Drought, Psychosocial Stress, and Ecogeographical Patterning:
Tibial growth and body shape in Samburu (Kenyan) pastoralist children

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**Running title**: Environmental stress in utero and child growth

## Abstract

**Objectives**: This study of Samburu pastoralists (Kenya) employs a same-sex sibling design to test the hypothesis that exposure in utero to severe drought and maternal psychosocial stress negatively influence children's growth and adiposity. As a comparison, we also hypothesized that regional climate contrasts would influence children's growth and adiposity based on ecogeographical patterning.

**Materials and Methods**: Anthropometric measurements were taken on Samburu children ages 1.8 – 9.6 years exposed to severe drought in utero and younger same-sex siblings (drought-exposed, *n* = 104; unexposed, *n* = 109) in two regions (highland, n = 128; lowland, n = 85). Mothers were interviewed to assess lifetime and pregnancy-timed stress.

**Results**: Drought exposure associated to lower weight-for-age and higher adiposity. Drought did not associate to tibial growth on its own but the interaction between drought and region negatively associated to tibial growth in girls. Also, drought exposure and historically low rainfall associated to tibial growth in sensitivity models. A hotter climate positively associated to adiposity and tibial growth. Culturally specific stressors (being forced to work too hard, being denied food by male kin) associated to stature and tibial growth for age. Significant covariates for child outcomes included lifetime reported trauma, wife status, and livestock.

**Discussion**: Children exposed in utero to severe drought, a hotter climate, and psychosocial stresss exhibited growth differences in our study. Our results demonstrate that climate change may deepen adverse health outcomes in populations already psychosocially and nutritionally stressed. Our results also highlight the value of ethnography to identifying meaningful stressors.

**Keywords:** climate change, maternal stress, child growth, tibia, skinfold thickness

**Research Highlights**

- Culturally-specific stressors influence tibial growth.
- Higher ambient temperatures, past trauma, and pregnancy-timed stressors all contribute to body composition differences.
- Climate change deepens the impact of existing vulnerabilities.

## INTRODUCTION

Climate change is exacerbating extreme weather events globally, and increasing the rate and scale of severe drought in East Africa specifically (Cook & Vizy, 2012, 2013; Funk, 2011; IPCC, 2022; Opiyo et al., 2015; Tierney et al., 2015), with detrimental effects on child health predicted based on historical data (Cooper et al., 2019). During a catastrophic drought in 2008-2009, hunger was widespread, and, whether or not it was directly drought-induced, fighting escalated between Samburu and their ethnic neighbors in northern Kenya (Anderson & Bollig, 2016).

Here, we report on child linear growth and body composition results from our larger, epigenetic study designed to measure the intergenerational impact of climate change on health in vulnerable regions by focusing on a known recent event – a severe drought affecting Samburu pastoralists in northern Kenya in 2008-2009. During this drought, pastoralists in Samburu County, Kenya lost 57% of their cattle and 65% of their sheep over the course of months (ILRI, 2010). We hypothesized intergenerational effects of the severe drought and employed a same-sex sibling pair design to test whether children exposed to this drought *in- utero* exhibit different growth and behavioral outcomes compared to unexposed siblings. (We will report on child behavioral outcomes and epigenetic results separately.) For comparison, we also evaluated climate effects through a comparison between sibling pairs in a hotter versus cooler region. Our design includes the effects on child outcomes of lifetime and pregnancy-timed maternal emotional stressors as captured on standardized and culturally-specific instrumentation.

East African pastoralist children are typically nutritionally stressed with growth indicators below international reference populations (Iannotti & Lesorogol, 2014; Pike, Straight, Hilton, & Österle, 2016; Tyler, Straight, & Hilton, 2018). We expected the stressors of severe drought to deepen existing vulnerabilities. Thus, we hypothesized higher adiposity, reduced weight, and also tibial growth, in children exposed to the 2009 drought in early gestation. As a comparison, we hypothesized that sibling pairs exposed in utero to a hotter climate region would also exhibit higher adiposity and lower body weight, but relatively longer tibia and longer tibiae relative to stature. Finally, we predicted that psychosocial stressors, culturally meaningful to Samburu mothers, would negatively impact their children's lower limb growth and body shape. Thus, our study uniquely examines three gestational exposures associated with child growth: severe drought, culturally meaningful forms of psychosocial stress, and ecogeographical patterning. Our intent with this integration is to determine the contribution of climate change to health outcomes in women and their children already experiencing precarity in the form of food and water insecurity, interpersonal violence, intercommunity and government-sponsored violence, gender inequality, and the emotional toll of all of these lived experiences.

*Ethnographic Background to the Study*

Samburu are polygynous ethnic marginals who inhabit semi-arid-lands in north central Kenya. They are among the world's communities engaging in climate-sensitive livelihoods in regions that force many families to live and work "close to their upper thermal limits" (IPCC, 2022). Their primary subsistence is based on cattle, sheep, and goats, with additional camel ownership for some lowland families. This subsistence pattern is supplemented by widespread livestock trade and in some families by wage labor and petty hawking. Over the past several decades, there has been a trend away from regular slaughtering for family food consumption towards selling small stock (goats and sheep) to purchase "gray foods" (maize and maize flour especially), sugar and tea leaves, and other items (Holtzman, 2009). Additionally, nomadic practices (the entire family moving with the herd) have become rarer, replaced with transhumance (young men moving with the herd, leaving a reduced milking herd with the rest of the family; Fratkin, 1998; Fratkin, Roth, & Nathan, 2004; Straight, 1997). These changes have been accelerated in the highlands (altitude ~1,800 meters) and have slowly and unevenly spread to the lowlands (altitude ~900 – 1200 meters depending on location). Conversely, relative to the lowlands, the highlands are associated with higher average rainfall, cooler daytime temperatures, more markets (including fresh produce), more schools, functioning clinics, government services, and wage labor jobs.

During the 2008-2009 drought, a combination of livestock loss, conflict, and trauma was evident. Massive losses in livestock posed a critical food security challenge to families and increased human injuries as already health-compromised individuals engaged in risky tasks to obtain fodder for their animals. Simultaneously, conflict pressed Samburu from multiple sides. Pokot pastoralists and Samburu fought over land tenure (Greiner, 2012) while Turkana pastoralists fought Samburu for reasons some Samburu attributed to water and pasture points and others attributed to political constituencies (Straight, 2009). Displacement of people and their herds affected all three groups, accompanied by psychosocial suffering and reduced access to critical environmental resources and health care (results of our current study; also, Straight & Hilton, 2009 personal observations; Straight, Pike, Hilton, & Österle, 2015).

*Environmental Perturbations, Climate, Distal Limb Segment Growth, and Body Shape*

According to the Developmental Origins of Health and Disease (DOHaD) hypothesis (e.g, Barker et al. 1995), gestational exposures have a lifelong impact on health. This bears on the evolutionary argument that fetuses are programmed in the womb for expected environments ("predictive adaptive responses" – PARs), with environments not matching "expectations' presenting a risk rather than a benefit. However, climate conditions, a variety of stressors, and exact stressor timing all play a role, potentially complicating the issue of detrimental versus adaptive responses (Gluckman, Hanson, & Beedle, 2007; Kuzawa & Thayer, 2011).

To investigate stressor timing, our study recruited participants based on their early gestational exposure to the severe drought. However, due to the length of the drought, some children were exposed beyond early gestation. Given overall hotter temperatures during the drought and average differences in temperature and rainfall in the hotter, dryer lowlands compared to the cooler, wetter highlands, some variation based on Bergmann's (1847) and Allen's (1877) rules (ecogeographic patterning) might be expected. Bergmann's rule would predict a potentially negative association between body weight and drought as well as lowland residence, while Allen's rule would predict relatively longer tibiae for Samburu children exposed to high ambient temperatures in utero (Leonard, 2015).

We selected the leg (i.e., crural) region of the lower limb for in-depth investigation due to its easily measurable direct association with the underlying tibia and the fact that distal limb segments of the appendages are considered more environmentally sensitive relative to proximal limb segments (Holliday & Hilton, 2009; Holliday & Ruff, 2001; Roberts, 1953, 1978; Ruff, 2002; Trinkaus, 1981). Distal limb segment growth is sensitive to environmental perturbations, particularly at critical developmental time periods such as gestation and early childhood, and associated with lifelong health risks (Bogin & Verela-Silva, 2010). Thus, tibia length in combination with stature can be used to assess distal limb body segment proportional variation whereas tibia length in combination with age can be used to assess variation in growth.

Nutritional stressors and other environmental conditions are expected to play a role in body size and proportion (Katzmarzyk & Leonard, 1998; Lampl, Kuzawa, & Jeanty, 2003; Leonard & Katzmarzyk, 2010; Pomeroy et al., 2014), and previous studies have highlighted the complexity of adiposity in relation to climate, nutrition and stress (Kuzawa, 1998; Wells 2012a, b, c). Disaster studies are of particular importance with respect to adiposity, pointing to higher central adiposity and increased lifelong risk of obesity and type 2 diabetes in teens and adults exposed in utero to famine and extreme maternal stress (Cao-Lei, 2015; Tobi et al., 2018a). Thus, we included weight-for-age and skinfolds-for-age for in-depth investigation in order to assess overall body size and shape in response to gestational drought and emotional stress exposure, and in relation to lower limb proportion.

## METHODS

In order to examine the effects of early gestational exposure to severe drought, we employed a same-sex sibling pair design (*n* = 213; 104 drought-exposed, 109 younger, unexposed siblings, since some families had more than one eligible control sibling). The study commenced in October, 2017, with data collection undertaken by Straight and Hilton through July, 2019. Our recruitment methods and additional details about timing for the study are described in the Supporting file; demographic methods and additional recruitment details are described in Needham et al. (2021). Informed consent was accomplished at enrollment and repeated at each visit, and data collection occurred in a setting accommodating participant preferences, usually in or adjacent to family homes.

*Anthropometry*. The outcome measures for this study were tibia length for age, tibia index for age, with weight for age used for a body size comparison, stature measured for comparison to tibia, and skinfold thicknesses used to assess subcutaneous peripheral and torso fat. Tibia length for age provides information for comparisons against commonly used human growth databases whereas tibia index for age allows for a nuanced examination of eco-geographical patterning within the Samburu. We avoided using body mass index (BMI) because of its lack of sensitivity and specificity for assessing body fat in children under nine years of age and in children with high BMI – or lower BMI, as in our sample. For young children with low BMIs, skinfold thickness has been suggested to be more accurate (Freedman, et al., 2013; Rothman, 2008; Vanderwall, Clark, Eichhoff, & Carrel, 2017).

All child ages were documented with vaccination or birth records. For the study design, we selected younger unexposed siblings to avoid early childhood exposure to the drought in older siblings. Given the relatively small Samburu population in areas highly affected by the drought and the strict age, sex, and drought exposure criteria of the study, child participant ages ranged from 2.5 years to 9.6 years, with a single 1.8-year-old lowland female outlier. Models were tested with all participants but also re-tested excluding the outlier.

Anthropometry was supervised by CEH, and undertaken by a single, trained multilingual research assistant to avoid inter-rater differences. CEH observed and recorded the measurements while the research assistant called them out. Training (2017, 2018) and refresher trainer (2019) included validation measures against CEH's measures. Weight, skinfold thicknesses, tibia length, and stature (to calculate tibia index) measurements followed WHO protocols and Lohmann procedures (Lohmann, Roche & Martorell, 1988; WHO, 2006) as well as those procedures noted by Weiner and Lourie (1981). Weight (in kgs) was recorded using a Seca 869 flat scale, and stature (in cm) was recorded using a Seca stadiometer (Seca GmbH & Co. KG, Hamburg, Germany). Triceps, subscapular, and suprailiac skinfold measures were taken using Lange skinfold calipers. Tibial length (in cm) was measured using a Lufkin tape measure. For each anthropometric variable, three measures were taken, recorded, and the average for these measures was calculated to obtain the final value for the variable. Lower limb measurements consisted of direct measurements of maximum tibia length. After palpation to establish and mark anatomical landmarks, this measurement was taken from the proximal-medial border of the tibia to the distal malleolus (Weiner and Lourie, 1981).

*Reference Sample*

Frisancho's compact disk accompanying his *Anthropometric Standards* (2011) includes age- and sex-specific z-score calculations for lower leg length and lower leg index derived from the third National Health and Nutrition Examination Survey (NHANES III). For the reference populations in that program, lower leg length is estimated in two steps: 1) stature – sitting height = total leg length; 2) total leg length – upper leg length (inguinal crease to top of patella) = lower leg length (see also Bogin & Varela-Silva, 2008, 2010). Lower leg index = lower leg length/stature*100. Our models are comparative within the same population, based on differences between drought and control siblings and between lowland/hot versus highland/cooler region, and therefore, Frisancho's program was appropriate. Given the derived measurements available from NHANES III, we maintained the precision of our drought sibling pair data and sibling pair statistical models by entering unadjusted sibling pair tibia measurements into the lower leg length and lower leg index components of Frisancho's z-score program. For comparison, we performed sensitivity models that added a malleolar height estimate to sibling pair tibia measurements to calculate a lower leg length measurement. Findings were consistent across models (see Supporting file). The adjustment, based on malleolar height data analyzed in Kasabova & Holliday (2015), is as follows: lower leg length = tibia length + malleolar height (where malleolar height = stature in centimeters * 4.67%).

Finally, as all drought-exposed children and many of the paired sibling controls were over five years of age and our study compares within a population, skinfold thickness and weight for age z-scores were also calculated based on NHANES III. This ensured consistency with tibia z-scores and also avoided mixing WHO standards with reference. WHO Standards are based on longitudinal data in healthy, breast-fed infants following strict guidelines. In contrast, WHO References are based on cross-sectional data mixing children breastfed in infancy with non-breastfed, without guidelines. WHO Standards differ both conceptually and methodologically from reference, and the growth patterns observed using WHO Standards are consistent across populations globally, while, in contrast, the growth patterns observed using WHO References differ by population. Moreover, z-score differences between WHO, NHANES III, and other reference populations exhibit differing age-dependent patterns (Turck et al., 2013; Yasin and Filler, 2013). Leroy and colleagues (2015) offer a mathematical explanation for age-dependent patterns in linear growth. Regarding skinfold thicknesses specifically, Kramer et al. emphasize the appropriateness of NHANES III as it is “the last known available collection of skinfold and arm circumference measurements predating the recent obesity trend in children, and has the advantage of all growth metrics being from the same cohort of children” (Kramer et al., 2021, p4). Since our purpose is comparative within a population (see also Kramer, 2021), we have used z-scores derived from NHANES III for all children in the sample.

Additionally, though z-scores are age- and sex-specific, we have used age as a covariate in all models because of the age-dependent patterns in z-scores generally and because of the age differences in our sample.

*Ethnographic Methods for Assessing Psychosocial Stress*. A dichotomous drought versus control comparison is methodologically robust. Nevertheless, on its own, it fails to capture the experiential entailments of severe drought for pregnant Samburu women. Our ethnographic methods and our iterative process producing our stressor scores provide insights that are simultaneously descriptive and quantifiable.

For the first month of the study (October 2017), Straight (conversational in the Samburu vernacular and fluent in Kiswahili) engaged in participant-observation, informal discussions, and unstructured interviews concerning the difficulties of pregnancy generally, and during drought. This, in addition to Straight's previous ethnographic research, provided the foundation for modifying standardized instrumentation as appropriate, creating culturally-specific instrumentation, and for Straight's interviews of all participant mothers.

Based on the ethnography and pilot phase, two culturally-specific stressors were identified and added to instrumentation: 1) being forced by the husband or other male kin to work too hard during a pregnancy (hereinafter 'forced work'); 2) being denied food by the husband or other male kin during a pregnancy (hereinafter 'denied food').

For the data collection phase, culturally modified standardized instrumentation and culturally-specific instrumentation was implemented. Additionally, women were asked open-ended questions about stressors, hardships, and any other difficulties they experienced during each drought-exposed or unexposed pregnancy. Question order (drought- versus control pregnancy) was varied. If women identified few or no problems, they were prompted with questions about the type of work they performed.

After completing their responses, participant mothers were asked about *n'gaman*, a Samburu pregnancy concept encompassing the "personality" of the pregnancy, including food cravings and avoidances, behavioral and mood changes, and often, changes in attitudes towards husbands that include fear, avoidance, and even feelings of hatred. Some Samburu husbands rely on intermediaries during their wives' pregnancies so that they can identify their pregnant wives' food and other needs. Similarly, many Samburu women observe avoidance of sexual intercourse during a portion or the entirety of the pregnancy (Straight, 2005: 96-97), which can exacerbate fear if they believe their husband might pressure them to engage in sexual relations.

Responses to 'forced work' and 'denied food' were retained as separate, dichotomous (yes/no) pregnancy-timed variables. Based on responses to all instrumentation, a weighted, composite score of all other pregnancy-timed stressors (hereinafter 'other emotional stressors') was calculated for each drought and control pregnancy to include as a predictor variable for psychosocial stress. Thus, three maternal stressors were used as primary exposure variables: 'forced work', 'denied food' and 'other emotional stressors'. However, 'other emotional stressors' was collinear with drought ($r_s \geq 0.7$) and was therefore excluded from models. Instead, ‘other emotional stressors’ was tested in place of drought in sensitivity models. Finally, a lifetime maternal trauma score was calculated for all traumas reported by each participant up to each drought and control pregnancy (hereinafter ‘maternal lifetime trauma’) to be included as a potential covariate.

Detailed methods for translation, instrumentation, and scoring of the ‘other emotional stressors’ and ‘maternal lifetime trauma’ variables are described in the Supporting file.

*Sensitivity Analyses.* We performed the following sensitivity analyses: 1) comparison of fetal mortality between drought and unexposed pregnancy timing; 2) within sex models for weight and adiposity, because of sex-specific differences for those outcomes; 3) tibia models using historical weather data instead of drought and climate region exposures; 4) tibia models testing drought and climate region exposures with older, non-related children and adolescents unexposed to severe drought in utero; 5) comparison of tibia models to estimated malleolar height adjustment models. These models and their methods can be found in the Supporting file.

*Statistical Methods*. Due to the sibling pair design, we employed linear mixed models, with mother as random effect. The statistical analyses were performed in IBM® SPSS® software, version 27 of the SPSS system for Mac, Copyright © 1989, 2019 IBM Corporation and its licensors.

To avoid model bias (Conroy & Murray, 2020), we created directed acyclic graphs (DAGs) using the DAGitty program (http://www.dagitty.net/dags.html; Textor, van der Zander, Gihlthorpe, Liśkiewicz, & Ellison, 2016), which takes causal biological relationships and potential biasing paths into account, and calculates a minimal sufficient adjustment set. We created a DAG with maternal drought exposure, pregnancy-timed psychosocial stress, and region of residence as the main predictors and used it to show the causal relationships assumed in the creation of our models (Figure 1).

Additional covariates not included by DAGitty as part of the minimal adjustment set (including sex) were selected using an iterative method and checking model fit at each step with Bayesian and Akaike's Information Criterion (BIC and AIC). Covariates from this process were compared to backward and stepwise regression to check for stability of the covariates (Lima, Davies, Kaler, Lovatt, & Green, 2020). Covariates showing high correlation ($r_s \geq 0.7$) were not included together in the same models. Covariates are described in the Supporting file. We also tested for two-way interactions between each of the four exposure variables. There were significant interactions within sex groups, which are noted in results.

**RESULTS**

*Weather during early gestation.* Based on historical weather data (Table 1; see detailed methods and data in Supporting file), mean ambient daytime maximum temperature exposures were comparably high during the 2009 drought and lowland pregnancies compared to control and highland pregnancies respectively. Cumulative rainfall in early gestation, on the other hand, was lowest during the drought.

*Descriptive Demographic Statistics.* For this sample of 213 children, 46% of them are male and 54% are female. (Table 2). Additionally, 77% of child participants ever attended school, while 23% have never attended. The mean of parents' highest grade completed are less than first grade for mothers and less than third grade for fathers. Over half of families are polygynous and over half of mothers and fathers have engaged in some form of cash earning activity. There is substantial variation in livestock holdings and camels are seen exclusively in the lowlands for our sample.

*Descriptive Anthropometric Statistics*. Based on our study design, drought exposed children are older than their unexposed siblings conceived after the drought, while lowland sibling pairs are comparable in age to highland sibling pairs. From Table 3, drought exposed children's mean tibia length is longer (not surprising given the mean age difference), and with a somewhat better z-score mean compared to unexposed siblings. Drought exposed children's mean tibia index value is also slightly greater and z-score mean is substantially better compared to unexposed siblings. Also, not surprising given the age difference, drought-exposed children are taller on average than unexposed siblings; their z-score mean is also better. Similarly, drought children have higher average body weight than same-sex unexposed siblings. However, drought children's body weight for age mean z-score is lower than unexposed siblings. For skinfold thickness measurements, we note that the drought children have lower mean values than those seen for their unexposed siblings and lower mean z-scores. This is in contrast to findings in our models detailed below, which adjust for age and include mother as a random effect.

Table 4 presents the anthropometric values for the lowland and highland groups categories. As noted, mean ages for these groups are comparable. The lowland/hot region children have longer absolute tibia lengths, higher tibia index values, are slightly taller on average, slightly heavier in body weight, have higher central adiposity (subscapular and suprailiac skinfold thicknesses), and have better mean z-scores for these variables relative to that of highland/cooler region children. In contrast, lowland children's mean triceps skinfold thickness and corresponding z-score mean values are slightly lower compared to highland children.

*Other Emotional Stressors variable.* As noted in Methods, due to the high correlation of 'other emotional stressors' with drought-exposure, this variable was excluded from models but included in place of drought exposure in sensitivity models. Child outcomes were not associated with the 'other emotional stressors' variable with the exception of triceps skinfold for age. However, the effect size is near zero (results not shown) and is not considered biologically meaningful. The individual stressors included in this composite variable might associate to child outcomes but, as there are over 20 individual stressors identified based on standardized instruments, this requires a separate study.

*Tibia variables*. Our hypothesis was not supported for drought exposure in utero (drought; control as reference) and *tibia length for age* (Table 5) or *tibia index for age* (Table 6) in the primary models. Since the forced work and denied food variables are on the causal pathway from drought exposure to the outcomes, drought exposure was also tested without those variables, with similar results. Thus, the total effect of drought is not being obscured by testing for those variables in the same model. However, in interaction models in girls but not boys, the interaction between drought and lowland exposures negatively associated to *tibia length for age* (Estimate = -0.49, $P \leq 0.05$, CI -0.97, -0.01) and *tibia index for age* (Estimate = -0.44, $P \leq 0.01$, CI -0.77, -0.1) (Results not shown). Additionally, drought and weather exposure in utero influenced tibial growth in sensitivity models. In tibia models using historical weather data instead of drought and climate region exposures, 'mean maximum daytime ambient temperature exposure' and 'historically low rainfall' in early gestation had a medium to large positive effect on tibial growth (*tibia length for age* and *tibia index for age*), in models with all sibling pairs included and in models of sibling controls. Effect sizes and directions of effect were similar for maternal psychosocial stress exposures as in primary models. In contrast, in tibia models testing drought and climate region exposures with older, non-related adolescents unexposed to the drought, drought exposure had a medium, negative effect on *tibia length for age* and too small an effect on *tibia index for age* to be biologically meaningful. However, climate region results were similar to sibling pair models: hot/lowland region had a large, positive effect on tibial growth.

Our hypothesis was supported for hot/lowland climate exposure, which positively associates to *tibia length for age* compared to highland exposure. Tibia length in children of lowland mothers is 0.4 standard deviations higher than in children of highland mothers relative to international reference populations, which is a large magnitude of effect. Lowland exposure also positively associates to *tibia index for age*. Our hypothesis that maternal psychosocial stress would negatively influence tibial growth was only partly supported for culturally-specific pregnancy-timed stressors. 'Forced work' positively, and 'denied food' negatively, influence *tibia length for age* and *tibia index for age*.

*Child's age, gestational exposure to maternal lifetime trauma,* maternal status as *widowed, divorced, or unmarried mothers* or *children of second or later polygynous wives*, and livestock wealth also influenced children's tibial growth.

*Stature.* Drought and hot/lowland region exposures did not associate to *height for age* (Table 7), although the direction of effect was similar to tibial growth. Exposure to maternal psychosocial stress influenced *height for age*, although not always in the expected, negative direction. Being the child of a widowed, never married, or divorced mother and number of milk cows also influenced stature.

*Weight*. As predicted, drought exposure in utero negatively influences children's *weight for age*, with a large magnitude of effect (Table 8). Children exposed to severe drought in utero weigh nearly 0.4 standard deviations less than same-sex sibling controls. Additionally, in interaction models, in girls but not boys, the interaction between drought and 'denied food' negatively associated to *weight for age* with large magnitude of effect (Estimate = -0.82, $P \leq 0.01$, CI -1.46, -0.17; Results not shown). Neither climate region exposure nor the pregnancy-timed stressors significantly influence *weight for age* in primary models. Contrary to expectations that exposure in utero to a hotter climate would negatively influence children's body weight, in sex-stratified models (Supporting file), lowland residence had a positive influence on *weight for age*, particularly in boys. Exposure in utero to maternal lifetime trauma, mother's employment, and child's own school attendance also influenced children's body weight.

*Skinfold thickness.* As expected, drought exposure in utero and hotter/lowland climate positively influence adiposity, although not for all outcomes. Adiposity in girls was higher than boys overall and drought and climate also more strongly and positively influenced adiposity in girls compared to boys. Moreover, in boys but not girls, the interaction between drought and lowland exposures negatively associated to central adiposity (*suprailiac skinfold thickness for age*). Exposure to maternal psychosocial stress influenced adiposity in sex-stratified models, although, contrary to expectations, directions of effect were not always positive (Supporting file). Drought exposure positively associates to peripheral fat (*triceps skinfold for age*) (Table 9) and torso fat (*suprailiac skinfold for age*) (Table 11) with a large and positive magnitude of effect, but not *subscapular skinfold for age* (Table 10). Hot/lowland climate exposure does not associate to peripheral fat (*triceps skinfold for age*), but does positively associate to *subscapular skinfold for age* and *suprailiac skinfold for age*. Also, children's age (negatively) and school attendance (positively) influenced adiposity.

*Sensitivity Analyses.* Besides the tibial growth sensitivity models described above, (1) The ratio of spontaneous abortions compared to live births was higher during the drought compared to unexposed pregnancies after the drought; (2) In within sex comparisons of *weight for age*, effect sizes for drought, climate exposures, and maternal psychosocial stress were larger for boys than for girls. In contrast, effect sizes were larger for girls than for boys for all three adiposity outcomes; (3) Tibia models with malleolar height adjustment were similar, with same directions of effect, to primary models.

## DISCUSSION

Our results indicate that children exposed to the 2009 severe drought in utero have lower body weight (particularly in boys) and higher adiposity (particularly in girls) compared to their same sex siblings conceived after the drought ended. Same-sex sibling pairs in the hot (lowland) climate region also had higher adiposity relative to their cooler (highland) counterparts; additionally, lowland sibling pairs had relatively longer tibiae and longer tibiae in proportion to stature. Changes observed in body weight, distal limb growth, and adiposity are consistent with adaptive responses to heat and other stressors. Yet, the impact of the 2009 severe drought on tibial growth is more nuanced. Based on the initial primary models, drought exposure did not appear to have an effect on tibial growth. However, the interaction between drought and lowland exposures negatively influenced girls' tibial growth. Additionally, in sensitivity models including both older (unrelated) and younger (same-sex sibling) controls, drought is negatively associated with tibial growth. In contrast, in sensitivity models separately testing weather exposures, both 'high mean maximum daytime ambient temperature' and 'historically low rainfall' had a positive effect on tibial growth, even for siblings not exposed to the 2009 drought. While sibling controls were not exposed to any severe droughts in utero, some were nevertheless exposed to heat or low rainfall.

Climate change is not only increasing the frequency and severity of droughts, it is also causing an increase in heat waves and more volatile rainfall patterns generally in East Africa (Gebrechorkos, Hülsmann, and Bernhofer, 2019; IPCC, 2022). This is important to interpreting the contrasts between our tibia findings in the primary and sensitivity models. Exposure interactions from primary models suggest that lowland girls may be more vulnerable than boys to the impact of drought on tibial growth. In sensitivity models, the direction of effect for low rainfall in particular points to the role of variables we could not measure retrospectively (discussed in more detail below). Additionally, our sensitivity model findings within control siblings highlight that even during more "typical" seasons, high ambient temperatures and more volatile rainy seasons exacerbating maternal stress have an impact on children's growth. Finally, our findings demonstrate the influence on children's growth of culturally-specific forms of maternal psychosocial stress, maternal lifetime trauma, maternal social capital (wife status in a polygynous society), and maternal resources (livestock). Thus, climate change deepens the impact of vulnerability for individuals who are already psychosocially and resource-stressed. Samburu women experience heat waves and drought cycles as an irreducible part of their entire daily lived experience as they cope as resiliently as possible with the full force of gender inequalities, inadequate access to health and education, and as they move across the landscape to reach drinking water for their families and water and pasture for their livestock.

*Tibia and Stature*

<u>Maternal psychosocial stress</u> has a strong impact on Samburu children's stature and tibial growth. Gender inequality is pervasive in Samburu society. Women are dependent on male kin for access to a milking herd for food security, their labor is likewise controlled by male kin, their reproductive potential is central to the livestock exchanged from the groom's to the bride's family at marriage, and corporal punishment of women continues to be a culturally acceptable practice. Women do have options, including an institutionalized practice of *kitala*, running away to seek protection and shelter in the home of natal kin (Straight & Holtzman, 2003). Also, if they

have sons, women's status is enhanced and their sons typically act on their behalf. As they age in general, and also if their husbands marry second or later wives, older women and first wives experience increased choices and autonomy (Straight, 2007). On balance, these cultural factors create varying degrees of vulnerability for most women. We considered psychosocial stressors that women specifically identified as well as stressors from standardized instrumentation modified for use in Samburu.

We hypothesized reduced stature and tibial growth in drought-exposed children and children of psychosocially stressed mothers, and our findings partly supported these hypotheses. The two stressors that Samburu women identified, feeling that husbands/or other male kin had *forced the participant mother to work too hard during the pregnancy (negative association)* and *denied them food (positive association),* are significantly associated with tibial growth (*tibia length for age* and *tibia index for age*), as well as *stature,* but in contrasting directions. *Tibia length for age* and *tibia index for age* values (and also stature) of those children whose mothers reported 'being forced to work too hard while pregnant' with them are lower than that of the other children. Feeling that husbands or other male kin had forced the participant mother to work too hard during the pregnancy of her drought-exposed and/or unexposed child is a symbolically and physiologically complex event. It suggests she may have engaged in exhausting daily physical activity. Psychosocially, it also reflects her relative powerlessness in a gender system wherein men exert control over her labor. Simultaneously, it points to possible transgressions of cultural norms because she should have been buffered, as women are considered to be physically and metaphysically fragile during pregnancy (Straight, 2007: 80).

Surprisingly, *tibia length for age* and *tibia index for age* values and also *stature* of children of mothers who felt they were 'denied food' during the pregnancy are higher than those of other children. The 'denied food' variable positively associates to mother's employment and being a widow, divorced, or never married woman; and negatively associates to the number of milk animals available to her (Supporting file). An association between total family livestock per wife and 'denied food' is not significantly correlated. Simply put, the most vulnerable and milk animal poor women are those most likely to have reported that their husbands or male kin denied them food, regardless of the family's overall wealth. This suggests that women's precarity has an observable impact on their children's linear growth. The positive association between being denied food and children's linear growth is intriguing and may reflect an accelerated growth response to early gestational food restriction.

Higher maternal lifetime trauma negatively associates to most growth outcomes in primary models, sex stratified models, or both. Maternal lifetime trauma included deaths of the participant mother's own parents or children, witnessing fatalities from climbing trees to get fodder for animals or during other hazardous livestock husbandry activities, war exposure with fatalities, and witnessing accidental deaths or suicide completion. Higher maternal lifetime trauma predicts lower values for *tibia length for age* and *height for age* with moderate to medium effect sizes.

Although maternal lifetime trauma and being denied food moderately associate to other variables (Supporting file), there are, surprisingly, no regional or drought exposure patterns for being forced to work too hard. The fact that gestational exposure to maternal forced work is uncorrelated with drought, weather, region, or livestock wealth, yet, consistently and negatively associates to children's tibial growth and stature with medium to large magnitudes of effect points to 'maternal forced work' as a strong, independent factor for children's overall linear as well as lower limb (tibia) growth. The latter is notable given that reduced lower limb growth serves as a proxy for lifetime health effects (Bogin & Varela-Silva, 2010).

Drought and Ecogeographical Patterning. Based on historical climate data, early gestational mean daytime ambient temperatures were very high for both 2009 drought and lowland pregnancies. We hypothesized longer tibiae in lowland children, particularly relative to stature, based on Allen's rule. However, we expected psychosocial and nutritional stress during the 2009 drought to offset the impact of higher ambient temperatures and ecogeographical patterning on tibial growth. Our hypothesis was supported for the hot lowland/cooler highland comparisons and equivocal for drought/non-drought comparisons. Lowland children's *tibia length for age* and *tibia index for age* z-scores are almost half a standard deviation more than their highland counterparts. Although not statistically significant, *height for age* has a moderate effect size in the same direction.

Our hypotheses were not supported for the drought comparison in the primary tibia models. However, they were supported for *tibia length for age* (but not *tibia index for age*), in sensitivity models that included both the younger, same-sex sibling controls and older, unrelated controls (Supporting file). That is, with older controls included, drought-exposed children had shorter relative tibia length compared to children who were not exposed to the 2009 or any other severe drought in utero. However, they do not exhibit biologically meaningful differences in tibia proportionality to stature. In contrast, in sensitivity models using historical weather data (Supporting file), early gestational exposure to high mean maximum daytime ambient temperature and historically low rainfall positively associated to both *tibia length for age* and *tibia index for age* with moderate to medium effect sizes, while within controls, the effect sizes were larger, as high as 0.95 standard deviations. Pregnancy-timed maternal stress, lifetime maternal trauma, and maternal social status all associated to tibial growth in these weather models, which therefore separately accounted for heat, rainfall, and psychosocial stressors. The positive association of tibia length and proportion with heat might suggest ecogeographical patterning. However, the positive association of low rainfall points to the influence of unmeasured stressors, such as malaria infections that typically increase during rainy seasons.

Likely because of theoretical differences between biomedical and evolutionary approaches to environmental predictors of lifelong health (Schell & Magnus, 2007), the evolutionarily selective influence of ecogeographical patterning has not been considered in studies of gestational drought and famine exposure. Nevertheless, body proportion variation based on environmental differences, particularly temperature, is well established (e.g., Eveleth & Tanner, 1976; Leonard, 2015; Little & Johnson, 1987; Roberts, 1953; Pomeroy et al., 2021; Stinson & Frisancho, 1978). Distal limb segments, particularly tibia length, seems to account for much of the variation in limb proportion (Bogin, 2010; Holliday & Ruff, 2001). There are at least two factors shaping body weight and tibial growth in resource-stressed regions with high ambient temperatures, which may counteract one another for tibial growth: (1) processes of thermoregulation relevant to hotter ambient temperatures, for which the ratio of body surface area to body weight is the most determinant (Leonard, 2015); (2) phenotypic plasticity in response to stress (heat, psychosocial, nutritional) that may lead to tradeoffs, such as smaller body size and sacrificing lower, particularly distal, limb segments to protect brain growth (Frisancho, Borkan, & Klayman, 1975; Katzmarzyk & Leonard, 1998; Lampl, Kuzawa, & Jeanty, 2003; Leonard & Katzmarzyk, 2010; Pomeroy et al., 2014).

Berghänel, Heisterman, Shülke, and Ostner (2017) offer a hypothesis providing additional insight concerning the opposing forces of developmental constraints observed in our study. They report a tendency towards accelerated growth and maturation with early gestational timing of maternal stress; and reduced growth and slower maturation with later gestational timing of maternal stress. In some situations, these opposing forces may result in no apparent growth changes. We took stressor timing into account in recruiting for our study: all children experienced the drought in early gestation. However, maternal lifetime trauma was also important in our study and some children experienced stressors in subsequent gestational periods whether due to prolonged drought exposure, psychosocial and nutritional stressors of varied causes, and/or more days of higher daytime ambient temperatures.

Samburu children's tibial growth reflects adaptation to high daytime ambient temperatures, which is most clearly demonstrated in lowland/highland comparisons and in sensitivity analyses directly examining mean daytime ambient temperatures in early gestation, as determined for each pregnancy based on historical weather data. Additionally, maternal psychosocial stress (mostly negative) and also rainfall deviation (positive) associations in sensitivity analyses point to the multiple forces influencing Samburu children's tibial growth and stature.

*Body weight.*

Based on higher ambient temperatures and ecogeographical patterning, we hypothesized reduced body weight in drought-exposed and lowland sibling pairs, compared to unexposed same sex siblings and highland sibling pairs. We also hypothesized reduced weight in children whose mothers were psychosocially stressed. Our hypotheses were supported for drought exposure, the opposite of expectations for lowland/highland comparison, and only partly supported for maternal psychosocial stress because of different directions of effect. Boys had lower *weight for age* than girls overall. On the other hand, girls, but not boys, had lower weight at older ages relative to reference populations.

In spite of the physiological challenges of gestation, pregnant women have only recently been identified in climate change policies as a high-risk group for adverse pregnancy outcomes, and relatively few studies address maternal and newborn health in relation to climate change (United Nations, 2017; Chersich, 2020). However, numerous studies have linked gestational exposures to fetal, child, and adult health outcomes in drought-prone environments, particularly in Africa and India. Birth weight and body weight differences feature prominently in these studies. A Turkana birth study linked maternal nutrition and morbidity to fetal outcomes and infant birth weight (Pike, 2000) and a recent study across 19 African countries found increased temperature and low rainfall in early gestation or pre-gestation predicted lower birth weights (Grace, Davenport, Hanson, Funk, & Shukla, 2015). Neither study followed infants from gestational exposures to childhood or later life. However, a study of drought effects in India found that prenatal exposure to drought predicted low weight-for-age in childhood, particularly for males and lower caste children and children of less educated mothers (Kumar, Molitor, & Vollmer, 2014), a finding similar to our weight-for-age results. Regarding lifelong effects, a study of historical birth data in the Gambia found evidence that premature death in young adulthood is ten times more likely in individuals born during the ‘hungry season’ (Moore et al., 1997).

Pregnancy-timed stressors influence Samburu children’s body weight, with notable sex differences. Girls of mothers who reported ‘forced work’ had higher body weight than other girls, in contrast to boys of ‘forced work’ mothers, who had lower body weight compared to other boys. On the other hand, both boys and girls whose mothers reported ‘denied food’ had higher weight values for age compared to children whose mothers did not report being denied food, in primary and sex stratified models. Children of mothers with higher maternal lifetime trauma had lower values for *weight for age*, particularly in girls, based on sex stratified *weight for age* sensitivity models (Supporting file).

Turning to drought and climate region, drought-exposed children’s body weight of both sexes was almost 0.4 standard deviations lower than that of unexposed same-sex siblings. For region, based on sex-stratified models (Supporting file), the body *weight for age* of lowland children was higher than their highland counterparts, particularly in boys. This unexpected finding might be partly explained by the influence of lifetime maternal trauma. Based on Spearman correlations, maternal lifetime trauma is positively correlated to highland residence. Also, based on nutrition measures in our separate, adolescent study (Iannotti et al., 2021), there appear to be lower intakes of protein and fat in highland Samburu children. Maternal employment buffered body weight in both sexes and children’s own school attendance buffered body weight in boys but not girls.

Replicating the conditions of drought and famine in pregnant rats and sheep, Ross and Desai (2005) found that both maternal dehydration and gestational nutrient restriction result in low-birthweight offspring, which is consistent with body weight in Samburu children exposed to severe drought. Furthermore, postnatal growth patterns depended on postnatal nutrient availability, with nutrient restriction leading to typical body size while increased postnatal nutrient availability led to rapid catchup growth and higher body weight and fat than typical.

*Adiposity*

We hypothesized higher adiposity in drought-exposed, lowland, and maternally psychosocially stressed children to meet the energetic demands of heat stress, chronically low caloric and nutrient availability, psychosocial stress, and pathogen exposure. We could not measure maternal dietary intakes and maternal infection status retrospectively. Climate and maternal psychosocial stress associated to higher peripheral adiposity in both sexes but particularly in girls. For central adiposity, there were opposing directions of effect by stressor for girls compared to boys. In general, girls had higher peripheral fat for age and somewhat higher central adiposity for age than boys. Both girls and boys had lower peripheral fat at older ages relative to reference populations. The age pattern for central adiposity was stronger in girls. Girls had lower *subscapular and suprailiac skinfold for age* values at older ages while boys had lower *subscapular skinfold for age* but somewhat higher *subscapular skinfold* relative to reference populations.

Exposure to the 2009 drought strongly and positively influenced both peripheral fat (*triceps skinfold thickness*) and central fat (*suprailiac skinfold thickness*). Exposure to the hotter lowland climate region also positively influenced children's central fat (*subscapular* and *suprailiac skinfold thickness for age*) compared to children exposed to the cooler highland region.

Both pregnancy-timed psychosocial stressors ('forced work' and 'denied food') positively influenced girl's peripheral fat (*triceps skinfold thickness for age*). In contrast, there was only a small positive association of 'forced work' on peripheral fat in boys, and 'denied food' had no effect. The influence of these stressors on central fat also differed by sex: 'Forced work' positively, and 'denied food' negatively, associated to central adiposity in boys (both *subscapular and suprailiac skinfold thickness for age*). However, these directions of effect were reversed in girls: 'forced work' negatively, and 'denied food' positively associated to central adiposity (*suprailiac skinfold thickness* only) (Supporting file).

Body fat provides an important energy store for meeting the costly demands of physiological stress from infection, nutrient deprivation, heat stress, dehydration, and psychosocial stress. As such, it has been characterized as a "risk management" strategy, buffering short term demands for the sake of long-term survival and reproduction (Kuzawa, 1998; Wells, 2012b). Higher body fat in hotter ambient temperature settings may be a response to differential nutritional stress and pathogen loads (Wells 2012a, b; Wells and Cortina-Borja, 2013). If energy reserves do not keep up with energetic demands, children's linear growth may be reduced. On the other hand, children's body fat has been found to buffer these tradeoffs in a study of Amazonian forager-horticulturalists (Urlacher et al., 2018). Higher adiposity in drought-exposed and lowland children might be buffering tibial growth, which might partly explain the lack of association between drought exposure and tibial growth in the primary models. This is in addition to the fact (based on historical weather data) that some same-sex siblings unexposed to any severe drought events in utero were nevertheless exposed to heat and low rainfall events.

Sex differences in adiposity are well known, although there are fewer studies in young children (Orsso, 2020): U.S. girls have been found to have slightly more fat at birth (assessing infant body composition using air displacement plethysmography) (Davis et al., 2019); and Pumé girls have been found to have more peripheral fat (triceps skinfold thickness) in childhood than boys (Kramer, et al., 2021). Based on an overview paper, adipose tissue at birth and infancy has a persisting influence on adiposity in childhood and adolescence (Orsso, 2020). Our study's sex difference results for adiposity are consistent with previous studies.

*Fetal Mortality*. Given the anticipated effects of heat stress and indirect effects of maternal pathogen status, and maternal food and water insecurity, our study considered selective pressures on fetal survival as a potential factor in observed child outcomes. Based on participant mothers' reports for fetal losses and infant deaths of all neighboring women pregnant during the drought or during participant mothers' control pregnancies, infant mortality did not significantly differ in a sensitivity test but fetal losses during the drought were higher compared to typical season pregnancies (Supporting file). This suggests that selective pressure on embryos, potentially resulting in reduced variation in surviving drought-exposed fetuses, cannot be ruled out with respect to growth patterns we report for our sample's drought-exposed children (Tobi et al., 2018b).

*Limitations.* This is a cross-sectional, observational, and retrospective study. We could not capture early gestational maternal exposure to environmental contaminants and parasites. Also, although we captured women's reports about foods they could not access during the pregnancy (scored in pregnancy-timed stressors), and perceptions of deliberate denial of food by male kin in our psychosocial measures, we could not reliably capture early gestational nutrition. Recall bias of stressors for drought compared to control pregnancies is also possible. Women reported more 'other emotional stressors' for drought pregnancies even though drought pregnancies occurred earlier than controls. There was not a statistically significant difference between drought and control pregnancies in women's reporting of intimate partner violence, being forced to work too hard or being denied food. Finally, given the narrow criteria necessary to achieve the study design, children's ages ranged from 1.8 years to 9.6 years. We adjusted for age in all models in addition to using age- and sex-specific z-scores. A prospective study incorporating our multidisciplinary methodologies is warranted.

*Conclusion: Integrating Drought, Psychosocial Stress, and Ecogeographical Patterning*. This retrospective pregnancy cohort study of a severe drought in northern Kenya includes maternal psychosocial stress and a regional climate comparison to better understand the impact of climate change on vulnerable communities. This study's most important takeaway points are its evidence first, of the impact of multiple stressors on child growth and body composition differences, including higher ambient temperatures, past trauma, and pregnancy-timed stressors – especially culturally specific psychosocial stressors. Second, the overall increase in heat waves and rainfall volatility caused by climate change is influencing children's growth and adiposity even between severe drought events. Combined, these findings indicate that climate change is deepening the impact of existing stressors in low-income, climate vulnerable communities like Samburu, who are engaging in climate-sensitive livelihoods near their upper thermal limits.

In highly mobile communities such as those of pastoralists and hunter-gatherers, climate stress is an entangled component of daily lived experience that is not easily separated from other stressors. During drought, pastoralist physical activity levels increase because nearby water sources dry up, pasture is harder to reach, and livestock food must be cut from skinny trees while individuals are shaking from hunger. For pregnant women, this increased physical activity in hotter environments while already psychosocially and nutritionally stressed compounds health risk by potentially adding dehydration, heat stress, and illness. Additionally, as livestock become thin, less milk is available and livestock are sold at lower prices to exchange for other foods, if livestock can be sold at all. Samburu children exposed to drought and/or the hotter lowland region in utero adapt to heat, maternal psychosocial stress, and other anticipated postnatal energetic demands by accumulating relatively more body fat. This appears to buffer tibial growth in both drought-exposed and drought-unexposed children in the hot lowlands, although less so for drought-exposed lowland girls. Additionally, lowland children and children exposed to high daytime ambient temperatures during early gestation exhibit ecogeographical patterning in tibia proportion – again, whether or not they were exposed to any severe drought events in utero. Consistent with numerous studies, drought-exposed children also have lower body weight – but so do children in the cooler highlands, particularly boys. This suggests that lifelong maternal psychosocial trauma (higher in highlands in this study), dietary differences (lower protein and fat intake in the highlands in another Samburu study), and other factors are contributing to reduced growth overall in highland children and may be exaggerating the influence of ecogeographical patterning on tibial growth.

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*Conflict of Interest*. There were no conflicts of interest to report for this study.

*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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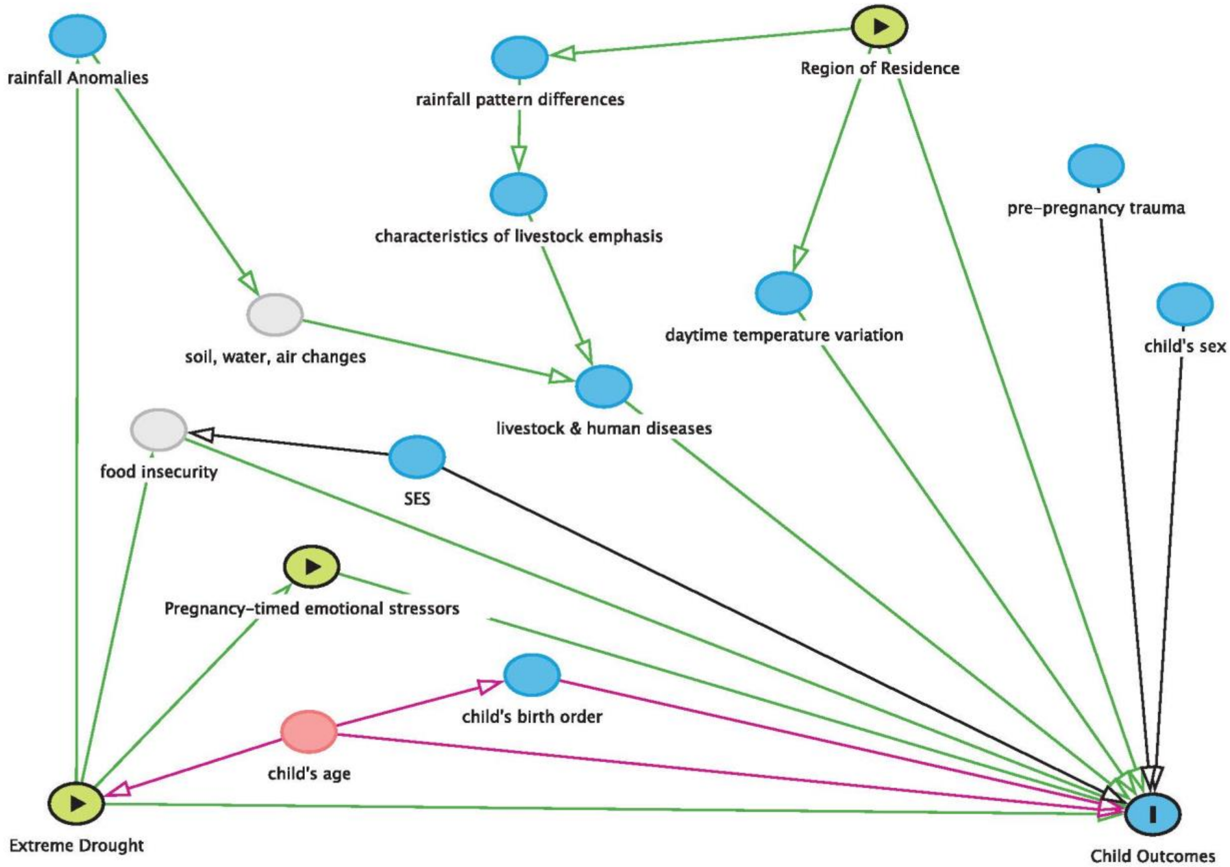


Figure 1. Directed acyclic graph (DAG) for our models using the daggity program (http://www.dagitty.net/dags.html). Legend (reproduced from daggity.net):

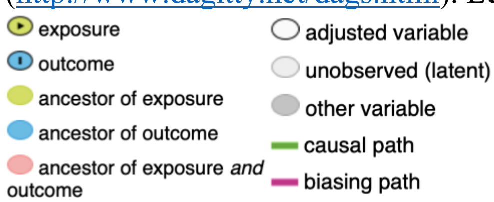

**Table 1. Historical Weather Data**

| Parameter | Drought Early Gestation | Controls Early Gestation | Lowland Early Gestation | Highland Early Gestation |
|---|---|---|---|---|
| Early Gestation Rainfall (mm) | 79.21 | 185.49 | 122.02 | 141.29 |
| Early Gestation Mean Ambient Temperature (Celsius) | 39.05 | 35 | 40.76 | 34.47 |

**Table 2. Descriptive Demographic Statistics (N=213)**

| Variable | | N | Percent | Mean (SD) | Range (min, max) |
|---|---|---|---|---|---|
| ***Child Demographic Characteristics*** | | | | | |
| Gender | Male | 98 | 46% | | |
| | Female | 115 | 54% | | |
| Age (in years) | Overall | 213 | | 6.72 (1.96) | 7.8 (1.8, 9.6) |
| | Male | 98 | | 6.7 (2) | 7.2 (2.5, 9.6) |
| | Female | 115 | | 6.7 (1.9) | 7.3 (1.8, 9.1) |
| Drought exposure | Drought Group | 104 | 49% | | |
| | Sibling Controls | 109 | 51% | | |
| Region | Highland | 128 | 60% | | |
| | Lowland | 85 | 40% | | |
| ***Maternal Stressors*** | | | | | |
| Forced Work | Yes | 22 | 10% | | |
| | No | 191 | 90% | | |
| Denied Food | Yes | 25 | 12% | | |
| | No | 188 | 88% | | |
| Other Emotional Stressors | | 213 | | 2.92 (2.82) | 15 (0, 15) |
| Maternal Lifetime Trauma | | 213 | | 0.84 (0.94) | 4 (0,4) |
| ***Family Structure*** | | | | | |
| Child of Widow/Unmarried/Divorced | | 16 | 8% | | |
| Child of Polygynous 1st Wife | | 44 | 21% | | |
| Child of Polygynous 2nd or later wife | | 56 | 26% | | |
| Child of Monogamous wife | | 97 | 45% | | |
| ***Family Socioeconomic Indicators*** | | | | | |
| Per Wife Cows | | 213 | | 9.15 (14.11) | 100 (0, 100) |
| Per Wife Small Stock | | 213 | | 32.29 (47.61) | 350 (0, 350) |
| Mothers' Milk cows | | 213 | | 0.97 (1.56) | 10 (0, 10) |
| Mothers' Milk Small Stock | | 213 | | 5.81 | 32 |

| | | | | | |
|---|---|---|---|---|---|
| | | | | (5.9) | (0, 32) |
| Mother Ever Employed | Yes | 110 | 52% | | |
| | No | 103 | 48% | | |
| Father Ever Employed | Yes | 127 | 60% | | |
| | No | 86 | 40% | | |
| Child Ever Attended School | Yes | 162 | 77% | | |
| | No | 49 | 23% | | |

**Table 3. Descriptive Growth Statistics, Drought (N=104) and Controls (N=109)**

| | Drought Mean (SD) | Controls Mean (SD) | Drought Range (min, max) | Controls Range (min, max) |
|---|---|---|---|---|
| Child age | 8.52 (0.34) | 5.006 (1.16) | 1.7 (7.9, 9.6) | 5 (1.8, 6.8) |
| Tibia length (cm) | 30.14 (2.24) | 23.7 (3.13) | 12 (24, 36) | 14 (17.5, 31) |
| zTibia length for age | -0.61 (0.78) | -0.77 (0.73) | 4.16 (-2.88, 1.29) | 3.93 (-2.52, 1.42) |
| Tibia Index (to stature) | 24.61 (0.96) | 23.04 (1.36) | 5.1 (22.1, 27.2) | 6 (20.1, 26.1) |
| zTibia index (to stature) for age | 0.19 (0.51) | -0.26 (0.61) | 2.66 (-1.14, 1.52) | 3.02 (-1.82, 1.2) |
| Height in cm | 122 (6) | 102.53 (8.98) | 31.77 (104.27, 136.03) | 45.13 (79, 124.13) |
| zHeight for age | -1.15 (0.94) | -1.21 (0.88) | 4.61 (-3.6, 1.01) | 4.52 (-3.38, 1.14) |
| Weight (kg) | 20.1 (2.54) | 14.4 (2.32) | 14.14 (13.38, 27.52) | 9.93 (9.01, 18.94) |
| zWeight for age | -1.6 (0.52) | -1.03 (0.66) | 2.77 (-2.89, -0.12) | 4.31 (-3.19, 1.11) |
| Triceps skinfold thickness (mm) | 5.94 (1.52) | 7.2 (1.83) | 8.66 (2, 10.66) | 9 (4, 13) |
| zTriceps for age | -1.11 (0.68) | -0.66 (0.86) | 4.62 (-4.42, 0.2) | 4.08 (-3.12, 0.96) |
| Subscapular skinfold thickness (mm) | 4.3 (0.72) | 4.47 (1.02) | 4 (3, 7) | 5.5 (3, 8.5) |
| zSubscap for age | -0.71 (0.31) | -0.68 (0.61) | 1.71 (-1.57, 0.14) | 3.56 (-2.77, 0.79) |
| Suprailiac skinfold thickness (mm) | 4.58 (1.45) | 5.77 (2.24) | 7 (2, 9) | 12.33 (2, 14.33) |
| zSuprailiac for age | -0.66 (0.44) | 0.21 (0.77) | 1.96 (-1.62, 0.33) | 3.96 (-1.5, 2.46) |

**Table 4. Descriptive Growth Statistics, Highland (N=128) and Lowland (N=85)**

| | Highland Mean (SD) | Lowland Mean (SD) | Highland Range (min, max) | Lowland Range (min, max) |
|---|---|---|---|---|
| Child age | 6.74 (1.94) | 6.69 (1.99) | 7.2 (2.5, 9.6) | 7.3 (1.8, 9.1) |
| Tibia length (cm) | 26.48 (4.16) | 27.4 (4.29) | 19 (17.5, 36) | 17 (18, 35) |
| zTibia length for age | -0.85 (0.79) | -0.46 (0.64) | 4.16 (-2.88, 1.29) | 3.77 (-2.35, 1.42) |
| Tibia Index (to stature) | 23.53 (1.47) | 24.22 (1.24) | 6.9 (20.1, 27) | 6.5 (20.7, 27.2) |
| zTibia index (to stature) for age | -0.19 (0.63) | 0.19 (0.49) | 3.26 (-1.82, 1.45) | 2.37 (-0.85, 1.52) |
| Height in cm | 111.95 (11.99) | 112.65 (13.43) | 51.73 (83.23, 134.97) | 57.03 (79, 136.03) |
| zHeight for age | -1.25 (0.88) | -1.08 (0.94) | 4.11 (-3.38, 0.73) | 4.74 (-3.6, 1.14) |
| Weight (kg) | 17.12 (3.71) | 17.28 (3.82) | 17.93 (9.6, 27.52) | 17.26 (9.01, 26.27) |
| zWeight for age | -1.33 (0.67) | -1.28 (0.63) | 4 (-2.89, 1.11) | 3.17 (-3.19, -0.03) |
| Triceps skinfold thickness (mm) | 6.65 (1.79) | 6.47 (1.81) | 11 (2, 13) | 7.67 (3.33, 11) |
| zTriceps for age | -0.87 (0.84) | -0.91 (0.76) | 5.38 (-4.42, 0.96) | 3.52 (-2.58, 0.94) |
| Subscap skinfold thickness (mm) | 4.24 (0.8) | 4.6 (0.98) | 4 (3, 7) | 5.5 (3, 8.5) |
| zSubscap for age | -0.78 (0.51) | -0.57 (0.4) | 3.42 (-2.77, 0.66) | 2.55 (-1.76, 0.79) |
| Suprailiac skinfold thickness (mm) | 4.85 (1.58) | 5.68 (2.38) | 9.67 (2, 11.67) | 11.33 (3, 14.33) |
| zSuprailiac for age | -0.33 (0.69) | -0.07 (0.84) | 3.65 (-1.62, 2.03) | 4.08 (-1.62, 2.46) |

**Table 5. zTibia Length for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | -0.51 | 0.3 | 203 | -1.74 | -1.1 | 0.07 |
| *Drought‡* | 0.002 | 0.2 | 188.58 | 0.12 | -0.39 | 0.39 |
| *Lowland* | **0.4*****| 0.12 | 102.93 | 3.37 | 0.16 | 0.63 |
| *Forced Work (yes)* | **-0.39*** | 0.17 | 203 | -2.29 | -0.72 | -0.05 |
| *Denied Food (yes)* | **0.39*** | 0.17 | 203 | 2.34 | 0.06 | 0.72 |
| Maternal Lifetime Trauma | **-0.15**** | 0.06 | 145.87 | -2.57 | -0.26 | -0.03 |
| Child of widow/ divorced/ unmarried | **-0.42*** | 0.21 | 106.08 | -1.96 | -0.84 | 0.005 |
| Milk cows | **0.1*** | 0.043 | 106.29 | 2.35 | 0.02 | 0.19 |
| Milk small stock | **-0.03*** | 0.01 | 103.36 | -2.35 | -0.05 | -0.004 |
| Age (years) | 0.04 | 0.05 | 201.44 | 0.72 | -0.07 | 0.14 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For precision, model uses tibia length to derive z scores (see explanation in text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table 6. zTibia Index for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **-0.8***** | 0.2 | 204 | -3.95 | -1.20 | -0.4 |
| *Drought‡* | -0.05 | 0.14 | 187.96 | -0.38 | -0.33 | 0.23 |
| *Lowland* | **0.42***** | 0.08 | 103.21 | 5.17 | 0.26 | 0.58 |
| *Forced Work (yes)* | **-0.24*** | 0.12 | 204 | -1.99 | -0.47 | -0.002 |
| *Denied Food (yes)* | **0.25*** | 0.12 | 203.97 | 2.12 | 0.02 | 0.47 |
| Child of 2nd or later polygynous wife | **0.18*** | 0.09 | 101.71 | 1.97 | -0.001 | 0.35 |
| Milk cows | 0.04 | 0.03 | 103.54 | 1.36 | -0.02 | 0.09 |
| Per wife cows | **-0.006*** | 0.003 | 104.78 | -2.07 | -0.01 | -0.0002 |
| Age (years) | **0.15***** | 0.04 | 199.89 | 4.042 | 0.08 | 0.22 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For precision, model uses tibia length to derive z scores (see explanation in text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table 7. Height for Age, Adjusted Model**

| Parameter | Estimate[†] | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **-1.27*** ** | 0.37 | 201 | -3.47 | -2.01 | -0.55 |
| *Drought*[‡] | -0.23 | 0.24 | 188.49 | -0.96 | -0.701 | 0.24 |
| *Lowland* | 0.14 | 0.15 | 103.72 | 0.99 | -0.14 | 0.43 |
| *Forced Work - Yes* | **-0.4** | 0.2 | 201 | -1.95 | -0.8 | 0.005 |
| *Denied Food - Yes* | **0.44*** | 0.2 | 201 | 2.2 | 0.05 | 0.84 |
| Maternal Lifetime Trauma | **-0.25*** ** | 0.07 | 148.52 | -3.56 | -0.39 | -0.11 |
| Child of widow/unmarried/divorced | **-0.6*** | 0.26 | 107.34 | -2.31 | -1.11 | -0.08 |
| Milk cows | **0.11*** | 0.05 | 107.47 | 2.11 | 0.007 | 0.22 |
| Milk small stock | **-0.04**** | 0.01 | 104.65 | -2.94 | -0.07 | -0.01 |
| Middle perceived wealth - yes | 0.23 | 0.14 | 102.82 | 1.63 | -0.05 | 0.5 |
| Mother's highest grade | 0.06 | 0.03 | 105.19 | 1.7 | -0.01 | 0.12 |
| Age (years) | 0.07 | 0.06 | 201 | 1.14 | -0.05 | 0.2 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For precision, model uses tibia length to derive z scores (see explanation in text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table 8. zWeight for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **-0.73**** | 0.24 | 200 | -3.05 | -1.2 | -0.26 |
| *Drought*‡ | **-0.38*** | 0.17 | 200 | -2.3 | -0.71 | -0.06 |
| *Lowland* | 0.04 | 0.09 | 109.83 | 0.49 | -0.13 | 0.22 |
| *Forced work (yes)* | -0.06 | 0.13 | 197.39 | -0.43 | -0.32 | 0.21 |
| *Denied Food (yes)* | 0.11 | 0.13 | 188.1 | 0.87 | -0.14 | 0.37 |
| Maternal Lifetime Trauma | **-0.1*** | 0.04 | 132.85 | -2.2 | -0.18 | -0.01 |
| Mother Employed (yes) | **0.2*** | 0.09 | 102.4 | 2.32 | 0.03 | 0.38 |
| Child attend school (yes) | **0.19** | 0.1 | 200 | 1.88 | -0.01 | 0.39 |
| Per wife cows | **0.006*** | 0.003 | 104.59 | 2.02 | 0.00008 | 0.01 |
| Age (years) | -0.07 | 0.04 | 200 | -1.5 | -0.15 | 0.02 |
| Male | **-0.34***** | 0.08 | 98.88 | -4.06 | -0.5 | -0.17 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table 9. zTriceps Skinfold Thickness for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **1.04***** | 0.32 | 201.48 | 3.24 | 0.41 | 1.67 |
| *Drought*‡ | **0.66**** | 0.22 | 188.88 | 2.96 | 0.22 | 1.09 |
| *Lowland* | -0.03 | 0.11 | 99.83 | 0.27 | -0.26 | 0.19 |
| *Forced work (yes)* | 0.29 | 0.18 | 193.56 | 1.61 | -0.07 | 0.64 |
| *Denied Food (yes)* | 0.18 | 0.17 | 183.63 | 1.09 | -0.15 | 0.52 |
| Age (years) | **-0.33***** | 0.06 | 198.08 | -5.51 | -0.44 | -0.21 |
| Male | **-0.23*** | 0.11 | 99.07 | -2.09 | -0.45 | -0.11 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table 10. zSubscap Skinfold Thickness for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **-0.65**** | 0.21 | 195.49 | -3.06 | -1.08 | -0.23 |
| *Drought‡* | -0.04 | 0.15 | 190.71 | -0.25 | -0.33 | 0.26 |
| *Lowland* | **0.23**** | 0.08 | 106.55 | 2.87 | -0.07 | 0.39 |
| *Forced work (yes)* | 0.12 | 0.12 | 181.3 | 0.99 | -0.11 | 0.34 |
| *Denied Food (yes)* | -0.1 | 0.11 | 170.25 | -0.88 | -0.31 | 0.12 |
| Maternal Lifetime Trauma | 0.07 | 0.04 | 126.66 | 1.7 | -0.01 | 0.14 |
| Child attend school (yes) | **0.19*** | 0.09 | 189.99 | 2.11 | 0.01 | 0.36 |
| Mother's milk camels (yes) | 0.24 | 0.15 | 96.88 | 1.6 | -0.05 | 0.54 |
| Age (years) | 0.003 | 0.04 | 196.93 | -0.08 | -0.08 | 0.08 |
| Male | **-0.16*** | 0.07 | 95.93 | -2.22 | -0.3 | -0.02 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

**Table 11. zSuprailiac Skinfold Thickness for Age, Adjusted Model**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **2.005***** | 0.24 | 199.2 | 8.3 | 1.52 | 2.48 |
| *Drought‡* | **0.3** | 0.17 | 183.66 | 1.77 | -0.03 | 0.63 |
| *Lowland* | **0.25**** | 0.09 | 101.07 | 2.73 | -0.07 | 0.43 |
| *Forced work (yes)* | -0.1 | 0.14 | 196.91 | -0.71 | -0.37 | 0.17 |
| *Denied Food (yes)* | 0.1 | 0.13 | 188.9 | 0.79 | -0.16 | 0.36 |
| Per wife small stock | -0.002 | 0.002 | 101 | -1.4 | -0.005 | 0.0009 |
| Per wife cows | **0.01*** | 0.005 | 101.15 | 2.07 | 0.0004 | 0.02 |
| Age (years) | **-0.33***** | 0.04 | 193.2 | -7.41 | -0.42 | 0.24 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * $P \leq 0.05$, ** $P \leq 0.01$, *** $P \leq 0.001$.

**Supporting Materials for:** Drought, Psychosocial Stress, and Ecogeographical Patterning: Tibia growth and body shape in Samburu (Kenyan) pastoralist children

## Recruitment, Timing, Informed Consent

Recruitment criteria for participant mothers consisted of self-identification as belonging to a Samburu family, rural residence, first trimester of pregnancy of a live child occurring during the 2008-2009 extreme drought based on vaccination record or birth certificate, and at least one live child of the same sex who was unexposed to the drought either in utero or in early childhood. These criteria necessitated broad coverage across Samburu County and the border area of Samburu/Laikipia Counties on rutted tracks or off road. Nevertheless, between October 2017 and December 2018, we successfully enrolled 123 triads, of whom, 11 were later found not to meet the inclusion criteria due to immunization record errors or other disqualifying reasons, 4 families declined to participate after initial enrollment, and 3 families moved out of the study area. One mother was found (based on second visit interviews) to have spent the drought pregnancy in an urban area after meeting the gestational timing criteria but subsequently returned to the rural area. Her results are excluded from drought-based models but retained for non-drought models. We successfully completed data collection with 105 triads: 105 mothers, 104 drought-exposed children + 1 child excluded for drought models, and 109 control siblings (four mothers had more than 1 eligible same-sex sibling control).

Initial recruitment and consent and assent processes, and pilot interviews with participant mothers, were undertaken by Straight (fluent in Kiswahili and conversational in Samburu vernacular) and two multilingual Samburu team members, one male and one female, in October 2017. Beginning in January, 2018 and through summer 2019, the same multilingual Samburu female team member worked with Straight on consent and assent and all interviews with participant mothers. Straight additionally engaged in participant-observation, building on long-term research with Samburu communities (since 1992). Ethnographic work with Samburu mothers included identification of the most stressful events that women experience during pregnancy. Anthropometry with children was undertaken by Hilton with the same primary multilingual Samburu team member for all anthropometry and with undergraduate assistants.

## Maternal stressor instrumentation

Here we describe maternal psychosocial stressor and trauma score (exposures) methods in further detail. Methods not described here because not relevant to this paper, include children's behavioral, psychosocial, and prosocial emotion instrumentation, saliva sampling in children, and psychosocial outcomes in mothers. Those methods will be described in future papers. For saliva sampling and telomere methods, see Needham et al., 2021.

*Instrumentation and Interviewing Methods for Participant Mothers.*

In order to elicit Samburu women's cultural knowledge and culturally-shaped experiences of personal trauma and environmental disaster, we created culturally-specific instruments to use alongside standardized instruments modified for use in Samburu (Madigoe, Burns, Zhang, and Subramaney, 2017). To accomplish this, we:

- conducted pregnancy thematic interviews with a panel of Samburu mother experts to create culturally-specific stressor instrumentation and modify standardized instrumentation;
- conducted participant observation with a subset of caregivers and their children;
- administered the Life Experience Checklist (LEC-5, full Interview version, Weathers, 2013a) with all participant mothers;
- administered the Abuse Assessment Self-Report (AAS), modified to include culturally-specific abuse questions with all participant mothers;
- conducted open-ended ethnographic interviews with all mothers concerning their experiences during each pregnancy and structured questions relevant to culturally-specific idioms of distress in addition to administering a standardized instrument, the Post-Traumatic Stress Disorder Checklist for Diagnostic and Statistical Manual of Mental Disorders (DSM), 5th Edition (PCL-5) (Weathers, 2013b). Idioms of distress and PCL-5 variables are not relevant to this paper and will not be described here.

*Translation.*

The LEC-5 was first translated and back translated in 2015 (Straight et al., 2019, 2020) by a team of multilingual research assistants working with Straight. Recruitment, informed consent, and pilot materials were translated and back translated by that same team in October 2017. All of those instruments were cross-checked in 2018, in the process described below, when transitioning from October 2017 and January 2018 pilot data collection to comprehensive data collection.

In June, 2018, Straight, Hilton, and a team including a clinical psychology graduate student (S. M. Haft, WMU), an undergraduate anthropology student, and five multilingual Samburu research assistants, undertook translations and back translations in a process of five days duration. This team composition was necessary, as some Western diagnostic concepts were not easily understood across cultural boundaries but ultimately, after much discussion and description in English, Kiswahili, and Samburu, proved to have recognizable correspondence to Samburu behaviors. Questions were modified in this process to be culturally meaningful to Samburu while maintaining consistency with what the question was designed to capture. In some cases, deficiencies in psychological instrumentation for cross-cultural application were noted and will be addressed in separate papers. Such deficiencies were addressed by extensive note-taking during interviews to allow appropriate coding of data. Data coding was performed by Straight for mothers' instrumentation and children's prosocial emotion instrumentation, and by a clinical psychology graduate student (S. M. Haft) for child psychosocial instrumentation, with coding decisions checked in collaboration with Naugle and two additional clinical psychology graduate students. Data entry was performed by clinical psychology and statistics graduate students; and cleaning was performed by Straight, Haft, and five additional biostatistics, psychology, and gender studies graduate and undergraduate students working, cross-checking data they had not entered.

*Life Experience Checklist for Diagnostic and Statistical Manual of Mental Disorders* (DSM), 5th Edition (LEC-5) (Weathers et al., 2013a): The LEC-5 interview consists of 9 questions focused on early life stressful experiences and 17 questions focused on lifetime stressful experiences related to natural disaster, fire or explosion, transportation accidents, serious accidents of other kinds, exposure to toxic substances, physical assault, assault with a weapon, sexual assault, other unwanted or uncomfortable sexual experience, combat or war-zone exposure, captivity, life-threatening illness or injury, severe human suffering, sudden violent death, sudden accidental death, serious harm caused to others, and any other stressful experiences. For each question, participants are asked whether they experienced it directly, witnessed it, heard about it, or whether it doesn't apply to them. They are additionally prompted about the timing and description of the event, what impact it had on them, and other details. We conducted the LEC-5 interview using similar techniques as for structured ethnographic interviews, while maintaining consistency with the instrument's guidelines. In order to reduce bias and elicit the experiences that were most salient for participants, no prompting was done to emphasize experiences occurring during their 2008-2009 extreme drought- or control-pregnancies from experiences at other times, and this instrument was administered first. The timing prompts for each event permitted capturing which events, if any, occurred during the drought- and control-pregnancies.

*Abuse Assessment Self-Report* (AAS) (McFarlane et al., 1992): The AAS consists of five items, developed specifically to identify pregnant women's experiences of abuse. The questions focus on life-time history of physical violence and experiences of physical and sexual abuse and fear of spouses and other persons specific to the current pregnancy. We administered the questionnaire late in the interview process, prompting for lifetime and then for events specific to the drought- and control-pregnancy, varying the order so that some women were asked first about the drought-pregnancy while others were first asked about the control-pregnancy. Question order did not alter the pattern of responses. Based on a panel of Samburu women experts and open-ended question pilot interviews, the AAS was modified to include questions about whether spouses and others deliberately withheld food from the participant or forced the participant to engage in what she perceived to be excessive or inappropriate work during one of both pregnancies. It is also noteworthy that the question about fearing one's spouse is multivalent for Samburu women, who may fear a spouse related to physical or emotional abuse but additionally if they fear that a husband will not respect cultural proscriptions on sexual intercourse that women may follow during some or all of their pregnancies.

*Process for creating 'other pregnancy-timed stressors' composite score variable.*

Using a culturally grounded approach (Miller et al., 2006) reflecting deep ethnographic engagement, we sought to capture the myriad elements that together, comprise the daily lived experience of extreme drought for Samburu pastoralist women living in a harsh climate in which unpredictability is chronic. For many Samburu women, patriarchal cultural practices mean that interpersonal violence and deliberate deprivation are a part of daily life. Chronic low-intensity warfare with other indigenous communities adds an additional stressor.

- Draw from open-ended textual data, interpreting through an ethnographic lens.
- Straight met with Naugle and clinical psychology students to discuss Samburu cultural understandings and experiences.

- One clinical psychology PhD student performed a first pass, entering as separate exposure categories, each element of stress or trauma that mothers described for each pregnancy as captured in the LEC-5, AAS, and structured and open-ended interviews.
- Straight and Naugle met to discuss culturally appropriate weighting of separate events.
- After a group consult with Straight, another clinical psychology PhD student (with clinically relevant experience working in Rwanda and Uganda) revisited the first pass, revised categories, consulting Naugle as needed for cultural relevance, and assigned weights to each category.
- Straight and Naugle checked the weights in consultation with the student and reached consensus on adjustments.
- Straight and Naugle finalized category weights, which were used to create a summed pregnancy-timed stressor score variable for use in our statistical models. These can be refined to sub-scales as relevant for future papers.

*Lifetime Maternal Trauma variable*.

All events from the LEC-5 (including traumatic childhood events such as loss of parents), AAS, and structured and open-ended interviews used to create the 'other pregnancy-timed stressors' score variable were used to create the lifetime maternal trauma variable as follows:

Using the same weighting of events as for the pregnancy-timed stressors, only the highest weighted events were retained. These included deaths of the participant mother's own parents or children, witnessing fatalities from climbing trees to get fodder for animals or during other hazardous livestock husbandry activities, war exposure with fatalities, and witnessing accidental deaths or suicide completion.

The trauma score for the drought-exposed pregnancy included all qualifying events occurring throughout the mother's lifetime up to the pregnancy. The trauma score for the control (drought unexposed) pregnancy included all qualifying events occurring throughout the mother's lifetime up to that pregnancy. Since all drought-exposed children are older than controls, this means that any qualifying events the mother experienced during the 2008-2009 drought are included in the pregnancy score for her control (drought-unexposed) child's pregnancy, as well as qualifying events post-drought up until the control pregnancy.

*Correlations between maternal stressors and other variables*

The following maternal stress and trauma exposure Spearman correlations were drawn upon for interpreting results in the Discussion: 'Other emotional stressors' is positively correlated with drought exposure ($r_s = 0.67$, $P \leq 0.001$) and early gestational daytime temperature ($r_s = 0.32$, $P \leq 0.001$); and negatively correlated with early gestational rainfall anomaly ($r_s = -0.41$, $P \leq 0.001$). Due to the high correlation of 'other emotional stressors' with drought-exposure, this variable was excluded from models but included in place of drought exposure in sensitivity models. It was non-significant for all three child outcomes (results not shown).

A participant mother being 'denied food' by husband or other male kin is positively correlated with her employment ($r_s = 0.21$, $P \leq 0.01$) and with being a widow, divorced, or never married ($r_s$

= 0.23, $P \leq 0.001$); and negatively correlated with milk small stock ($r_s = -0.17$, $P \leq 0.01$) and milk cows ($r_s = -0.19$, $P \leq 0.01$). 'Forced work' is not correlated to drought exposure, region of residence, weather, or livestock. A participant mother's 'lifetime maternal trauma' is positively correlated to highland residence ($r_s = 0.195$, $P \leq 0.01$) and her employment ($r_s = 0.15$, $P \leq 0.05$), and negatively correlated to per wife cows ($r_s = -0.19$, $P \leq 0.01$), per wife small stock ($r_s = -0.16$, $P \leq 0.05$), and per wife camels ($r_s = -0.2$, $P \leq 0.01$).

**Methods for Sensitivity Tests and Other Variables**

Educational Indicators. Women were asked to report on their own and their husbands' highest grade attained and also on the highest grade attained for their children, and whether the child was currently in school. Mothers' and fathers' highest grade were tested as potential covariates. Given the variation in children's ages, a dichotomous variable of ever attended school (including preschool, which is widespread in Samburu beginning by age 3 years) was created for children's education and tested as a potential covariate.

Economic Indicators. Women were asked to report how many cows, sheep or goats (small stock), and camels their family owned and how many dairy animals (cows, sheep or goats, and camels) that were allocated to them personally. The number of animals for each family was divided by number of wives to create a 'per wife' variable for each type of livestock. Per wife livestock variables and milk animals were each tested as potential (ordinal) covariates. Additionally, women were asked how much cash their family spent each month. Monetary income is challenging to collect accurately in Samburu but women know the amount of cash their families spend. Thus, 'cash spent' was used as an additional wealth measure and tested as a potential covariate. Women were also asked to report on their own and their husbands' employment. Given the high number of 'never employed' individuals, dichotomous variables were created for mothers' and fathers' employment, and tested as potential covariates.

*Mother's wife status.* Since many Samburu are polygynous, participant mothers were asked to report the number of wives for their husbands and their own rank (first, second, third wife, etc.). Wife status was coded into four categories, which were tested as potential covariates: first polygynous wife; monogamous wife; second or later polygynous wife; and a fourth category that included widows, women who had never married, and women who had separated permanently or semi-permanently (*kitala*). Virginity until marriage is not expected in Samburu but pregnancy before initiation is stigmatized, and having children without marrying confers low status. Divorce is rare in Samburu but *kitala* ('running away') is institutionalized and common. Women who are widowed, never married, or *kitala* all live in varying degrees of precarity, reliant on their husbands' (typically male) kin or their natal families for access to livestock and support. Widows should retain access to the herds they were allocated while their husbands are alive, but in practice, their status varies with whether they have sons, the age of those sons (older sons can advocate for their mothers), and the reliability of their husbands' family.

*Immune System* (All Child Participants): Caregivers were queried on whether children were ill at the present, yesterday, or in the past month, and what the symptoms were. For contagious or severe illness, caregivers were asked if the child had received treatment (traditional or biomedical). Caregivers were also asked whether they thought their child tended to get sick the same as neighboring children their age, more often, or less often. Immune system variables were tested as covariates, were non-significant for the lower leg and body weight outcomes, and set aside from adjusted models.

*Fetal and Infant Mortality for Sensitivity Test (Table S1, Figure S1)*. Pregnancy losses and infant mortality of neighbors are known and discussed among Samburu women, but discussing their own pregnancy and infant losses is sensitive. For this reason, Straight and the same female team member interviewed women concerning their reproductive histories, including fetal and child mortality by preparing them for the questions beforehand in a culturally appropriate and respectful tone. Near the end of interviews, in order to estimate differences in fetal and infant mortality between extreme drought and typical years, each of our 105 participant mothers was asked to recall how many mothers were pregnant in their areas for their drought and control pregnancies. Rural Samburu families live in dispersed compounds and know the neighboring families in their general area, relying on the same village clinics. After establishing the number of pregnancies, each participant mother was asked how many children were born alive from those pregnancies and how many women lost their pregnancies. After this, each woman was asked how many of the live-born children from those pregnancies died from any cause in the first two years of life. Of the 105 women asked, 89 responded with confidence in their estimates. Given women's sensitivity about their own fetal and child losses, these estimates about neighboring women are likely to be reliable, while women's reports about their own losses are likely to reflect underreporting.

We compared hypothesis tests for fetal loss ratio and for infant death ratio between drought and control pregnancies. Since most women have healthy births, we observed a clump of zeros with non-negative continuous values as shown in Figure S1. We employed a two-part test (Lachenbruch, 2001) for data with mixed distributions for two independent samples. The test is obtained from the sum of Pearson's test to test the equality of proportions of zero values and a conditional t-test for the continuous distribution. The sum of the squares of these two test statistics has an asymptotic chi-square distribution with 2 degrees of freedom.
For a comparison between drought and typical season pregnancies of neighboring women, including women's own live born children participating in the study, drought-based fetal mortality is significant in comparison to typical season fetal-mortality (test-statistics = 6.99, $P$ = 0.03). In contrast, drought-based infant mortality is not significant in comparison to typical season infant mortality (test-statistics = 3.55, $P$ = 0.17). (See Figure S1.)

*Weather variables for Sensitivity Tests (Tables S7-S10; S14-S15 descriptive statistics)*. We obtained daytime temperature for early gestation using MODIS LST Land Surface Temperature (https://modis.gsfc.nasa.gov/) available on the Famine Early Warning Systems Network (FEWS NET: https://earlywarning.usgs.gov/fews), which acquires 0.05 x 0.05 degree spatial resolution in decadal increments (Famiglietti, Fisher, Halverson, and Borbas, 2018). We also obtained pentadal rainfall data from FEWS NET using Climate Hazards group Infrared Precipitation with Stations (CHIRPS), a high resolution (0.05 degrees) precipitation data set (Funk et al., 2015). For both temperature and rainfall, we obtained the entire historical data set for the latitude and longitude of the closest landmark to each participant mother's residence. Next, we calculated mean maximum daytime temperature and cumulative rainfall for a three-month period corresponding to each participant mother's early gestation based on the participant child's birth date. Since the effects of daytime ambient temperature are directly experienced, we used the first trimester. For premature infants, this would still capture a period before and including early gestation. We determined 36.41° Celsius as a cut point for tibial outcomes. Since many of the effects of low rainfall are indirect and experienced as food insecurity and environmental hazards in the weeks and months following the event, we obtained data for the three-month period prior to gestation (nine to twelve months before birth) and also for the three-month period corresponding to the first trimester of gestation (Grace, Davenport, Hanson, Funk, and Shukla, 2015). Rainfall for the three-months leading up to gestation performed better in models and were retained. Finally, we used the full historical rainfall data set (forty years, 1981 - 2020) to create z-scores reflecting the standard deviations away from historical average for each participant mother's early gestation rainfall (Nübler et al., 2020). We employed these z-scores to account for rainfall anomalies in sensitivity analyses within sibling controls. Lowland/highland region was collinear with early gestational mean maximum daytime ambient temperature exposure (Spearman $r_s = 0.68$, $P \leq 0.001$) and drought exposure was collinear with rainfall z-scores (Spearkman $r_s = 0.62$, $P \leq 0.001$) and not included in the weather models.

*Inclusion of Older Children for Sensitivity Tests (Tables S11-S12).* Methods for our adolescent study that we use for inclusion of older Samburu children are described in Ashley-Martin et al. (2021) and Iannotti et al. (2021). The two studies overlapped in timing of data collection, with the adolescent study undertaken in June-July, 2017 and the drought sibling pair study commencing in October, 2017 through July, 2019. Data collection for both studies was undertaken in the field by Straight and Hilton. Since all ages for the drought sibling pair study were documented with clinical records and birth certificates, we only included data from the adolescent study for those participants whose ages were likewise documented with vaccination or birth records and were 19 years or younger.

<u>*Tibia Measures for Inclusion of Older Children for Sensitivity Tests*</u>. Tibia measurements consisted of direct measurements of tibia length for the drought sibling pair sample, as stated in the paper. For the adolescent sample used for the sensitivity tests, tibiale height was measured following protocols of Weiner and Lourie (1969). To maintain the precision of the drought sibling pair data, sibling pair statistical models used z-scores obtained by entering unadjusted sibling pair tibia measurements into the "lower leg" and "lower leg index" components of the Frisancho (2011) z-score program. For the reference populations in that program, lower leg length is estimated in two steps: 1) stature – sitting height = total leg length; 2) total leg length – upper leg length (inguinal crease to top of patella) = lower leg length (see also Bogin & Varela-Silva, 2008, 2010). Lower leg index = lower leg length/stature*100.

For inclusion of our unrelated older adolescent controls in minimal adjustment sensitivity models for tibia length and tibia index without losing the precision of the sibling pair tibia measurements, a malleolar height estimate was deducted from adolescent tibiale height. The adjustment, based on malleolar height data analyzed in Kasabova & Holliday (2015), is as follows: tibia length = tibiale height – malleolar height (where malleolar height = stature in centimeters * 4.67%).

## Supporting File Figures

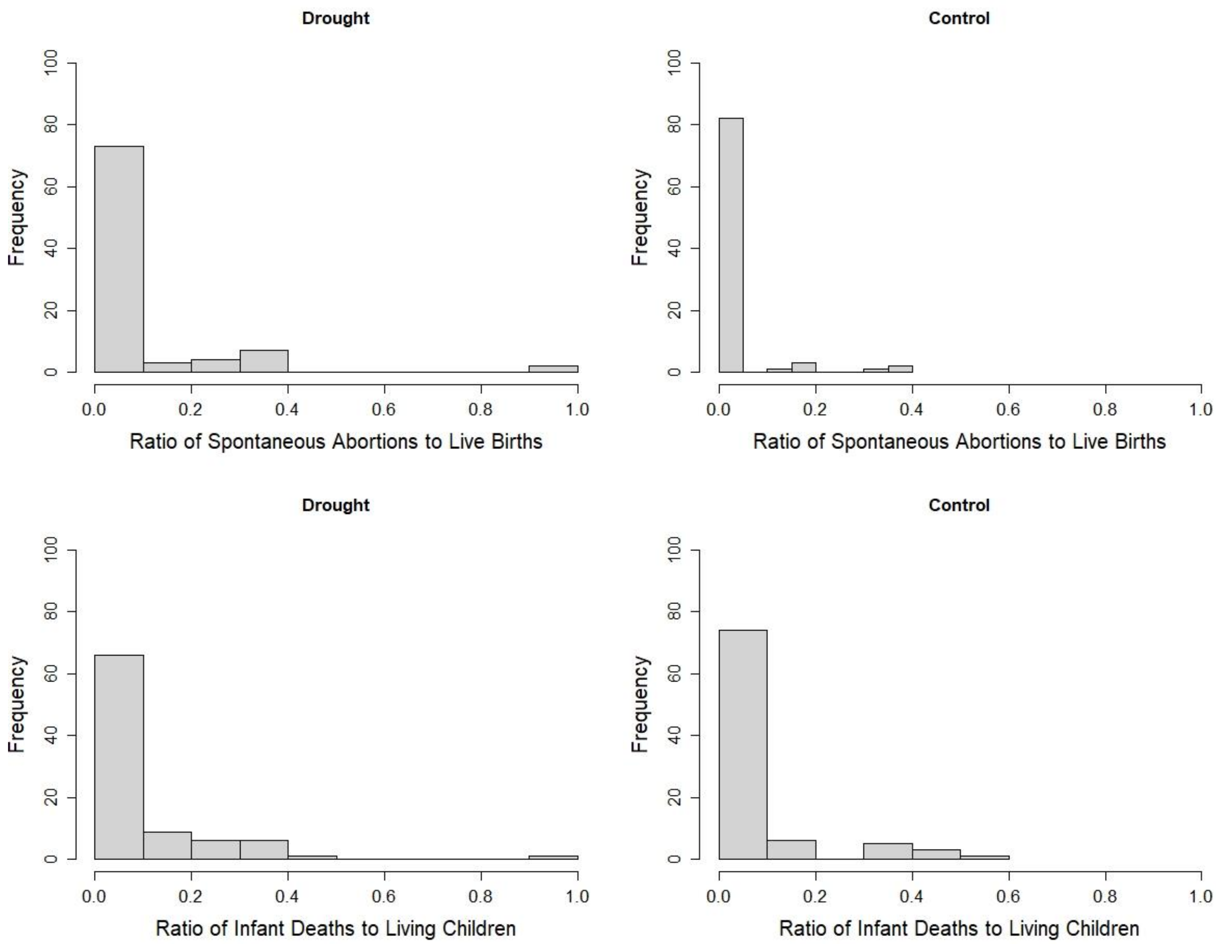


**Figure S1.** Fetal Mortality tests, frequency distributions.

## Supporting File Tables

### Table S1. Fetal and Infant Mortality – 2009 Drought compared to Typical Seasons

| Drought Live births | Drought Spontaneous Abortions | Drought Infant Deaths | Control Live Births | Control Spontaneous Abortions | Control Infant Deaths |
|---|---|---|---|---|---|
| 429 | 22 | 27 | 457 | 11 | 19 |

Data is based on 89 mothers responding with self-reported good recall out of 105 asked.

### Table S2. Weight for Age, Adjusted Model, Females only

| Parameter (N=115) | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | -0.36 | 0.35 | 103 | -1.04 | -1.05 | 0.33 |
| *Drought‡* | -0.36 | 0.24 | 103 | -1.49 | -0.84 | 0.12 |
| *Lowland* | 0.18 | 0.13 | 64.83 | 1.37 | -0.44 | 0.08 |
| *Forced Worked -Yes* | 0.11 | 0.17 | 99.84 | 0.64 | -0.23 | 0.45 |
| *Denied Food - Yes* | 0.16 | 0.16 | 103 | 0.97 | -0.16 | 0.48 |
| Maternal Lifetime Trauma | **-0.17**** | 0.06 | 71.84 | -3.04 | -0.28 | -0.06 |
| Mother Employ - Yes | **0.19** | 0.11 | 50.48 | 1.70 | 0.03 | 0.41 |
| Child attend school - Yes | -0.02 | 0.15 | 103 | -0.14 | -0.32 | 0.28 |
| Per wife cows | **0.01*** | 0.005 | 50.06 | 2.12 | 0.0006 | 0.02 |
| Age (years) | **-0.12** | 0.06 | 103 | -1.82 | -0.25 | -0.01 |

†. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

### Table S3. Weight for Age, Adjusted Model, Males only

| Parameter (N=98) | Estimate† | Std. Error | df | t | 90% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-1.23***** | 0.3 | 88 | -4.07 | -1.83 | -0.63 |
| *Drought‡* | **-0.37** | 0.21 | 88 | -1.71 | -0.79 | -0.06 |
| *Lowland* | **0.25*** | 0.12 | 46.45 | 2.02 | 0.0003 | 0.5 |
| *Forced Work - Yes* | -0.23 | 0.22 | 88 | -1.03 | -0.66 | 0.21 |
| *Denied Food - Yes* | 0.21 | 0.22 | 72.1 | 0.96 | -0.23 | 0.65 |
| Maternal Lifetime Trauma | -0.01 | 0.07 | 53.89 | -0.07 | -0.15 | 0.14 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mother Employ - Yes | 0.20 | 0.13 | 51.52 | 1.52 | -0.07 | 0.47 |
| Child attend school - Yes | 0.12 | 0.14 | 88 | 0.86 | -0.16 | 0.4 |
| Per wife cows | 0.003 | 0.004 | 50.17 | 0.85 | -0.005 | 0.01 |
| Age (years) | -0.02 | 0.06 | 88 | -0.4 | -0.14 | 0.09 |
| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S4. zTriceps Skinfold Thickness for Age, Adjusted Model, Females only**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **1.2*** | 0.48 | 106.7 | 2.51 | 0.25 | 2.14 |
| *Drought*‡ | **0.76*** | 0.33 | 102.16 | 2.28 | 0.1 | 1.42 |
| *Lowland* | -0.01 | 0.16 | 54.13 | -0.05 | -0.34 | 0.32 |
| *Forced work (yes)* | 0.33 | 0.24 | 103.53 | 1.39 | -0.14 | 0.8 |
| *Denied Food (yes)* | 0.27 | 0.23 | 105.58 | 1.21 | -0.17 | 0.72 |
| Age (years) | **-0.36***** | 0.09 | 106.49 | -3.98 | -0.53 | -0.18 |
| † Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S5 zTriceps Skinfold Thickness for Age, Adjusted Model, Males only**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **0.71** | 0.42 | 87.49 | 1.71 | -0.12 | 1.54 |
| *Drought*‡ | **0.54** | 0.29 | 81.21 | 1.82 | -0.05 | 1.13 |
| *Lowland* | -0.07 | 0.16 | 44.27 | -0.44 | -0.39 | 0.25 |
| *Forced work (yes)* | 0.26 | 0.29 | 85.21 | 0.89 | -0.32 | 0.85 |
| *Denied Food (yes)* | 0.06 | 0.28 | 67.19 | 0.21 | -0.5 | 0.62 |
| Age (years) | **-0.29***** | 0.08 | 85.76 | -3.73 | -0.45 | -0.14 |
| † Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S6. zSubscap Skinfold Thickness for Age, Adjusted Model, Females only**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval |
|---|---|---|---|---|---|

| | | | | | Lower | Upper |
|---|---|---|---|---|---|---|
| Intercept | -0.77 | 0.23 | 96.88 | -0.33 | -0.54 | 0.39 |
| *Drought*‡ | **0.31*** | 0.15 | 101.31 | 2.0 | 0.002 | 0.61 |
| *Lowland* | **0.14** | 0.08 | 62.12 | 1.78 | -0.02 | 0.3 |
| *Forced work (yes)* | 0.05 | 0.1 | 85.7 | 0.52 | -0.15 | 0.26 |
| *Denied Food (yes)* | 0.07 | 0.1 | 89.76 | 0.69 | -0.13 | 0.26 |
| Maternal Lifetime Trauma | -0.005 | 0.03 | 63.98 | -0.16 | -0.07 | 0.06 |
| Child attend school (yes) | 0.02 | 0.09 | 96.26 | 0.19 | -0.17 | 0.21 |
| Mother's milk camels (yes) | 0.23 | 0.18 | 49.37 | 1.27 | -0.13 | 0.59 |
| Age (years) | **-0.12**** | 0.04 | 100.87 | -2.84 | -0.2 | -0.04 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table S7. zSubscap Skinfold Thickness for Age, Adjusted Model, Males only**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **-1.69***** | 0.35 | 86.11 | -4.77 | -2.4 | -0.99 |
| *Drought*‡ | -0.4 | 0.26 | 79.47 | -1.56 | -0.91 | 0.11 |
| *Lowland* | 0.21 | 0.16 | 42.95 | 1.3 | -0.11 | -0.52 |
| *Forced work (yes)* | 0.4 | 0.26 | 83.35 | 1.56 | -0.11 | 0.91 |
| *Denied Food (yes)* | **-0.42** | 0.24 | 64.36 | -1.71 | -0.9 | 0.07 |
| Maternal Lifetime Trauma | 0.08 | 0.09 | 52.5 | 0.96 | -0.89 | 0.25 |
| Child attend school (yes) | **0.27** | 0.16 | 82.9 | 1.69 | -0.05 | 0.58 |
| Mother's milk camels (yes) | 0.15 | 0.25 | 43.23 | 0.62 | -0.35 | 0.66 |
| Age (years) | 0.11 | 0.07 | 85.65 | 1.57 | -0.03 | 0.25 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table S8. zSuprailiac Skinfold Thickness for Age, Adjusted Model, Females**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **2.13***** | 0.35 | 104.98 | 6.03 | 1.42 | 2.83 |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Drought*‡ | **0.42** | 0.24 | 100.38 | 1.73 | -0.06 | 0.89 |
| *Lowland* | **0.33**** | 0.12 | 50.22 | 2.74 | 0.09 | 0.57 |
| *Forced work (yes)* | -0.21 | 0.17 | 100.87 | -1.21 | -0.55 | 0.13 |
| *Denied Food (yes)* | 0.19 | 0.16 | 103.63 | 0.26 | -0.14 | 0.51 |
| Per wife small stock | 0.001 | 0.002 | 49.53 | 0.65 | -0.004 | 0.006 |
| Per wife cows | 0.002 | 0.007 | 49.68 | 0.37 | -0.01 | 0.02 |
| Age (years) | **-0.41***** | 0.06 | 104.6 | -6.36 | -0.54 | -0.28 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

### Table S9. zSuprailiac Skinfold Thickness for Age, Adjusted Model, Males

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| | | | | | Lower | Upper |
| Intercept | **1.31***** | 0.31 | 83.4 | 4.3 | 0.71 | 1.92 |
| *Drought*‡ | 0.19 | 0.22 | 76.39 | 0.89 | -0.24 | 0.62 |
| *Lowland* | 0.06 | 0.14 | 46.1 | 0.43 | -0.22 | 0.34 |
| *Forced work (yes)* | 0.25 | 0.22 | 87.18 | 1.11 | -0.2 | 0.69 |
| *Denied Food (yes)* | -0.1 | 0.23 | 70.3 | 0.65 | -0.56 | 0.35 |
| Per wife small stock | **-0.005*** | 0.002 | 46.04 | -2.53 | -0.01 | -0.001 |
| Per wife cows | **0.02**** | 0.008 | 46.05 | 2.99 | 0.007 | 0.04 |
| Age (years) | **-0.25***** | 0.06 | 79.91 | -4.31 | -0.36 | -0.13 |

† Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

### Table S10. zTibia for Age, Weather Variables Sensitivity Model, Sibling Controls

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-1.02***** | 0.3 | 99 | -3.42 | -1.62 | -0.43 |
| *Forced Work - Yes*‡ | **-0.48*** | 0.23 | 99 | -2.06 | -0.94 | -0.02 |
| *Denied Food - Yes* | **0.42*** | 0.21 | 99 | 2.04 | 0.01 | 0.83 |
| *Mean Daytime Ambient Temp early gestation ≥ 36.41° C - Yes* | **0.39**** | 0.13 | 99 | 3.03 | 0.13 | 0.65 |
| *Rainfall Anomaly - Yes* | **0.85** | 0.46 | 99 | 1.8 | -0.07 | 1.77 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Maternal Lifetime Trauma | **-0.19**** | 0.06 | 99 | -3 | -0.31 | -0.06 |
| Child of widow/ divorced/ unmarried | -0.28 | 0.24 | 99 | -1.14 | -0.75 | 0.2 |
| Milk cows | 0.06 | 0.05 | 99 | 1.13 | -0.03 | 0.16 |
| Milk small stock | -0.02 | 0.012 | 99 | -1.52 | -0.04 | 0.01 |
| Age (years) | 0.06 | 0.05 | 94.38 | 1.16 | -0.04 | 0.16 |
| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. No is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S11: zTibia for Age, Weather Variables Sensitivity Model, Sibling Pairs**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-0.67***** | 0.18 | 203 | -3.73 | -1.02 | -0.31 |
| *Forced Work - Yes‡* | **-0.37*** | 0.17 | 203 | -2.17 | -0.71 | -0.03 |
| *Denied Food - Yes* | **0.35*** | 0.17 | 203 | 2.06 | 0.02 | 0.68 |
| *Mean Daytime Ambient Temp early gestation ≥ 36.41° C - Yes* | **0.21** | 0.11 | 203 | 1.95 | -0.003 | 0.41 |
| *Rainfall Anomaly - Yes* | 0.2 | 0.18 | 185.97 | 1.1 | -0.16 | 0.57 |
| Maternal Lifetime Trauma | **-0.18**** | 0.06 | 151.58 | -3.08 | -0.3 | -0.07 |
| Child of widow/ divorced/ unmarried | -0.46 | 0.22 | 109.26 | -2.11 | -0.9 | -0.03 |
| Milk cows | **0.08** | 0.04 | 111.2 | 1.86 | -0.005 | 0.17 |
| Milk small stock | **-0.02*** | 0.01 | 107.44 | -2.07 | -0.05 | -0.0009 |
| Age (years) | 0.01 | 0.024 | 157.25 | 0.66 | -0.04 | 0.06 |
| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. No is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S12: zTibia Index for Age, Weather Variables Sensitivity Model, Sibling Controls**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-1.64***** | 0.29 | 96.73 | -5.59 | -2.22 | -1.06 |
| *Forced Work - Yes‡* | **-0.42** | 0.24 | 100 | -1.79 | -0.89 | 0.05 |
| *Denied Food - Yes* | **0.38** | 0.21 | 100 | 1.84 | -0.03 | 0.79 |
| *Mean Daytime Ambient Temp early gestation ≥ 36.41° C - Yes* | **0.37**** | 0.13 | 100 | 2.88 | 0.12 | 0.63 |

| | | | | | | |
|---|---|---|---|---|---|---|
| *Rainfall Anomaly - Yes* | **0.95*** | 0.47 | 100 | 2.01 | 0.01 | 1.89 |
| Child of 2nd or later polygynous wife | **0.39**** | 0.15 | 100 | 2.68 | 0.1 | 0.68 |
| Milk cows | 0.01 | 0.04 | 100 | 0.33 | -0.07 | 0.1 |
| Per wife cows | -0.003 | 0.005 | 100 | -0.59 | -0.01 | 0.007 |
| Age (years) | **0.12*** | 0.05 | 92.64 | 2.16 | 0.01 | 0.22 |
| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. No is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S13: zTibia Index for Age, Weather Variables Sensitivity Model, Sibling Pairs**

| Parameter | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-1.1***** | 0.17 | 192.97 | **-6.61** | **-1.42** | **-0.77** |
| *Forced Work - Yes‡* | **-0.34** | 0.18 | 204 | -1.93 | -0.69 | 0.008 |
| *Denied Food - Yes* | 0.27 | 0.17 | 204 | 1.59 | -0.07 | 0.61 |
| *Mean Daytime Ambient Temp early gestation ≥ 36.41° C - Yes* | **0.18** | 0.11 | 204 | 1.7 | -0.03 | 0.39 |
| *Rainfall Anomaly - Yes* | 0.14 | 0.19 | 186.9 | 0.72 | -0.23 | 0.51 |
| Child of 2nd or later polygynous wife | 0.21 | 0.14 | 104.13 | 1.51 | -0.07 | 0.48 |
| Milk cows | 0.02 | 0.04 | 108.39 | 0.44 | -0.06 | 0.09 |
| Per wife cows | 0.001 | 0.004 | 107.68 | 0.27 | -0.007 | 0.01 |
| Age (years) | 0.03 | 0.02 | 151.5 | 1.23 | -0.02 | 0.08 |
| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. No is reference for yes/no variables. Bold indicates significance, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. | | | | | | |

**Table S14. zTibia Length for Age for daggity minimal adjusted model with unrelated older Samburu children ages 9-19 years (N=84) added to sibling pair sample (n=213),**

| Parameter (Total N=300) | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-1.17***** | 0.14 | 233.16 | -8.29 | -1.44 | -0.89 |
| *Drought‡* | **-0.21**** | 0.08 | 226.46 | -2.61 | -0.38 | -0.05 |
| *Lowland* | **0.42***** | 0.10 | 151.62 | 4.01 | 0.21 | 0.62 |
| Age (years) | **0.12***** | 0.01 | 224.87 | 9.84 | 0.1 | 0.15 |
| Male | -0.09 | 0.1 | 217.25 | -0.96 | -0.28 | 0.1 |

| †. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For precision, model uses tibia length to derive z scores (see explanation in text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001. |
|---|

**Table S15. zTibia Index for Age daggity minimal adjusted model with unrelated older Samburu children ages 9-19 years (N=84) added to sibling pair sample (n=213)**

| Parameter (Total N=300) | Estimate† | Std. Error | df | t | 95% Confidence Interval | |
|---|---|---|---|---|---|---|
| Intercept | **-0.6***** | 0.1 | 228.75 | -6.1 | -0.8 | -0.4 |
| *Drought‡* | 0.09 | 0.06 | 228.84 | 1.6 | -0.02 | 0.2 |
| *Lowland* | **0.39***** | 0.07 | 149.76 | 5.31 | 0.24 | 0.53 |
| Age (years) | **0.11***** | 0.009 | 224.3 | 12.8 | 0.1 | 0.13 |
| Male | **-0.07** | 0.07 | 222.52 | -1.09 | -0.21 | 0.06 |

†. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For precision, model uses tibia length to derive z scores (see explanation in text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at 0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table S16. zLower Leg Length for Age Sensitivity Model for Validity Comparison, Using Malleolar Height Adjustment in Sibling Pairs**

| **Parameter** | **Estimate†** | **Std. Error** | **df** | **t** | **95% Confidence Interval** | |
|---|---|---|---|---|---|---|
| | | | | | **Lower** | **Upper** |
| Intercept | 1.11 | 0.27 | 203 | 4.06 | 0.57 | 1.65 |
| *Drought‡* | -0.12 | 0.18 | 188.3 | 0.52 | -0.48 | 0.24 |
| *Lowland* | **0.33**** | 0.11 | 103.25 | 3.004 | 0.11 | 0.55 |
| *Forced work (yes)* | **-0.35*** | 0.16 | 203 | -2.23 | -0.66 | -0.04 |
| *Denied Food (yes)* | **0.35*** | 0.15 | 203 | 2.3 | 0.05 | 0.66 |
| Maternal Lifetime Trauma | **-0.15**** | 0.05 | 146.5 | -2.75 | -0.25 | -0.04 |
| Child of widow/ divorced/ unmarried | **-0.4*** | 0.2 | 106.38 | -2.003 | -0.79 | 0.004 |
| Milk cows | **0.09*** | 0.04 | 106.6 | 2.32 | 0.01 | 0.17 |
| Milk small stock | **-0.02*** | 0.01 | 103.68 | -2.38 | -0.04 | -0.004 |
| Age (years) | 0.08 | 0.05 | 201.11 | 1.58 | -0.02 | 0.17 |

†Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For comparison to Table 4 in main text, this model uses lower leg length with a malleolar height adjustment to derive z scores (see Methods in main text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table S17. zLower Leg Index for Age Sensitivity Model for Validity Comparison, Using Malleolar Height Adjustment**

| **Parameter** | **Estimate**† | **Std. Error** | **df** | **t** | **95% Confidence Interval** | |
|---|---|---|---|---|---|---|
| | | | | | **Lower** | **Upper** |
| Intercept | **-0.95*** ** | 0.17 | 204 | 5.69 | 0.62 | 1.28 |
| *Drought*‡ | -0.19 | 0.12 | 189.49 | -1.62 | -0.42 | 0.04 |
| *Lowland* | **0.35*** ** | 0.07 | 103.4 | 5.22 | 0.22 | 0.48 |
| *Forced Work (yes)* | **-0.19*** | 0.1 | 204 | -1.96 | -0.38 | -0.001 |
| *Denied Food (yes)* | **0.19*** | 0.1 | 202.72 | 2.05 | 0.007 | 0.38 |
| Child of 2nd or later polygynous wife | **0.15*** | 0.07 | 101.88 | 2.1 | -0.008 | 0.3 |
| Milk cows | 0.03 | 0.02 | 103.68 | 1.27 | -0.01 | 0.07 |
| Per wife cows | **-0.005*** | 0.002 | 105.02 | -2.02 | -0.009 | 0.00008 |
| Age (years) | **0.22*** ** | 0.03 | 201.36 | 7.25 | 0.16 | 0.28 |

†. Estimates of fixed effects of linear mixed model. ‡. Focal predictors are italicized. For comparison to Table 5 in main text, this model uses lower leg index based on a malleolar height adjustment to derive z scores (see Methods in main text). Control is reference for drought exposure condition; highland residence is reference for region; no is reference for yes/no variables. Bold indicates significance at <0.1, with * P ≤ 0.05, ** P ≤ 0.01, *** P ≤ 0.001.

**Table S18: Additional Descriptive Statistics**

| Parameter | N | Percent. | Mean (SD) | Range (min, max) |
|---|---|---|---|---|
| Child's Birth Order | 213 | | 3.83 (2.13) | 11 (1, 12) |
| 24hr symptoms 0, 1, 2+ | 213 | | 0.55 (0.65) | 2 (0, 2) |
| Father's #Wives | 213 | | 1.73 (0.98) | 5 (1, 6) |
| Household Size | 213 | | 9.37 (4.44) | 21 (3, 24) |
| Mothers' Milk Camels | 213 | | 0.1 (0.36) | 2 (0, 2) |
| Per Wife Camels | 213 | | 0.51 (1.45) | 10 (0, 10) |
| Per Wife Cash Spent Monthly (Kenya Shillings) | 213 | | 3,589 (3,065.73) | 19,600 (400, 20,000) |
| Mother Highest Grade | 213 | | 0.8 (2.04) | 8 (0, 8) |
| Father Highest Grade | 213 | | 2.66 (3.99) | 8 (0, 12) |
| Lowest Self-Perceived Wealth | 41 | 19% | | |

| | | | | |
|---|---|---|---|---|
| Middle Self-Perceived Wealth | 125 | 59% | | |
| Highest Self-Perceived Wealth | 47 | 22% | | |
| | Drought Mean (SD) | Controls Mean (SD) | Drought Range (min, max) | Controls Range (min, max) |
| Lower Leg length (cm)† | 35.86 (2.49) | 28.49 (3.53) | 13.2 (29.1, 42.3) | 15.4 (21.4, 36.8) |
| zLower Leg for age† | 1.26 (0.74) | 1.09 (0.66) | 3.85 (-0.8, 3.05) | 3.58 (-0.46, 3.12) |
| Lower Leg Index† | 29.28 (0.96) | 27.71 (1.36) | 5.03 (26.85, 31.87) | 6.04 (24.76, 30.8) |
| zLower Leg index for age† | 2.46 (0.43) | 1.89 (0.54) | 2.26 (1.34, 3.6) | 2.48 (0.61, 3.09) |
| | Highland Mean (SD) | **Lowland Mean (SD)** | **Highland Range (min, max)** | **Lowland Range (min, max)** |
| Lower Leg length (cm)† | 31.71 (4.70) | 32.66 (4.91) | 20.9 (21.4, 42.3) | 19.7 (21.7, 41.4) |
| zLower Leg for age† | 1.05 (0.73) | 1.36 (0.61) | 3.85 (-0.8, 3.05) | 3.47 (-0.35, 3.12) |
| Lower Leg Index† | 28.20 (1.46) | 28.89 (1.24) | 6.94 (24.76, 31.7) | 6.47 (25.4, 31.87) |
| zLower Leg index for age† | 2.05 (0.58) | 2.35 (0.48) | 2.91 (0.61, 3.51) | 2.37 (1.23, 3.6) |
| †. For precision, sibling pair models do not add malleolar height estimates to tibia measurements. Since malleolar height is included in reference population measurements for the z-score program, malleolar height has been added to calculate lower leg descriptive statistics. Models were also repeated with malleolar height included, without changing significance, direction or magnitude of effect. | | | | |

**Table S19 Weather Variable Sensitivity Models Descriptive Statistics Drought (N=104) compared to Controls (N=109)**

| Parameter | Drought Mean (SD) | Controls Mean (SD) | Drought Range (min, max) | Controls Range (min, max) |
|---|---|---|---|---|
| Early Gestation Rainfall Anomaly z-score | -0.04 (0.55) | 0.71 (0.57) | 2.11 (-1.23, 0.88) | 3.5 (-1.2, 2.3) |
| Early Gestation Rainfall (mm) | 79.21 (38.72) | 185.49 (97.43) | 156.71 (1.69, 158.4) | 390.14 (4.14, 394.28) |

| | | | | |
|---|---|---|---|---|
| Early Gestation Mean Ambient Temperature (Celsius) | 39.05 (3.64) | 35 (4.9) | 17.32 (28.32, 45.65) | 18.86 (26.0, 44.88) |

**Table S20: Weather Variable Sensitivity Models Descriptive Statistics: Highlands (N=128) compared to Lowlands (N=85)**

| Parameter | Highlands Mean (SD) | Lowland Mean (SD) | Highlands Range (min, max) | Lowland Range (min, max) |
|---|---|---|---|---|
| Early Gestation Rainfall Anomaly z-score | 0.32 (0.63) | 0.39 (0.74) | 2.7 (-1.23, 1.47) | 3.47 (-1.2, 2.27) |
| Early Gestation Rainfall (mm) | 141.29 (79.06) | 122.02 (107.36) | 343.8 (33.45, 377.25) | 392.6 (1.69, 394.28) |
| Early Gestation Mean Ambient Temperature (Celsius) | 34.47 (3.92) | 40.76 (3.2) | 15.42 (26.02, 41.44) | 15.98 (29.67, 45.65) |

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