human biology and warrant additional focal follows study with larger sample sizes. As these daily activities manifest in mineral nutrition, we found evidence of low zinc status in nearly one half of the adolescents and extensive nutrient inadequacies, exceeding 50% across most nutrients. Anemia and infectious disease morbidities were highly prevalent and associated with poor mineral status. Our findings reinforce the multifactorial nature of human nutrition and suggest the need to intervene at multiple levels. Further, the variation in mineral nutrition across contexts confirms how change in the environment and liveslihoods impact human biology. Strategies to address the proximal factors of increased access to nutrient-dense foods and reduced infection might be combined with household interventions to better ensure livestock ownership and productivity. Broader contextual issues of climate change and degraded environmental conditions will require policy level action and concerted efforts across multiple actors, but must also remain a priority. Our study points to high risk of health and developmental consequences in these youth arising from malnutrition and in our view, merits attention.

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There were not conflicts of interest to declare for this study, “Mineral Nutrition of Samburu Adolescents: A Comparative Study in Pastoralist Communities in Kenya.”

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author, subject to restrictions imposed by Kenya's National Commission for Science, Technology, and Innovation (NACOSTI). The data are not publicly available due to NACOSTI rules and privacy or ethical restrictions.

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Table 1. Socio-economic and demographic characteristics, by residence†

	Highlands (n=97)	Lowlands (n=64)	All (n=161)	P value‡
ADOLESCENT CHARACTERISTIC				
Age, yrs	12.9 (2.2)	15.6 (2.5)	13.7 (2.5)	<0.001
Sex, % female	50.5	53.1	51.6	0.746
Birth order	4.2 (2.4)	3.5 (2.1)	3.9 (2.3)	0.106
Total number of siblings	5.6 (1.9)	5.3 (2.0)	5.4 (1.9)	0.311
Currently in school, %	89.7	48.4	73.3	<0.001
Girls, %	89.8	38.2	68.7	<0.001
Boys, %	89.6	60.0	78.2	0.002
Total years of school	6.4 (2.8)	4.7 (4.1)	5.71 (3.4)	0.002
Girls	6.6 (2.3)	3.2 (3.7)	5.1 (3.4)	<0.001
Boys	6.2 (3.2)	6.3 (3.9)	6.3 (3.2)	0.902
HOUSEHOLD CHARACTERISTIC				
Mother wife #, %				0.231
Wife 1	71.0	59.0	66.2	
Wife 2	19.4	31.2	24.0	
Wife 3+	9.7	9.8	9.7	
Monthly expenditures, US$§	53.3 (46.6)	128.6 (72.6)	83.2 (68.9)	<0.001
Livestock ownership				
Total TLU	6 (5-7)	17.1 (12-33.2)	9 (7-12)	<0.001
Per wife TLU	5 (3-7)	9.8 (6.5-14.68)	6.5 (5-8)	<0.001
Total dairy TLU	2 (1-2)	4.5 (3-17.1)	2 (2-3)	<0.001
Per capita dairy TLU	0.2 (0.17-0.21)	1.26 (0.71-1.5)	0.33 (0.23-0.4)	<0.001

†Means (SD) reported for normally distributed, continuous variables including: age; birth order; total number of siblings; total years of school. Medians (95% CI) reported for continuous variables non-normally distributed including: monthly expenditures; and livestock ownership variables.
‡ P value reported from ttest for normally distributed continuous variables; Wilcoxon rank sum (Mann Whitney) for non-normally distributed continuous variables; and chi squared for dichotomous variables.
§Reported in Kenyan Shillings converted to US$ - 2017 (*0.00948 in June 30, 2017).

Table 2. Nutrition and health status of Samburu adolescents, by residence†,§

	Highlands (n=97)	Lowlands (n=64)	All (n=161)	P value‡
Mineral biomarkers				
Copper, mg/L	0.9 (0.1)	1.12 (0.1)	1.01 (0.2)	<0.001
Below reference range, %	0	0	0	-
Magnesium, mg/L	35.30 (5.3)	38.50 (7.6)	36.57 (6.5)	0.002
Below reference range, %	3.09	4.69	3.73	0.601
Selenium, µg/L	140.0 (136.3-143.7)	205.0 (194.0-220.5)	155.0 (149.0-164.5)	<0.001
Below reference range, %	8.25	0	4.97	0.018
Zinc, mg/L	5.0 (1.1)	5.4 (1.3)	5.2 (1.2)	0.045
Below reference range, %	54.64	37.50	47.83	0.033
Zinc:Copper ratio, mg/L	5.4 (1.3)	4.7 (1.1)	5.2 (1.3)	0.006
Below reference range, %	84.54	93.75	88.20	0.076
Anthropometry				
Body mass index (BMI)	14.4 (1.9)	15.7 (2.2)	14.9 (2.1)	<0.001
MUAC, cm	18.0 (2.7)	19.3 (2.8)	18.5 (2.8)	0.004
Triceps skinfold thickness, mm[b]	5.3 (5.0-6.0)	6.0 (5.2-7.0)	5.7 (5.3-6.0)	0.342
Subscapular skinfold thickness, mm	4.0 (4.7-5.0)	6.7 (6.1-7.1)	5.3 (5.0-6.0)	<0.001
Arm fat area, mm	21.2 (19.3-22.9)	26.1 (23.5-29.3)	23.0 (21.5-24.3)	<0.001
Arm muscle area, mm	1.1 (0.7- 2.1)	1.5 (0.8-2.3)	1.2 (0.8-2.0)	0.332
Other health markers				
Hemoglobin, g/dL	12.9 (1.4)	12.0 (1.94)	12.5 (1.7)	0.001
Anemia, %	21.31	50.00	28.92	0.011
Any morbidities, %	53.6	40.6	48.5	0.107

†Means (SD) reported for normally distributed, continuous variables including: copper; magnesium; zinc; zinc:copper ratio; BMI; MUAC; hemoglobin concentrations. Medians (95% CI) reported for continuous variables, non-normally distributed including: selenium; triceps skinfold thickness; subscapular skinfold thickness; arm fat area; and arm muscle area.
‡ P value reported from ttest for normally distributed continuous variables; Wilcoxon rank sum (Mann Whitney) for non-normally distributed continuous variables; and chi squared for dichotomous variables.
§Healthy reference ranges were: zinc (mg/L) 5.04-8.46; copper (mg/L) 0.59-1.03; magnesium (mg/L) 27-49; selenium (ug/L) 116-314; cadmium (ug/L) <1.04; lead (ug/dL) <2.23; mercury (ug/L) <5.29; and zinc:copper ratio 6.6-10.8.

Table 3. Primary food source and food providers among adolescents

Primary food source†			
	Frequency		Percent
Home	127		78.9
Cattle camp	3		1.9
School	31		19.3
Total	161		100
Food Providers, 24 h intake‡			
	Provider 1 Frequency	**Provider 2 Frequency**	**Mean Percent**
Aunt	3	4	2.2
Father	1	-	0.3
Grandmother	10	10	6.2
In-laws	1	2	0.9
Mother	120	113	72.4
Mother's co-wife	4	4	2.5
Neighbor	4	5	2.8
Other relative	1		0.3
School	6	6	3.7
Self	3	5	2.5
Sister	8	9	5.3
Warrior	1	2	0.9
Total	161	161	100.0

†Youth were asked where they get more or most of their food at that time, representing the primary food source in recent weeks leading up to the interview.
‡ Youth indicated providers, primary (provider 1) and others (provider 2), of food in the 24 hour recall interview. Among all the youth, a maximum of two providers were reported. Mean percent was the average between providers 1 and 2.

Table 4. Daily dietary intakes of Samburu adolescents, by residence[†]

	Highlands (n=97)		Lowlands (n=64)		All (n=161)			
	Total intake (95% CI)	Inadequacy Proportion (95% CI)	Total intake (95% CI)	Inadequacy Proportion (95% CI)	Total intake (95% CI)	P value[‡]	Inadequacy Proportion (95% CI)	P value
Energy, kcal	1912.7 (1723.3-2102.0)	-	2206.1 (1954.9-2457.3)	-	2028.9 (1877.4-2180.5)	0.061	-	-
		-						
MACRONUTRIENTS								
Carbohydrate, g	366.0 (326.8-405.2)	-	353.7 (292.0-415.3)	-	361.1 (327.5-394.8)	0.7241	-	-
Protein, g	52.2 (47.5-57.5)	-	66.0 (63.4-73.7)	-	59.5 (57.5-62.1)	<0.001	-	-
Fat, g	19.8 (16.5-24.0)	-	33.5 (28.5-36.0)	-	24.8 (20.2-28.5)	<0.001	-	-
VITAMINS								
Vitamin A, µg	615.0 (243.6-615.0)	0.45 (.35-.55)	0.0 (0.0-20.0)	0.68 (.56-.79)	254.0 (10.18-615)	0.033	0.54 (.46-.61)	0.003
Vitamin B_{12}, µg	1.9 (0.9-1.9)	0.55 (0.45-0.64)	0.0 (0.0-1.8)	0.63 (0.52-0.75)	1.8 (0-1.85)	0.323	0.58 (0.51-0.65)	0.246
Vitamin C, µg	1.8 (0-1.8)	0.83 (0.75-0.90)	1.8 (0-3.6)	0.92 (0.85-0.99)	1.8 (0.1-1.80)	0.776	0.86 (0.81-0.92)	0.081
Vitamin E, µg	0.05 (0.05-0.08)	1.00 (1.00-1.00)	0.09 (0.05-0.09)	1.00 (1.00-1.00)	0.05 (0.05-0.05)	0.537	1.00 (1.00-1.00)	0.251
Folate, µg	257.0 (206.0-291.8)	0.60 (0.51-0.69)	387.5 (310.0-428.6)	0.41 (0.29-0.52)	300.0 (257-322)	<0.001	0.52 (0.45-0.60)	0.007
MINERALS								
Calcium, mg	697.5	0.80 (0.72-0.87)	340	0.69 (0.57-0.80)	697.5	0.785	0.75 (0.69-0.82)	0.113

	(630.0-748.2)		(250.9-782.3)		(444.07-720.90)			
Magnesium, mg	339.5 (309.2)	0.47 (0.38-0.57)	443.15 (234.97)	0.28 (0.18-0.39)	380.7 (285.4-404.7)	0.024	0.40 (0.33-0.47)	0.012
Selenium, µg	21.8 (12.7-34.5)	0.63 (0.54-0.73)	59.6 (44.2-69.6)	0.38 (0.26-0.50)	37 (21.9-51.7)	<0.001	0.53 (0.45-0.61)	0.001
Zinc, mg	9.1 (8.0-11.0)	0.36 (0.27-0.45)	11.6 (11.1-14.2)	0.24 (0.14-0.34)	10.95 (9.1-11.6)	0.002	0.31 (0.24-0.38)	0.078

†Means (SD) reported for normally distributed, continuous variables including: energy; carbohydrates; magnesium; and probability of inadequacy for all nutrients. Medians (95% CI) reported for continuous variables, non-normally distributed including: protein; fat; vitamins A, B12, C, and E; folate; calcium; selenium; and zinc.
‡ P value reported from ttest for normally distributed continuous variables; Wilcoxon rank sum (Mann Whitney) for non-normally distributed continuous variables; and chi squared for dichotomous variables.

Table 5. Generalized linear models of mineral status among the youth[1]

	COPPER			MAGNESIUM			SELENIUM			ZINC			ZINC:COPPER RATIO		
	β	SE	P	β	SE	P	β	SE	P	β	SE	P	β	SE	P
CONTEXT **Area Of Residence**															
Residence (highlands=0, lowlands=1)	0.087	0.032	0.006	-	-	-	49.655	7.135	0.000	-1.044	0.314	0.001	-0.704	0.353	0.046
HOUSEHOLD **Livestock ownership**															
Total dairy TLU	-	-	-	-0.160	0.048	0.001	-	-	-	-	-	-	-	-	-
Total number of dairy sheep or goats	-	-	-	-	-	-	0.314	0.135	0.020	-	-	-	-	-	-
Per capita dairy TLU, quartiles	-	-	-	-	-	-	-	-	-	0.161	0.088	0.068	-	-	-
Per household TLU, quartiles	-	-	-	1.440	0.428	0.001	-	-	-	-	-	-	-	-	-
Polygyny															
Wife number of mother[3]	-0.027	0.015	0.060	-	-	-	-	-	-	-0.266	0.129	0.039	-	-	-
INDIVIDUAL **Mineral/Metal Biomarkers**															
Cadmium	0.018	0.007	0.015	0.569	0.308	0.065	-	-	-	-	-	-	-	-	-
Copper	-	-	-	-	-	-	-	-	-	1.432	0.681	0.036	-	-	-
Lead	-	-	-	-	-	-	3.488	1.314	0.008	-	-	-	-	-	-
Magnesium	-	-	-	-	-	-	1.694	0.406	0.000	-	-	-	-	-	-
Mercury	-	-	-	4.902	2.594	0.059	-	-	-	-	-	-	1.555	0.698	0.026
Selenium	0.001	0.000	0.001	0.085	0.010	0.000	-	-	-	0.014	0.003	0.000	0.006	0.003	0.105
Nutrient and Dietary Intakes															
Protein, % of daily kcal	-	-	-	-	-	-	-	-	-	4.675	1.809	0.010	-0.001	0.000	0.108
Total folate, µg	-	-	-	-	-	-	-	-	-	-0.001	0.000	0.043	-	-	-
Total vitamin A, µg	-	-	-	0.001	0.000	0.033	-	-	-	-	-	-	-	-	-
Total vitamin C, µg	-	-	-	-	-	-	0.092	0.057	0.108	-	-	-	-	-	-
Any meat, 24 hours	-	-	-	-	-	-	-	-	-	-0.463	0.267	0.083	-0.492	0.274	0.072
Any vegetables, 24 hours	-0.046	0.025	0.065	-	-	-	-	-	-	-	-	-	-	-	-
Health Status															

BMI	-0.012	0.005	0.016	-	-	-	-	-	-	-	-	-	0.141	0.047	0.003
Arm muscle area, mm^2	-	-	-	-	-	-	0.515	0.278	0.064	-	-	-	-	-	-
Hemoglobin concentration, g/dl	-	-	-	1.062	0.251	0.000	3.870	1.394	0.005	-	-	-	-	-	-
EBV	-	-	-	0.000	0.000	0.070	-	-	-	-	-	-	-	-	-
Morbidities[2]	-	-	-	-6.604	3.469	0.057	-	-	-	-0.591	0.333	0.076	-	-	-

[1]Generalized linear models (GLM) were used to account for nonlinearity in the error terms of the dependent variable. Models were adjusted for total energy intake and child age. Significant associations reported at P<0.10.

[2] Child reported number of different morbidities experienced in previous 24 hours. For the magnesium model, children reporting three or more different morbidities showed significant association, and for the zinc model, children reporting two or more morbidities showed significant association, P<0.10.

[3] Wife number of the mother was specified as: 1=1st wife; 2=second wife; 3=third or higher wife