Longitudinal growth faltering among young children in Burkina Faso

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Abstract

Growth faltering, when children fail to attain expected height and/or weight for their age in relation to growth of a standard reference population, is associated with increased mortality and morbidity and decreased educational attainment and earning potential. Despite programming and policy efforts to prevent it, growth faltering remains a salient issue in many low- and middle-income countries. Knowledge that growth faltering is concentrated in the first two years of life is largely based on cross-sectional studies that pool data from separate cohorts of children in different age ranges. This limits our understanding of the timing of growth faltering along an individual child's growth trajectory. Combining a longitudinal anthropometric dataset comprised of 5,039 Burkinabè children aged 6-28 months with remotely sensed climate data, we characterize longitudinal growth faltering among individual children to determine optimal timing and nature of growth interventions.

To determine the timing of onset and continued intensity of growth faltering among individuals, we visualized individual growth curves by quintiles and selected centiles of attained length at 27 months and used two-stage regression models to establish whether growth faltering happens through continuous or distinct episodes of slow growth. First, we regressed each individual child's length on their age using linear spline regressions and extracted model fit parameters representing the smoothness of the growth curve (R^2), initial length at study entry (intercept), and average velocities in each age period (coefficients for each age spline). Next, we regressed these parameters on individual-level attained length at study end. Growth faltering manifests as both lower growth velocity and greater heterogeneity in growth velocity amplitude. The most influential period for growth is 9-11 months. Children who started short stayed on their initial trajectories and ended short, and taller children had smoother, faster growth.

We explored the bi-directional temporal relationships between linear (length) and ponderal (weight) growth velocities to understand how current growth conditions influence both linear and ponderal growth, and how they relate to each other. Using multi-level mixed effects models, we investigated the concurrent and lagged associations between linear and ponderal growth velocity, controlling for time trends, seasonality, and morbidity. Among individuals, faster ponderal growth is associated with faster concurrent and subsequent linear growth, while faster linear growth is associated with slower future weight gain.

Using harmonic regression models with higher order sine and cosine terms, we determine how peak timing in indicators for growth faltering are related to peaks in temperature, precipitation, and vegetation. Length and weight velocity are slowest twice a year, coinciding both times with the highest temperatures, as rains are beginning and ending, and with peak fever and diarrhea incidence. This challenges the popular notion that children are most vulnerable to growth faltering during the rainy season. Pathogens causing diarrheal disease and fever thrive and have more opportunities to infect children while temperatures are high, and precipitation is low.

Children who experience the most extreme growth faltering are likely to be less resilient to systematic growth-limiting conditions (repeated infection, inadequate feeding) as well as episodic insults to growth (acute infections). The same growth limiting conditions affect both linear and ponderal growth. Future research should focus on ways of improving environmental conditions to support growth.

Acronyms and Abbreviations

AIC: Akaike information criteria
BIC: Bayesian information criteria
CBT: Compartment bag test
CFU: Coliform forming units
CHIRPS: Climate hazards infrared precipitation with stations
CHIRTS: Climate hazards center infrared temperature with stations
CI: Confidence interval
CSB+: Corn soy blend plus
CSWB: Corn soy whey blend
DHS: Demographic and Health Surveys
GPS: Global positioning system
HAD: Height for age difference
HAZ: Height-for-age z-scores
HFIAS: Household food insecurity access scale
IRB: Institutional review board
LAD: Length for age difference
LAZ: Length-for-age z-scores
LMIC: Low- and middle- income countries
LMS: Lamda-Mu-Sigma
LVZ: Length velocity z-score
MAM: Moderate acute malnutrition
MPN: Most probable number
MUAC: Mid-upper-arm circumference
NDVI: Normalized Difference Vegetation Index
NOAA: National oceanic and atmospheric administration
RUSF: Ready-to-use supplementary food
SAM: Severe acute malnutrition
SC+: Supercereal plus
UNICEF: United Nations International Children's Emergency Fund
WaST TIG: Wasting-stunting technical interest group
WAZ: Weight-for-age z-scores
WHO: World Health Organization
WHZ: Weight-for-height z-scores
WLZ: Weight-for-length z-scores
WVZ: Weight velocity z-score

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Chapter 1: Introduction

Background and significance

Growth faltering, characterized by slower weight or length growth than expected in relation to a standard reference population measured in ideal growth conditions, is indicative of undernutrition and is a sensitive measure of overall child health (1–3). Extreme growth faltering is associated with morbidity and mortality in the short term and decreased cognitive function and earning potential as well as increased risk of chronic disease later in life (4). Populations with high levels of growth faltering experience loss of human capital and slow economic development as a result (5). Currently, extreme linear (length-related) growth faltering affects 21.3% of the world's children under five, and 6.9% are affected by extreme ponderal (weight-related) growth faltering (6).

In children, growth faltering has been observed to be concentrated within the first 1,000 days of life, from conception to two years of age (7). However, this representation of the timing of growth faltering is largely based on cross-sectional studies that pool data across separate cohorts of children in different age ranges. A limited number of longitudinal studies have observed growth over time in children from populations with high levels of growth faltering, and similarly find that on average, linear growth faltering starts in utero and continues throughout the first three years of life (8–11). Since growth faltering has rarely been observed longitudinally among individuals at fine time intervals in a large population of children, we know when growth faltering happens on average or at cross-sections of different age categories, but knowledge of the patterns and timing of growth faltering along an individual child's growth trajectory is limited.

Longitudinal growth studies among healthy children have shown that normal growth is saltatory, with extended periods of little-to-no growth punctuated by short phases of growth (12). This growth process has yet to be studied in children with sub-optimal growth; we do not know if children who experience growth faltering are shorter than expected for their age because of intermittently slow growth, or constant slow growth.

In addition, there are two distinct types of growth faltering – linear and ponderal. Studies have shown that extreme ponderal growth faltering (wasting, weight-for-length z-scores < -2 SD from the reference population mean) often precedes extreme linear growth faltering (stunting, length/height-for-age z-scores < -2 SD from the reference population mean) (13), and that when the two co-occur, risk of mortality is high (14). However, the temporal relationships between the two have mainly been studied using attained size z-scores, which include information on past growth up to the point of measurement and thus reflect the cumulative effects of the child's growth environment. The use of attained size z-scores is not granular enough to allow for assessment of how changes in length and weight relate to each other, and precludes the identification of sensitive periods of growth in one parameter that may predict growth in the other.

Last, numerous studies have demonstrated that the timing of growth faltering has seasonal patterns, occurring more often in the rainy, pre-harvest seasons than the dry, harvest seasons, in the context of sub-Saharan Africa (15). These studies form the basis of our collective knowledge about the seasonal timing of growth faltering and have informed the yearly scheduling of growth interventions. Unfortunately, modeling of growth seasonality in these studies is limited by categorization (often dichotomization) of seasons into large periods of time based on assumptions about when climatic conditions change. Relying on these broad

categorizations ignores the reality of climatic variability across time and space and does not allow for understanding of differential effects of separate climatic conditions on growth. Growth seasonality models should instead consider season as a continuous process made up of several climatic dimensions.

These limitations in previous work on the timing of growth faltering in children limit the information that policy makers and programmers have on hand to design interventions that can prevent undernutrition. Globally, we are off-track to meet the nutrition targets of the Sustainable Development Goals to reduce the number of stunted children to 82 million and lower the proportion of wasted children to 3% by 2030 (16). Interventions will only become more challenging amidst the COVID-19 pandemic and climate change (16, 17). Deepening understanding of the timing and patterns of growth faltering among individuals, including the timing of onset and sustained intensity over long periods of time, the temporal relationship between linear and ponderal growth velocities, and the influence of seasonal climatic conditions on timing of growth faltering will inform improved intervention design and contribute to eliminating all forms of undernutrition.

Specific aims and hypotheses

The goal of this dissertation research is to use longitudinal data to characterize growth faltering among individual children to determine optimal timing and nature of growth interventions, through the following specific aims:

Aim 1: Determine the timing of onset and continued intensity of linear growth faltering along the individual growth curves of children aged 6-27 months in Burkina Faso by establishing whether growth faltering happens through constantly slow growth or distinct episodes of slow growth.

Hypothesis 1: Linear growth faltering is intermittent among children 6-27 months in Burkina Faso.

Aim 2: Investigate temporal dependencies in linear and ponderal growth velocity among children 6-27 months in Burkina Faso.

Hypothesis 2: Slow-downs in ponderal growth velocity precede slow-downs in linear growth velocity among children 6-27 months in Burkina Faso.

Aim 3: Establish the relationship between peaks in climatic exposures (temperature, precipitation, and vegetation) and peak timing of growth faltering among children 6-27 months in Burkina Faso.

Hypothesis 3: Climatic exposures each peak at different times; thus the worst growth faltering period has different lag periods with each of the climatic exposures, but coincides most closely with peaks in precipitation, among children 6-27 months in Burkina Faso.

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Chapter 2: Review of the Literature

Introduction

Growth is one of the most important indicators of proper development and health in children; slower than average gains in either weight or height (or both) are associated with increased mortality and morbidity in the short term, and decreased cognitive function, educational attainment, and earning potential in the long-term (1). Reduced agricultural work capacity due to poor growth additionally contributes to a vicious cycle of decreased food availability, leading to more undernutrition that perpetuates poverty and slow economic development in countries with high burdens of undernutrition (1–3). Growth faltering, when children fail to attain expected height and/or weight at each age in relation to growth in a standard reference population, may be caused by many conditions that inhibit growth. It is typically measured by declines in length/height-to-age, weight-to-age, or weight-to-length/height ratios relative to the World Health Organization (WHO) growth reference population (4). If these ratios fall below two standard deviations from the WHO norm, determined based on averages from high socio-economic status children representing all regions of the world (5), children are considered wasted (low weight-for-length/height (WLZ/WHZ)), stunted (low length/height-for-age (LAZ/HAZ)), or underweight (low weight-for-age (WAZ)). Undernutrition designated by these indicators underlies an estimated 45% of all deaths among children under five in low- and middle- income countries (LMIC) (6).

In LMICs, growth faltering is common despite programming and policy efforts on multiple fronts aimed at encouraging appropriate growth (7). In 2020, 21.3%, or 144 million of the world's children were stunted, while another 6.9%, or 47 million were wasted (8). Both nutrition specific programs that provide food and micronutrient supplements, and nutrition

sensitive programs targeting agriculture to nutrition linkages have had limited success in improving growth as measured by changes in WLZ and LAZ (9–11). The persistence of all forms of malnutrition despite intense efforts and resources spent to minimize the problem indicates that current interventions and policies are not as effective as needed to meet the Sustainable Development Goal targets of reducing the number of stunted children to 82 million and lowering the proportion of wasted children to 3% by 2030 (3). One research area with potential to increase the effectiveness of nutrition interventions by informing their timing and nature is the study of growth faltering at the individual-level, including the timing of onset and intensity of duration, the relationship between different types of growth faltering (length vs weight), and how the timing of growth faltering relates to environmental exposures.

Growth faltering

Influencers of growth

While the growth potential of an individual is determined by genetics, a complex set of dietary and environmental factors will determine their actual growth trajectory (12). In conditions that favor sufficient intake of the appropriate micro- and macro-nutrients, coupled with a complex set of environmental factors that allow children to absorb and utilize the nutrients they obtain, a child will reach their growth potential (12). But whether these conditions are met depends on the basic, underlying, and immediate drivers of nutritional status as summarized in the original UNICEF conceptual framework for malnutrition (13) and later updated and built upon in the Lancet 2008 and 2013 series on maternal and child nutrition (6, 14). The socio-economic, geographic, and political contexts of an environment all influence poverty levels and basic access to food, sanitation, and healthcare. These factors interact to dictate the underlying food security, health, and hygiene circumstances of a household, and the quality of care for a

child, which affect the immediate determinants of nutritional status: dietary intake and infection (6, 13).

Intake of certain nutrients, especially zinc and quality protein found in animal sourced foods, are essential to the biological mechanisms involved in bone growth (12). For infants under 6 months, the WHO recommends early initiation of breastfeeding within one hour after birth so that infants obtain the benefits of the nutrient- and antibody- rich colostrum (15), and exclusive breastfeeding (16). While exclusive breastfeeding is associated with large decreases in mortality, reduced risk of chronic disease, increased intelligence, and higher body mass index, no effects have been observed on linear growth (17). For children 6-23 months, the WHO recommends continued breastfeeding, introduction of diverse complementary foods at 6 months with 2-3 tastes per day and increasing complementary meal frequency and amount around 9 months, to 3-4 larger meals per day (18). Across multiple country contexts, the quality (diet diversity, overall diet quality) and quantity of complementary foods has been shown to be positively associated with growth outcomes, including increases in HAZ and reduced underweight (19, 20).

Inflammation in the body due to infection slows growth through a number of mechanisms; it has an inhibitory influence on the anabolic processes that build organs and tissues (12), and can also lead to malabsorption of nutrients through permeability of the small intestinal walls and increased risk of microbial translocation (21). When children suffer from inadequate dietary intake and high disease incidence, the human body adapts by strategically allocating the limited nutrients available, prioritizing survival and immune function, and downregulating growth, leading to growth faltering (22). Infection and inadequate dietary intake often interact in a cycle whereby illness leads to nutrient loss and malabsorption and loss of appetite, reducing the

adequacy of dietary intake, which then leads to growth faltering and compromised immunity, increasing risk for infection (23–25).

Intergeneration cycle of malnutrition

Growth faltering can perpetuate over multiple generations in an inter-generational cycle. If a woman's early life environment was not conducive to proper growth and development, this affects her body composition and height into her teenage, pre-pregnancy years. Short adult women give birth to low birthweight infants, likely due to a combination of inadequate nutrient supply to the fetus and restricted room for growth in the uterus (26). Low birthweight is in turn associated with growth failure (along with a host of other issues such as low cognitive and psychomotor development, and higher risk for chronic disease later in life (6, 27)), continuing the cycle of growth faltering and several forms of malnutrition passed from generation to generation.

Catch-up growth

If growth inhibiting conditions ameliorate, and other conditions favorable to growth are present, children may experience catch-up growth, whereby their growth velocity exceeds the normal statistical range for their age for a defined period of time, bringing them back to their pre-growth faltering trajectory (28). A study of over 6,800 children from India adopted in Sweden found that the majority who suffered from growth faltering caught up in both height and weight after two years in Sweden (29). Sound evidence of catch-up growth in the first few years of life is considered weak by some (30), who criticize the use of LAZ/HAZ to track growth progress over time, due to its calculation using standard deviations from cross-sectional data (31). In the same study on Indian children adopted in Sweden, the most severely stunted children had the fastest catch-up growth, but their catch-up and final heights post puberty were limited (29).

Nevertheless, studies have shown that meaningful catch-up can occur mid-childhood and in adolescence (32), as well as immediately after periods of diarrhea in early childhood, especially among boys (33). Timing of interventions targeting growth should thus consider the potential for catch-up growth, and research should seek to understand how interventions can use periods of catch-up growth to their advantage in maximizing their effectiveness.

Food systems perspective

At a broader systems level, diets and nutrition, and subsequently growth are influenced by complex food systems that are themselves influenced by environmental, infrastructural, political, socio-cultural, demographic, and economic drivers (34). Agricultural systems that produce, store, transport, market, and distribute food interact with health and environmental systems that dictate access to services and resources, which all come together to influence household and individual decision-making. Framing growth faltering as a consequence of the complex interactions among multiple systems and sectors is useful in understanding potential intervention points to promote child growth. Our food systems are rapidly adapting to meet the needs of a growing population that is dealing with climate change and globalization, so considering the food systems lens is essential to policies and programs for child growth moving forward (35).

Growth assessment

By definition, to assess growth at the individual-level, one needs multiple observations over time on a single individual. Assessment of growth faltering is done using anthropometric measurements to indicate a child's attained size at cross-sections or their growth velocity longitudinally (36). Normally, such anthropometric measurements include weight, recumbent length (for children under two years) or standing height, and head and mid-upper-arm

circumferences (37). Attained size measured at any given cross-section for age includes inherent information about all past growth up to the point of measurement and can be a good indicator of the cumulative effects of growth-limiting conditions. Longitudinal growth velocity indicates growth levels around the time of measurement, and can allow for understanding of current growth-limiting conditions (38, 39). Measures of tempo indicate the timing of onset of periods of growth (or growth spurts) (40, 41). Failure to consider measures of tempo can bias interpretation of measurements of attained size because an individual's overall growth trajectory may not be well-represented by their size at any given age due to differences in the timing of onset of growth-rate changes (42). Growth assessment using longitudinal measures allows for determination of the growth processes through which one reaches an attained size at a given age.

Attained size

Measures of attained size differ between sexes and change as children age, and are thus most often assessed using age- and sex- standardized z-scores (36). These z-scores can either be calculated internally among a sample based on the sample means and standard deviations or can be calculated based on an external reference population. In calculating attained size z-scores, the Lambda-Mu-Sigma (LMS) method can be used to adjust for skewed distributions and allow the mean and standard deviation of size to vary with age. The LMS method accounts for size differences across age using Box-Cox transformations to remove skewness (Lambda), median size (Mu), and the coefficient of variation (Sigma) (43, 44). The most common reference population used to calculate external z-scores is the population of children measured for the WHO Child Growth Standards. These children represent high-socio-economic status populations who are assumed to live in ideal growth conditions and come from six countries (Brazil, Ghana, India, Norway, Oman, USA) across all major world regions (5).

As described briefly in the introduction, extreme growth faltering is assessed against the WHO growth reference population as children who have LAZ/HAZ < -2 SD from the median considered stunted (<-3 severely stunted), those with WLZ/WHZ < -2 SD from the median considered wasted (<-3 severely wasted), and those with WAZ < -2 SD from the median considered underweight (<-3 SD severely underweight). Severe wasting can also be defined by a mid-upper-arm circumference below 11.5 cm (45). The common use of stunting as a measure of individual child health has been criticized as inappropriate, as the indicator was originally designed for use in assessing population levels of undernutrition and is based on a statistically derived, biologically arbitrary cut-off (46). As a result, researchers may be underestimating the true prevalence of linear growth faltering, which exists along a continuum, and placing undue burden on individual caregivers for their children's health, when in reality, the prevalence of stunting reflects larger structural issues that affect entire communities (46). Others have criticized the use of HAZ to assess growth over time given the increase in SD as children age due to the construction of HAZ from cross sectional data. The same researchers have proposed the use of absolute length/height-for-age differences (LAD/HAD), which are calculated by subtracting a child's length/height from the median for their age in the reference population, to assess growth progress over time (31).

In addition to assessment with z-scores, attained size can also be assessed using conditional size measures obtained by extracting residual error from regression of size on preceding size measures to get an attained size measure that is the difference between observed and expected size (36). The advantage of these conditional measures is that they account for regression to the mean, a repeated measures phenomenon, in which outlier measurements are followed by subsequent measurements that are closer to the mean, making normal variation in

measurements due to random measurement error appear to be real changes (47). Last, indices based on set standards or ratios, such as body mass index (ratio of weight to height^2), can be used to assess attained size. Both conditional size measures and growth indices may be used as ways of comparing the attained size between different children in the same population (36).

Growth velocity

Growth velocity measures a change in body size between time periods (ages). Most often, growth velocity is defined as the change in size units (cm for height, kg for weight) divided by the change in time between measurements (days, months, etc.), but it has also been charted as changes in percentile ranks per time unit (48). Growth velocities can be assessed either as absolute velocity, or in reference to a growth velocity standard. The WHO Child Growth Standards released growth velocity references in 2009, which can be used to calculate length- and weight- velocity z-scores (LVZ, WVZ) that compare a child's growth velocity at a given age to the standard reference population (49).

Growth modeling methods

Several methods for modeling growth over time and detecting growth faltering are described by auxologists William Johnson, Yu-Kang Tu et al, and J. Argyle (36, 48, 50). The simplest of the described methods is tracking average z-scores over time. Other approaches are based on conditioning, and include life course plots, path analysis, regressions with conditional growth velocity measures, and conditional regression models. Each of these approaches involves conditioning current growth on previous measures to quantify the relationship between growth velocity and some outcome conditional on size at the first measurement (36, 48, 50). Regression with change scores can be done by regressing an outcome on growth velocity during different time periods, to identify critical windows of time for growth in relation to a particular outcome

(50). Last, multi-level models (mixed-effects growth curves that consider repeated measures to be level one variables clustered within each individual), latent growth curve models (jointly modeled associations between latent growth factors and later outcomes), and growth mixture models can be used to model the growth of each individual child in a sample as well as obtain the overall sample average growth. Growth mixture models can further be used to assess variation in growth trajectories within specified groups (36, 50). To select the most appropriate models, the Akaike Information Criteria (AIC) and/or Bayesian Information Criteria (BIC) can be used to balance model fit and parsimony (50). The AIC and BIC scores are both calculated by subtracting the log-likelihood ratio of the model from the number of terms in the model, with the lowest scores signifying the best balance of fit and parsimony. While both AIC and BIC penalize the models for each additional term and reward model fit, the BIC penalizes the complexity of a model more heavily than the AIC (51).

Timing of growth faltering

To date, the scientific community's understanding of the timing of growth faltering is based largely on cross sectional studies that combine multiple datasets from separate cohorts of children across different age ranges. Knowledge of patterns and timing of growth faltering among individual children is limited based on the current research. An important study by Victora et al. in 2010 showed the "worldwide timing of growth faltering" using cross-sectional data from 54 countries. They found that children in LMICs in all regions of the world experience growth faltering between 6-24 months, with more and more children considered stunted as age increases. This study helped to identify the critical "window of opportunity" for growth during the first 1,000 days of life (from early pregnancy through 2 years) (52), providing important information about optimal timing of interventions to prevent growth faltering. It has served to

galvanize financial support for programs and policies aimed specifically at this window of opportunity (32). A more recent study by Leroy et al. used HAD instead of HAZ to assess linear growth deficits in children under five from 51 different countries, and found continued deterioration in linear growth even after the 1,000 day window (53).

Despite the influence these studies have had and the importance of their findings, the analyses are based on ecological, cross-sectional data, so interpretation of the results is limited in terms of what they really tell us about the timing and pattern of growth faltering among individuals within a population. Cross-sectional studies cannot distinguish between continuing cases of growth faltering (prevalence) and new cases (incidence) (54), and using cross-sectional data to draw conclusions about growth is inappropriate given that to measure a growth trajectory, one needs growth measurements on the same individual at multiple time points (36, 48).

Several longitudinal child growth studies done in Guatemala, Malawi and the Gambia, as well as a recent Knowledge Initiative study that combined data from 31 longitudinal cohorts, have found, similar to the cross-sectional studies, that on average linear growth faltering starts in utero/at birth, but that it continues throughout the first three years of life (32, 55, 56). The Knowledge Initiative study found that larger deficits at younger ages informed higher incidence of stunting later, and that stunting incidence was highest from birth to 3 months (54).

Studies of longitudinal growth in healthy children have determined that the growth process is saltatory, characterized by long periods of stasis interspersed with short growth spurts (57). The process of growth faltering among individuals has not yet been assessed in the same way. Understanding the longitudinal growth faltering process and timing among individual children in populations with high levels of growth faltering will allow for determination of whether children who experience growth faltering are shorter than expected for their age because

of continuously slower growth than taller children, or because of intermittent episodes of slow growth.

Relationship between linear and ponderal growth faltering

Programs that target undernutrition have historically considered the different types of growth faltering, linear (length) and ponderal (weight), as separate problems to be dealt with using distinct methods (58–61). Ponderal growth faltering has largely been associated with the factors that have immediate health effects such as infection and inadequate dietary intake due to food shortages, while linear growth faltering has been linked to the broader underlying conditions that influence growth, such as poverty and food insecurity (62). Multiple studies have established high levels of co-occurrence between wasting and stunting (63–65), with the prevalence of concurrent stunting and wasting surpassing 5% in some areas (59). When the two happen in the same individual at the same time, stunting is more severe, and risk of mortality increases (hazard ratio for both wasted and stunted = 12.25; 95% CI = 7.67, 19.58) (66). These concurrence studies use cross sectional data and cannot establish whether one form of growth faltering precedes or follows from the other. In addition, they likely underestimate the true burden of stunting and wasting concurrence, since assessing the indicators at a single time point may not capture all cases where stunting and wasting overlap given the transient nature of wasting and the later onset and continued duration of stunting (67). Surely, the use of stunting and wasting cut-offs instead of the entire range of z-scores also contributes to a likely underestimation of the issue (46).

In an effort to address some of these concerns, the temporal links between the different anthropometric measures involved in growth faltering is gaining traction as a question of interest among growth researchers (68). Evidence from these studies strongly indicates that episodes of

wasting or deficits in weight gain precede the development of stunting or have significant effects on attained height (63, 66, 77, 69–76). The hypothesis has thus emerged that sufficient weight growth that gives a child ample energy reserves may be a necessary condition to spur linear growth (78–80). At least one study also found significant associations in the other direction, with linear growth faltering associated with higher risk of wasting relapse in children who had recovered from moderate acute malnutrition (81). Differential levels of growth faltering and concurrent stunting and wasting have also been found based on the sex of the child; boys are often found to be more vulnerable than girls to concurrent wasting and stunting and seasonal deficits in both linear and ponderal growth (82, 83).

The time lag between ponderal growth deficits and linear growth deficits has also been explored. Richard et al. found that wasting in the earliest period of life between 0-5 months was not associated with future LAZ, but that wasting between 6-11 or 12-17 months was associated with decreased LAZ between 18-24 months (69). Another longitudinal study conducted over a period of 40 years in the Gambia revealed that wasting prevalence peaked when children were between 10-12 months, and stunting prevalence peaked at 24 months. Among children who had one of the forms of undernutrition at the 24-month mark, many were found to have experienced frequent bouts of the other type prior to 24 months of age (76). At the population level, average seasonal peaks in ponderal growth have been shown to precede average seasonal peaks in linear growth by 2-3 months, suggesting that linear growth is spurred by ponderal growth (55, 70, 84).

While a limited number of these studies have used the entire range of z-scores or looked at attained WLZ in relation to linear growth velocities (69, 77, 79, 84), most have defined linear and ponderal growth faltering using the rigid, biologically arbitrary cut-offs for stunting and wasting (46). In addition, most of these studies have used indicators of attained size, which do

not allow for understanding of the mechanisms underlying any relationship between linear and ponderal growth, since they summarize the cumulative effects of all growth conditions up to the point of measurement (38). Gaining clarity on the complex mechanisms underlying these temporal relationships between linear and ponderal growth faltering is important in program and policy design and can be partially achieved through investigation of the temporal dependencies between linear and ponderal growth velocities. Studying how the types of growth velocities are related will allow for understanding of how current conditions influence both linear and ponderal growth, improving upon the use of only cumulative growth indicated by attained size.

Seasonality of growth faltering

Defining seasonality

Seasonality is the cyclic nature of the occurrence of any type of event over a specified period of time, usually a year (85). There can be seasonality to cases of malnutrition just as there can be seasonality to climatic indicators such as temperature and precipitation. Each type of seasonality can be defined as periodic fluctuations in the magnitude, timing, and duration of the events, and visualized using curves that resemble waves. The seasonality represented by these curves has three main characteristics of interest: the maximum point on the curve, the amplitude from the peak to the nadir, and the shape of the curve, showing the duration of a seasonal increase. Multiple peaks could happen over the course of a year, or there could be just one peak, depending on the length of the cycle (85, 86).

Climate and growth seasonality links

The relationship between climatic seasonality and the seasonality of growth has been relatively well-studied since as far back as the late 1700s when a study on a single French boy followed from birth to 18 years of age pointed to seasonal differences in growth rate, with

greater increases in the boy's height seen during the summer months (87). Many studies since then (with sample sizes larger than N=1) on children living in places where the temperature varies widely throughout the year have shown that children often grow faster in the warmer spring and summer months than in the colder fall or winter months (88).

Early theories about direct links between seasonality and growth thus centered on day length and exposure to ultraviolet light. Physiologically speaking, these theories are tenable, since vitamin D3 obtained from exposure to ultraviolet light increases absorption of calcium, which has important roles in bone growth (88). Empirical evidence supporting these direct links between sunlight hours and growth has been demonstrated in a few studies. In 1929, Nylin showed that children treated with sunlamps grew faster than those not receiving sunlamp treatments, and a study done in the Congo, near the equator, showed that children grew faster in the dry season than the rainy season, but that differences in diet, temperature, and humidity did not appear to account for the disparity, leading them to conclude that the difference in growth was due to increased vitamin D3 during the dry season (88). More recent evidence from a randomized controlled trial in Bangladesh, however, shows no evidence of effects of prenatal vitamin D supplementation on linear growth (89).

Besides these direct physiological reasons for season being related to growth, there are many reasons why seasonal changes to the weather and climate are indirectly related to nutritional status, and these have been fairly well-studied. The immediate drivers of growth faltering (dietary intake and illness) are affected by climatic conditions in various ways. First, the agricultural cycle is closely related to nutrition through multiple pathways including food production and income from agricultural products that allows for increased spending on both nutritious foods and healthcare (90). This cycle is driven by seasonal patterns of temperature and

precipitation, which drive food production, income from agricultural products, agricultural labor needs, and time demands on caregivers (91). Second, transmission of infectious gastrointestinal and other diseases is influenced by seasonal climatic conditions, since temperature, humidity, and precipitation are key factors in the survival of infectious agents and pathogens (85, 92, 93).

Many studies examining climatic season and child nutrition have investigated these theoretical links. A recent review of such studies found that in rural areas of developing countries, children have been shown to grow faster (in terms of both linear and ponderal growth) in the dry period directly after the harvest (91). Seasonality of dietary intake was measured in only one study that qualified for the review. Intake, measured by energy per kg consumed was not found to be significantly different during the monsoon compared with the relatively dryer summer months among young children in Bangladesh, but intakes were found to be lower in the early winter and early summer months; thus some seasonality effects are noted (70, 91). Another more recent study in Bangladesh found that children measured during the harvest season were less likely to be wasted than those measured in the monsoon season when less food was available (94).

Seasonal differences in infection rate are also related to child nutritional status, both directly through conditions more favorable to disease transmission and through the amount of time caregivers spend providing care to their children (85, 91). Infection is highly correlated with season due to higher ambient temperatures that support pathogen survival, increased water contamination with fecal matter with increased precipitation, and food scarcity that increases host susceptibility during certain agricultural seasons (85). In addition, standing water leads to more mosquitoes that can transmit malaria and other infectious diseases when precipitation is high (92, 93). Children at different ages and different life stages may react differentially to

seasonal growth effects; thus, age should be considered an important variable when determining the relationship between climatic seasonality and growth. For example, while there are strong correlations between season and diarrhea, with peaks happening in the hottest months of the year and the early monsoon season right afterwards in countries that have monsoons, these effects are more pronounced for older children than they are for younger children (94). In addition, caregiver time demands are variable by season and can impact the quality of care that children get and subsequently how well they grow; for example, it has been shown that children are exclusively breastfed less often in the summer months that correspond with heavy agricultural periods than in the winter months (95).

Growth seasonality

The consensus from the most recent growth seasonality literature describing studies in sub-Saharan Africa and South Asia is that there is less weight gain (96–98), lower attained WLZ (70, 73, 99–103), and higher incidence of wasting (104) during the rainy, pre-harvest seasons compared to the dry, harvest seasons, likely due to the aforementioned pathways of more infections (91, 92, 96, 99), less time for caretaking (99, 101), and poor food availability (105, 106). Fluctuations in length or height measurements by season is less common; some studies report either no differences in height by season, or minimal differences (55, 102, 105), while others find similarities to weight metrics in that children have slower height gain (98) and more stunting (99, 101, 104) during the rainy season. Only a couple studies conducted in Ethiopia and Malawi have found that children gain length and weight faster during the rainy, pre-harvest season. The authors of these studies hypothesize that illness was more common in the dry, post-harvest season and was a more important driver to undernutrition than inadequate food access during the rainy season (107, 108).

Limitations of seasonality models

Despite knowledge of the importance of climatic seasonality for growth, little has been done to disentangle the effects of specific climatic conditions on growth. The majority of the studies that form the basis of our knowledge about growth seasonality are limited by their categorization of the seasonal exposure variable. A recent review of methods used to study growth seasonality in the African drylands found that over half of the 24 studies included in the review defined distinct "seasons" as 2-4 time periods throughout the year. An additional six of those studies based their conclusions on visualizations of nutrition outcomes by month (109). The assumption that the "season", whether that be defined as monsoon season, dry season, pre- or post-harvest season, always happens at the exact same time every year is problematic for a number of reasons. One, there is a fair amount of variability in when these seasons start each year (110, 111), and the brute assumption that they occur each year during the same months may lead to erroneous findings about the true seasonal timing of growth faltering (112). A model that considers the "rainy season" to be from June-September could show very different results than one that uses actual climate data on precipitation, which will show that rains do not start exactly on June 1, and do not end exactly on September 30. Second, lumping together all climatic conditions and calling them a "season" for the purposes of obtaining specific models that predict the timing of growth faltering fails to consider the potential interplay between temperature and precipitation, and the exact combinations of the two that lead to more or less growth faltering. Third, with climate change on the rise, the timing and intensity of these "seasons" will likely shift (113), and it will be important to have a precedent for models that use true climatic conditions to predict when growth faltering may occur instead of relying on historical averages delineated by month. Lastly, using season as a categorical predictor or control variable in growth

models makes it impossible to look at other aspects of the relationship between climatic seasons and growth, such as how the timing between rains may impact growth, or whether or not the first or last rains have more of an impact on growth than ones in the middle of the season.

Addressing these limitations by exploring the relationship between peak temperature, precipitation, and vegetation with peak timing of growth faltering among infants and young children, using models that can disentangle the effects of various climatic conditions on growth, will allow for a much deeper and more precise understanding of growth seasonality.

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Chapter 3: Methods

Study design and data sources

This is a time series analysis that combines multiple data sources. Aims 1 and 2, on constant versus episodic growth faltering and the temporal relationship between linear and ponderal growth velocities, employ a dataset comprised of monthly anthropometric (length, weight) measurements of ~6,000 children from Sanmatenga Province, Burkina Faso. For aim 3, on the seasonality of growth faltering, the anthropometric dataset was linked with remotely sensed daily climate data for maximum temperature (°C), precipitation (mm/5km^2/day), and vegetation (Normalized Difference Vegetation Index).

Anthropometric dataset

Setting

Data were collected in the center-north region of Burkina Faso, covering four departments of the Sanmatenga Province: Barsalogho, Kaya, Namissiguima, and Pissila. Burkina Faso is a dry and arid land-locked country in West Africa with high levels of food insecurity and suboptimal complementary feeding due to the agroecological, geographic, and demographic characteristics that make growing and trading a variety of nutrient-rich crops difficult (1). According to the most recent available data from the Burkina Faso Demographic and Health Survey published in 2010 (4 years prior to the start of data collection), 41.6% of Burkinabè children 18-24 months of age were stunted, and 19% were wasted in the same age category. The Sanmatenga Province is one of 45 provinces in Burkina Faso, and had roughly 640,000 inhabitants at the time data collection (2).

The population of Burkina Faso relies on rainfed agriculture as its primary economic activity, with 90% of the workforce employed in agriculture. In the center-North region of

Burkina Faso, growing seasons are shorter than average for the country, agriculture is less diversified, and rainfall variability is higher (3). The rainy season in Burkina Faso is unimodal, with most rains occurring between June and September. Since the period between 1920-1969, rainfall has declined by 15% and temperature has increased significantly (by 0.6 °C since 1975) (3, 4).

Data collection

Anthropometric data were collected between August 2014-December 2016 as part of the Food Aid Quality Review's field study on the comparative cost-effectiveness of four supplementary foods in the prevention of stunting and wasting among children 6-23 months. The original study was a longitudinal, four-arm cost-effectiveness trial with random assignment to study arm by geographic region that compared monthly rations of ~500 kcal/day of Corn Soy Blend Plus (CSB+) with oil, Corn Soy Whey Blend (CSWB) with oil, SuperCereal Plus (SC+), and Ready-to-use Supplementary Food (RUSF). Children participating in a blanket supplementary feeding program were enrolled at 6 months and measured monthly (length, weight, mid-upper-arm circumference) for 18 months during the intervention and for three consecutive months post-intervention. Across all four study arms, a total of 6,112 children were enrolled (CSB+: 1,519; CSWB: 1,503; SC+: 1,564; RUSF: 1,526). On average, children were measured 21 times, making for 129,944 observations over ~2.5 years.

Exclusion criteria for the original intervention were severe acute malnutrition at enrollment (a mid-upper-arm circumference < 11.5 cm) and age above 12 months, though enrolling children over 6 months was rare. All eligible children in the intervention zone were enrolled on a rolling basis until the desired sample size was reached after one year of enrollments. Intervention arms were geographically clustered, with recipients in each of four

distinct regions of the Sanmatenga Province receiving one of the four foods. For the purposes of investigating longitudinal growth patterns and the timing of growth faltering, we pooled all four intervention arms and analyzed the data irrespective of study arm. Given the significantly higher prevalence of end-line stunting and greater total number of wasted months among children in the CSWB arm compared to the other three study arms (5), we control for study arm in our analyses where appropriate.

Anthropometric data were collected by trained enumerators who participated in standardization exercises every three months. At monthly measurement visits, enumerators measured each child's length, weight, and mid-upper-arm circumference (MUAC) in duplicate and reported both measurements on paper forms. Duplicate measures were later averaged to obtain one measurement of length, weight, and MUAC per visit per child. Length was measured in the recumbent position (even in children 24-28 months, which was corrected for in analyses) using UNICEF length measuring boards (S0114530, UNICEF Supply Division, Copenhagen, Denmark). Weight was measured using digital scales (Seca 876, Olney, Maryland, USA). Scales were zeroed with the caregiver's weight, and children were handed to the caregivers to obtain their weight. This process was used to minimize agitation in the child. MUAC was measured using a standard tri-colored non-stretch MUAC tape.

At each monthly measurement visit, caregivers were asked if their child had experienced any illness in the previous two weeks, including fever, diarrhea, cough, rapid breathing, difficulty breathing, or confirmed malaria. In addition, caregivers gave self-reports of any fever or diarrhea on the day of measurement itself. Food security was assessed using the Household Food Insecurity Access Scale (HFIAS) (6) only twice per child, at study entry and exit.

In-depth interviews and in-home observations were conducted cross-sectionally spread over the course of the study, with a sub-sample of ~1,600 and ~250 caregivers respectively, to gather data on feeding practices including dietary diversity, breastfeeding, water quality (proxied by *E.coli* concentration), and handwashing. As children were enrolled on a rolling basis over a one-year period, and exited on a rolling basis, the food security, hygiene, and feeding practices data span all seasons. The geolocation of each distribution site and village was recorded using a Garmin eTrex 20 handheld Global Positioning System (GPS) device.

Nonparticipant observations of a subset of study children and their caregivers were conducted by female observers with the primary purpose of directly observing breastfeeding and complementary feeding practices, and understanding how food distribution recipients used the foods in the household. Each observation lasted for four consecutive days, in which the observer was in the household for 12 hours per day, from 6:00-18:00. During observations, observers followed the study child wherever they went, both within and outside the home. Each time the child was put to the caregiver's breast to breastfeed, the observer started a timer, and stopped the timer once the child was taken off the breast.

Diet diversity was assessed during in-depth interviews by asking caregivers to report everything that their child consumed during the previous 24-hour period, starting from the same time of the interview the previous day, up until the time of the interview. Enumerators coded the reported foods into a grid of 30 food groups adapted from that used by the Demographic and Health Surveys (7).

At the end of in-depth interviews and in-home observations, study participants were asked to provide a small (100 mL) water sample from their household drinking water source. Samples were mixed with a chromogenic growth medium for *E.coli* and assessed using the

Aquagenx compartment bag test for *E.coli* concentration (CBT kit, Aquagenx, Chapel Hill, NC, USA) after an incubation period of 24-48 hours (depending on ambient temperature). After the incubation period, enumerators estimated the number of coliform forming units (CFU) by noting which combination of the five compartments in the bag turned from yellow to green, and matching that to a most probable number (MPN) table based on WHO guidelines and provided in the compartment bag testing kit. *E.coli* concentration was classified as safe (<1 CFU/100 mL), intermediate risk (1-10 CFU/100 mL), high risk (>10-100 CFU/mL), or very high risk/unsafe (>100 CFU/mL) (8).

All data were double-entered into a CSPro database and checked for consistency (9); any discrepancies were corrected by referencing the paper forms. Data were further field cleaned by checking for implausible values for non-time-varying data such as birthdates; when necessary and possible, enumerators were sent back into the field to collect non-time varying missing data or verify implausible values (i.e., caregivers under age 10, children over age 5).

Remotely sensed climate data

Daily time series of three remotely sensed climatic variables, including the Normalized Difference Vegetation Index (NDVI), maximum temperature, and precipitation, were merged with the anthropometric data using GPS coordinates from each of the 199 villages in the study area. The NDVI was downloaded from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record of Advanced Very High Resolution Radiometer Surface Reflectance (10). For temperature and precipitation, we used the Climate Hazards center Infrared Temperature with Stations (CHIRTS) high-resolution daily maximum air temperature data (11), and the Climate Hazards Infrared Precipitation with Stations (CHIRPS) high-resolution daily precipitation data (12). All climatic data were downloaded at a $5km^2$ spatial resolution. Data

were downloaded, extracted from raster to points, and merged with the anthropometric dataset using R-studio (13).

Data preparation and cleaning

Prior to conducting data analyses, data were cleaned using a multi-step process to identify implausible values, investigate the randomness of missing and implausible values, and impute missing values. First, biologically implausible anthropometric values were classified using jackknifed residuals, according to the methods described in Shi et al. 2018 for identification of outliers in longitudinal growth data (14). In brief, after regressing length and weight measurements on the square root of age (to account for growth rate variation as children age) for each child separately, we flagged absolute values of the jackknifed residuals from these regressions above 5 as biologically implausible. Flagged values were examined manually before decisions were made to exclude them. In a few cases, upon manual examination of the measurements and their corresponding dates, it was clear that measurement dates were entered in error, as they made the child appear to be younger than at the previous month's measurement. In these cases, correct dates were imputed using the corresponding food distribution dates as a proxy for the measurement date. While the food distribution date can potentially be different from the measurement date if the child missed the distribution, and was measured at their home instead of the site, the standardized study procedures required children to be measured within the three days following their food distribution date. Roughly 7% of measurements from the original dataset (8,444 observations) were identified as biologically implausible or missing, with each child missing one value on average.

Once biologically implausible values were identified and set to missing, we assessed the prevalence and randomness of missingness by regressing indicators for missingness (including

implausible values) on a variety of factors including location, enumerator codes, and socio-demographic variables. Though we aimed to enroll children in our study at ~6 months of age and follow each child for 21 months (18 months during the intervention + 3 months post-intervention) until they reached 27 months of age, children in our sample range from 1-37 months, with the vast majority (99%) falling between 5-28 months. We thus restrict our analyses to children 5-28 months, though most analyses are done on children 6-27 months, as the sample sizes are small among those at the extremes. We further restrict analyses to children who had at least 20 repeated measurements. Our final dataset for analysis includes imputations for missing and implausible values using simple linear regressions of length or weight on time for each child and imputing the predicted values.

After assessment and imputation of missing and implausible values, the final dataset consisted of 5,039 children between 5-28 months (82% of original sample) who each had at least 20 repeated anthropometric measurements, adding up to 108,580 total observations. We conducted sensitivity analyses using a dataset consisting of only children who had full data (at least 22 measurements per child) with zero missing or implausible values. The sensitivity analysis dataset had 1,158 children (19% of original sample) and 25,476 total observations and had similar distributions of all key variables compared to the full dataset.

Variable specification

Growth Outcomes

Attained size indicators

Age and sex standardized LAZ, WLZ, and WAZ were calculated using the 2006 World Health Organization (WHO) Child Growth Standards macro for Stata (15, 16), and LAD was calculated manually in Stata using WHO growth reference tabulated median length/height values

(15). Z-scores identified as biologically implausible (+/- 6 SD for LAZ, +/- 5 SD for WLZ) were flagged automatically by the macro and removed. Final attained length (cm) was defined as the child's absolute length at the end of the study period.

Growth velocity indices

Absolute length and weight velocities were calculated by taking the difference between previous and current measurements, dividing by the time gap between them, and multiplying by 30.44 to get velocities in cm/month and kg/month for length and weight, respectively. Growth velocity z-scores were calculated manually in Stata using the tabulated Lambda-Mu-Sigma (LMS) parameters from the 2009 WHO Child Growth Standards (17). Because the WHO-2009 growth standards are restricted to children under 2, and the lowest granularity references available are in 2-month windows, we calculated velocity z-scores for each 2-month interval for children between 6-24 months. Velocity z-scores are thus constant between each two-month interval (e.g., 6-8 months, 8-10 months, 10-12 months, etc.) and can be interpreted as the extent to which a child's growth velocity in a given age interval differs from the growth velocity of the reference population in the same age interval, stratified by sex.

Climatic exposures

Since all three climatic variables were merged into the anthropometric dataset at the village level, each village has unique values for daily maximum temperature (°C), daily precipitation (mm), and daily NDVI. The NDVI takes remotely sensed images and divides the normalized difference between red and near infrared light bands by their sum to indicate the density of green vegetation. Values for NDVI range from -1 (water) to 1 (rainforest), with numbers close to zero corresponding to barren areas made up of rock or sand (10).

Morbidity exposures

We use dichotomous variables for current fever or diarrhea at the time of measurement, as well as reported upper-respiratory symptoms (cough, difficulty breathing, rapid breathing), and confirmed malaria in the two weeks prior to the interview. In the aim 3 growth seasonality harmonic models, morbidity exposures were each modeled as continuous variables for prevalence (percent of the population reporting each illness at a given time period). In addition, we coded a dichotomous indicator for any illness in the previous two weeks, combining all upper-respiratory symptoms, fever, diarrhea, confirmed malaria, accidents, or burns, which was also modeled as a continuous variable for prevalence of any illness in the aim 3 growth seasonality models.

Food and nutrition security exposures

We descriptively analyzed cross-sectional food and nutrition security data collected at different times throughout the study period. The HFIAS (6) was recorded for each study participant at two time-points – study entry and exit. In addition, for a subset of 1,615 participants who were subject to an in-depth interview, we collected data on household drinking water *E.coli* concentration based on the AquagenX Compartment Bag Test (18), and dietary diversity scores from 24-hour recalls of the child's diet on the day prior to the interview, calculated using the food groups from the Infant and Young Child Minimum Diet Diversity scale, ranging from 0-8 (19). On a further subset of 176 participants, we timed the number of hours the child was breastfed per day during four-day in-home observations.

Study arm/geographic region

In several models, we control for the original study arm in which the child was enrolled. Since the original trial was geographically clustered, in doing so we also control for geographic regions.

Analytic methods

Aim 1: constant versus episodic growth faltering

Growth curve visualization

We visualized children's individual growth curves to illustrate the timing of growth faltering among children in our sample using multiple methods. For each descriptive graph, we divide the sample into either quintiles or selected centiles of attained length to show how growth differs at different levels of attained length. We examine population-level shifts in LAZ among each of the attained length quintiles in our sample by plotting the distribution of LAZ at four selected ages (6,12,18, and 24 months) against a hypothetical WHO growth reference distribution curve with mean zero and standard deviation of one. To visualize what individual growth trajectories look like at different levels of attained length, we graph scatterplots of all children's length, length velocities, LAZ, and LAD using the sensitivity analysis dataset containing only full cases with no imputations. As this dataset has fewer children, we were able to plot the entirety of the sample from each selected centile of attained length. Visualizations were done in R-studio (13) and Stata 16.1 (20).

Modeling

To empirically assess the episodic versus continuous nature of growth faltering, we examine whether growth-curve smoothness is an important predictor of attained length using two stages of regression models. First, we regress each child's length on their age in individual linear regression models for each child, totaling 5,039 separate regression models. We extract model fit and diagnostic parameters from these models, including the R^2 and F-statistics as measures of curve fit and smoothness, constant values as a measure of initial length at 6 months, and age-term coefficients as a measure of average velocity. In the second stage, we regress the extracted

parameters on individual-level attained length at study end. The hypothesis is that if growth faltering is episodic, occurring intermittently, then a child's progress along their own growth curve will have more variance around that curve, and therefore a lower R^2 from simple regressions of their length on their age. Thus, higher values of R^2 indicate smoother growth, in which more of the variance in length is explained by age alone. Using this logic, it also follows that if higher attained length is the result of uninhibited growth spurts, a low R^2 could also be associated with the highest levels of growth.

To determine the appropriate functional form of the initial individual regressions of length on age for each child, we compared the AIC and BIC between a linear regression model with a cubic term for age, linear splines with 6 knots evenly spaced, linear splines with 4 knots, and cubic splines. We found that linear splines with 6 knots had the best fit for the data overall. Individual regressions for each child thus took the form for each child, *i*:

$$Length_i = \beta_{0i} + \beta_{1i} age + \sum_{k=1}^{K} b_k (age - \xi_k) + \ ;$$

where *K* is the number of knots, $(age - \xi_k)+$ refers to the k^{th} linear function with a knot at ξ_k, and $(age - \xi_k)+ = \begin{Bmatrix} age - \xi_k : if\ age - \xi_k > 0 \\ 0 : if\ age - \xi_k \leq 0 \end{Bmatrix}$.

We place six knots at 9, 12, 15, 18, 21, and 24 months; the slope of the relationship between length and age changes at each knot point based on the weight of each linear function, b_k. This regression was run separately for each child. Though we impose a common functional form on all individual's growth models, functional form may differ by child. We therefore perform sensitivity analyses to check the coefficients on R^2 when attained length is regressed on R^2 from each of the models using the candidate functional forms. We also note that since these are individual regressions of length on age, overfitting is not an issue.

After each child's growth curve was modeled separately, we extracted the model parameters and ran a second round of regressions to estimate the average association between model parameters and attained length, of the form:

$$Attained\ Length_i = \delta_{0i} + \delta_{1i}(R^2) + \delta_{2i}(Intercept) + \delta_{wi}(\sum_{k=1}^{K} b_k(age - \xi_k) +) + \varepsilon_i;$$

where for each child, i, δ_w is the coefficient for each age spline: 6-8 months, 9-11 months, 12-14 months, 15-17 months, 18-20 months, 21-23 months, and 24-28 months, the *Intercept* represents initial length, and R^2 represents the smoothness of growth from the individual model.

To check that our inferences about the biological nature of growth faltering were made irrespective of study arm, as this is a secondary analysis of data collected during an intervention trial, we checked for differences in mean R^2 by quintile, stratified by study arm, and found that in all study arms, the differences in R^2 from each quintile to the next is very similar. We can thus be confident in interpreting our findings with the assumption that provision of different types of food supplements did not influence growth trajectories over time.

Aim 2: temporal relationships between linear and ponderal growth velocities

To estimate the relationship between linear and ponderal growth indicators, we used multi-level mixed effects linear regression models with child-level random intercepts. To control for the effects of seasonality and overall time trends on child growth, we included trigonometric terms, and a continuous daily time indicator, centered at zero to represent the first day the study was initiated (21, 22). We investigated multiple functional forms to control for age in our models, and ultimately decided, for ease of interpretation, to stratify the models by narrow age categories, as well as by sex of the child, since our sample size is large enough to handle relatively fine stratifications. Age categories were set in three-month intervals, with separate

models for children 6-8 months, 9-11, 12-14, 15-17, 18-20, 21-23, and 24-28 months. Models were specified for the entire sample, as well as each age and sex category as follows:

$$Y_{id} = \beta_{0i} + \beta_{1id}G + \beta_{2id}PG + \beta_{3id}I + \beta_{4i}S + \beta_{5i}d + \beta_{6i}\sin(2\pi\omega d) + \beta_{7i}\cos(2\pi\omega d) + \beta_{8i}\sin(4\pi\omega d) + \beta_{9i}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{id};$$

where Y_{id} is the growth outcome for child *i* on study day *d*. Growth indicators for linear and ponderal growth are paired together by type (absolute velocity, velocity z-scores, attained size indicators) and serve as each other's outcomes and primary explanatory variables in separate models. Pairs include length and weight velocity, length velocity z-scores (LVZ) and weight velocity z-scores (WVZ), and LAZ and WLZ. The coefficient β_1 represents the explanatory growth variable, *G*, which is the opposing linear or ponderal growth indicator to the outcome (i.e., when the outcome is length velocity, the explanatory growth variable is weight velocity). The relationship between the previous month's measurement and the current measurement for the outcome is represented by the coefficient β_2, where *PG* is the previous month's measurement for the outcome variable. The effect of the explanatory growth variable on the outcome growth variable is therefore conditional on the previous growth trajectory of the outcome variable. Morbidity in the previous two weeks is controlled for by coefficient β_3, where *I* is a dichotomous indicator for any self-reported (by the caregiver) illness in the previous two weeks, and study arm, *S*, is controlled for by β_4. The coefficient β_5 represents a control for the overall time trend of the model. Seasonality is controlled for by the coefficients of the sine and cosine terms where ω is a constant equal to 1/365.25, representing the frequency of the annual cycle in days accounting for the 2016 leap year. Individual child level random effects are accounted for by α_i, and ε_{id} is the time-varying error term.

Each model was fit with concurrent indicators from the same month for both the outcome and explanatory growth indicators, as well as a lagged explanatory variable, with growth

indicators from the previous month in relation to the outcome indicator. For LVZ and WVZ models, in which growth indicators are constant for two-month periods of time, lagged growth indicators were those from two months ago in chronological time. In addition to these models, we ran harmonic regression models with each of the growth and morbidity indicators as outcomes and only the trigonometric and time indicator terms as the predictors, to investigate overall seasonal and time trends for each indicator.

Last, as a secondary analysis we fit ordinary least squares regression models to examine the relationship between LAZ or WLZ at the end of the study and total months of wasting or stunting measurements throughout the study period, respectively. We fit these models to increase generalizability of our analyses and be able to compare our results with those from previous studies that examined the relationships between early episodes of wasting (between 0-17 months) and later stunting or LAZ (after 18 months) and expand on those findings by also looking at the reverse (how early stunting effects later WLZ). These models took the form:

$$Y_i = \beta_0 + \beta_1 N + \beta_2 SA + \beta_3 StudyArm + \beta_4 Illness + \beta_5 Month + \mu_i;$$

where Y_i is end (~27 months of age) LAZ or WLZ for child *i*, the primary independent variable *N* is total number of wasted or stunted months throughout the study period, *SA* represents starting anthropometric z-scores, *StudyArm* indicates dummy variables for the original study arm, *Illness* is an indicator of the total number months in which an episode of illness was reported, and *Month* is an indicator from 1-12 for calendar month at the end of the study.

Aim 3: seasonality of growth faltering

Harmonic regression models, also commonly referred to as Fourier or Trigonometric regressions, were used to estimate the magnitude and timing of seasonal peaks in temperature, precipitation, NDVI and measures of morbidity, as well as nadirs in child growth metrics. This

method allows for the use of only two parameters, maximizing degrees of freedom and imposing symmetry and repetition in the rise and fall of the curves over the period of a year (23). In the simplest form of the models, referred to herein as base models, amplitude of the peaks was estimated using sine and cosine functions, and peak timing was estimated using a continuous daily calendar time indicator, centered with the origin at zero to represent the first day of the study (August 13, 2014). Base models were fit with multi-level mixed effects linear regressions (equation 1) for all outcomes except precipitation, which was fit using a negative binomial model (equation 2). Note that binary outcomes for morbidities were fit using both logistic and linear regressions, with almost identical results, so we use linear models for ease of interpretation:

1. $Y_{ijd} = \beta_{0ij} + \beta_{1ij}d + \beta_{2ij}\sin(2\pi\omega d) + \beta_{3ij}\cos(2\pi\omega d) + \beta_{4ij}\sin(4\pi\omega d) + \beta_{5ij}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{ijd}$;
2. $\log(E|Y_{ijd}) = \beta_{0ij} + \beta_{1ij}d + \beta_{2ij}\sin(2\pi\omega d) + \beta_{3ij}\cos(2\pi\omega d) + \beta_{4ij}\sin(4\pi\omega d) + \beta_{5ij}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{ijd}$;

where Y_{ijd} (or $\log(E|Y_{ijd})$ from equation 2) is the growth outcome, or climatic or morbidity exposure for child *i* in village *j* on study day *d* for linear models. The coefficient β_1 represents a control for the overall time trend of the model. Peak timing and magnitude are estimated by the coefficients of the sine and cosine terms where ω represents the frequency of the annual cycle in days accounting for the 2016 leap year and is a constant equal to 1/365.25. Individual child level random effects are accounted for by α_i, and ε_{ijd} is the time-varying error term. For each growth outcome and climatic variable, to determine the number of peaks per year, we examined graphs of the mean of the variable over time, as well as testing the statistical significance of 2π and 4π terms. Pairs of sine and cosine terms were removed if they were not statistically significant at the 5% significance level ($p<0.05$). If both 2π and 4π terms were significant and graphical representations of the variables indicated two peaks, both pairs of terms were kept in the model. While we recognize the importance of age as a predictor of growth

outcomes, and that seasonality patterns may be age-dependent (24), including age terms in these models would have over-complicated interpretation, and the time trend closely approximates the aging of the cohort; thus we did not include age as a covariate in these models. However, to visualize changes in anthropometry by age, we constructed heat plots to examine how anthropometric indicators change over time in relation to age.

Peaks and nadirs in timing for each curve were determined by ordering the predicted values for each outcome chronologically, taking their first derivatives, and identifying each point at which the value of the first derivative changed signs. To determine peak timing, the corresponding dates at each change point were noted as peaks when values changed from positive to negative, and nadirs when values changed from negative to positive. The lag period between each climatic variable and each growth outcome was calculated as the difference between the dates of climatic variable peaks and growth outcome nadirs. Magnitude of seasonal peaks was determined by taking the average difference in predicted yearly peak and nadir values to get the amplitude of the peak, representing its absolute intensity.

The statistical relationship between each of the climatic exposures and metrics of child growth was assessed separately for each climatic factor using multi-level mixed effects linear regressions by adapting the above equation as follows:

$$Y_{ijd} = \beta_{0ij} + \beta_{1ij}d + \beta_{2ij}\sin(2\pi\omega d) + \beta_{3ij}\cos(2\pi\omega d) + \beta_{4ij}\sin(4\pi\omega d) + \beta_{5ij}\cos(4\pi\omega d) + \beta_{6jd}C + \beta_{7ij}I + \alpha_i + \varepsilon_{ijd};$$

where the effects of the climatic exposure, *C*, is estimated by the β_6 coefficient, and any reported illness, *I*, in the past two weeks is controlled for by β_7. Unadjusted relationships between the climatic exposures and growth, as well as any illness and growth were also modeled. Models were stratified by child sex to test for differential effects by sex.

Ethics

The original study from which anthropometric data are derived was approved by the Tufts University Health Sciences Institutional Review Board (IRB #: 10899) and the ethics board of the Ministry of Health in Burkina Faso (#: 2013-10-090). It is registered on ClinicalTrials.gov under identifier NCT02071563. Secondary analysis for this dissertation was exempt by the Tufts University Health Sciences Institutional Review Board (IRB ID: STUDY00000255).

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Chapter 4: High-frequency repeated measures of over 5,000 infants aged 6-27 months reveals pattern of growth faltering in rural Burkina Faso

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This file includes: Main text, Figures 1 to 5, Tables 1 to 3, Supplemental Tables 1 to 3

Abstract

Linear growth faltering, or slower than expected growth in relation to a standard reference population for a given age and sex, is associated with increased mortality and morbidity. Understanding the age-related patterns of growth faltering within a population is important to crafting preventive policies and interventions; however, knowledge is limited by cross-sectional data. We examine the longitudinal characterization of the timing of growth faltering among young children. Using anthropometric data collected at monthly intervals between August 2014-December 2016, we investigate individual growth curves of 5,039 children ages 6-27 months in Burkina Faso (108,580 total measurements) to determine whether growth faltering occurs through intermittent episodes of slower growth, or continuously slow growth. We visualized individual growth curves by selected centiles of attained length (at ~27 months) and used two-stage regressions to evaluate the smoothness of growth curves by level of attained length. In the first stage, we individually regressed each child's length on their age using simple linear spline regressions, and extracted model fit and diagnostic parameters. Parameters included R^2 as a metric of curve smoothness, initial length at 6 months, and average velocity in each age block. In the second stage, we regressed extracted parameters on individual-level attained length at study end. Growth faltering manifests as both lower growth velocity throughout the observation period, and greater heterogeneity in growth velocity amplitude. Children with lower attained length start smaller (Quintile 1– 63.1 cm initial length; Quintile 5 – 68.4 cm) and remain on their initial trajectories, continuously growing slower than their taller counterparts. Growth during the period between 9-11 months was the most influential on attained length; for each cm/month increase in growth velocity during this period, attained length increased by 6.71 cm (95% CI: 6.59, 6.93) – almost double the second most influential period

from 12-14 months. In addition, a 0.01 increase in the R^2 (smoothness) from regression of a child's length on their age is associated with a 3.10 cm increase in attained length (95% CI: 2.80, 3.41), showing that smoother growth patterns are also associated with higher attained length. Children who experience the most extreme growth faltering are likely to be less resilient to systematic growth-limiting conditions as well as episodic insults to their growth. Future research should focus on ways of improving environmental conditions to support growth.

Significance statement

Understanding the timing of growth faltering (failure to reach expected growth in relation to standard reference population) in children is critical to appropriate targeting, timing, and nature of undernutrition interventions. Knowledge of the timing of growth faltering is primarily based on conclusions from cross-sectional studies. This study uses longitudinal anthropometric data from a cohort of young children in Burkina Faso to examine individual growth curves and identify the timing of growth faltering among individuals. Findings indicate that children who experience growth faltering have both greater variation in growth velocity over time, and consistently slower growth velocity than those who attain greater length. Shorter children likely experience chronic conditions that limit their growth rates and may be less resilient to episodic insults to optimal growth.

Introduction

Linear growth, measured by a child's length or height, is a sensitive indicator of the overall health of a child and their potential for thriving physically, cognitively, and economically throughout life (1, 2). Slower growth than expected compared to a standard reference population (3, 4) is referred to as linear growth faltering, and may be caused by numerous factors that inhibit growth. Typically, linear growth faltering is measured by declines in height-to-age ratios relative to the World Health Organization (WHO) standards (1, 5). These standards represent child growth in ideal environments; they were determined based on cross-sectional averages at each age, from high socio-economic status children representing all regions of the world (5). Growth faltering is associated with increased mortality and morbidities, as well as decreased cognitive function, educational attainment, and earning potential (2, 6), and remains a prevalent issue in low- and middle- income countries despite years of growth interventions (7).

Understanding the timing of growth faltering, including the timing of onset and the sustained intensity of sub-optimal growth (8) is critical to designing interventions and policies that effectively reduce the burden of growth faltering. To date, knowledge of the timing of growth faltering is largely based on cross sectional studies that pool data across separate cohorts of children in different age ranges, which fails to identify patterns in the timing of growth faltering among individuals within populations (3, 9–11). A landmark study by Victora et al. in 2010 used cross-sectional data from 54 countries to identify the critical window of opportunity for child growth in the first 1,000 days of life, from early pregnancy to 2 years (9), but leaves many important questions unanswered. While we know that more and more children experience growth faltering at each age between 3 and 24 months, we know little about when individual children experience their growth faltering during this period. Despite the inappropriate nature of

using cross-sectional data to assess growth of individuals, as one's growth trajectory is determined by current height or weight conditional on previous measurements (12), growth researchers and programmers have relied mainly on these cross-sectional analyses to inform their interventions due to lack of sufficient longitudinal growth faltering studies. While the normal growth process has long been understood to be saltatory, with extended periods of stasis punctuated by short phases of growth, likely within 24-hour periods (13), the extent to which this process occurs similarly among children with sub-optimal growth has not been examined in depth.

In this study, we use longitudinal data from a cohort of ~5,000 Burkinabè children measured monthly for an average of 22 months each, from ages 6-27 months, to determine the timing of growth faltering in individuals. We define human growth as the change in the size of body measurements between two subsequent ages (14), and combine several strategies for growth modeling, including conditional growth measures and individual growth curves. Using a mix of data visualizations, and individual regressions of length on post-natal age for each child in our sample, we seek to identify influential growth periods as children age, and understand if children who attain less height by the end of the study period (~27 months of age) were consistently growing slower than those who attain more height, or if they experienced episodic instances of slow growth that led to growth faltering.

Typically, researchers have chosen to use the binary metric of whether or not a child was stunted, defined having a length/height-for-age z-score (LAZ/HAZ) below -2 standard deviations from the WHO growth standard median to define growth faltering. However, the use of this biologically arbitrary cutoff to draw conclusions about an individual's growth instead of its intended use as a measure of population health can easily lead to misclassification of children as

having normal growth when in fact they experience growth faltering but do not fall below the cut-off (4). We therefore use quintiles and selected centiles of attained length (cm) at the end of the study period to differentiate between children's overall growth levels. We note a limitation of calculating attained length using this method: not all children were in the study for the exact same amount of time. However, we restrict our analysis to children who had a minimum of 20 measurements throughout the study period, which maximizes our sample size, as the average time in the study was 22 months, while minimizing bias from including children who exited the study earlier than 20 months.

Uncovering the timing of growth faltering among individuals will help determine if interventions should aim to prevent multiple distinct growth faltering episodes, or if they should be designed to prevent consistently slow growth. We hypothesized that when children end up with lower-than-average length for their age, they have experienced greater episodic bouts of growth faltering that cause them to deviate from their potential growth trajectories.

Methods

Study design and data source

This is a secondary analysis using data collected during a blanket supplementary feeding trial aimed at determining the comparative cost-effectiveness of four different supplementary foods in the prevention of stunting and wasting in children 6-23 months in Sanmatenga Province, Burkina Faso. Between August 2014-December 2016, children whose caregivers lived in the Sanmatenga Province and had thus been receiving a supplementary food starting during their pre-natal period as part of the blanket supplementary feeding program, were enrolled in the study when they reached 6 months of age and measured monthly (recumbent length, weight, mid-upper-arm circumference) for 18 months while receiving foods and for three consecutive months

post-intervention. A total of 6,112 children were measured an average of 21 times each, adding up to 129,944 observations over ~2.5 years. Further details of the original study are explained elsewhere (15).

Exclusion criteria for the original intervention were severe acute malnutrition (a mid-upper-arm circumference < 11.5 cm) and age above 12 months, though enrolling children over 6 months was rare. All eligible children in the intervention zone were enrolled on a rolling basis until the desired sample size was reached after one year of enrollments. Intervention arms were geographically clustered, with recipients in each of four distinct regions of the Sanmatenga Province receiving one of the four foods. For the purposes of investigating growth patterns and the timing of growth faltering, we pooled all four intervention arms and analyzed the data irrespective of study arm.

Anthropometric data were collected by trained enumerators who participated in standardization exercises every three months. Each measurement was done twice at each visit for quality control, and both measurements were recorded on paper forms and later double-entered into a CSPro database and checked for consistency (16).

Data preparation

Biologically implausible anthropometric values were classified using jackknifed residuals, according to the methods described in Shi et al. 2018 for identification of outliers in longitudinal growth data (17). Jackknifed residuals from regression of length and weight measurements on the square root of age with absolute values above 5 were flagged as biologically implausible and excluded. Roughly 7% of measurements from the original dataset (8,444 observations) were identified as biologically implausible or missing, and imputed using linear predictions from ordinary least-squares regression of length on age, with each child

missing one value on average. Missingness and implausibility were not found to be related to enumerators or socio-demographic variables.

Though we aimed to enroll children in our study at ~6 months of age and follow each child for 21 months (18 months during the intervention + 3 months post-intervention) until they reached 27 months of age, children in our sample range from 1-37 months, with the vast majority (99%) falling between 5-28 months. We thus restrict our analyses to children 5-28 months, though most analyses are done on children 6-27 months as the sample sizes are small among those at the extremes. As our primary outcome is attained length at the end of the study period, we further restrict analyses to children who had at least 20 repeated measurements.

After assessment and imputation of missing and implausible values, the final dataset consisted of 5,039 children between 5-28 months (82% of original sample) who each had at least 20 repeated anthropometric measurements, adding up to 108,580 total observations. We conducted sensitivity analyses using a dataset consisting of only children who had zero missing or implausible values, with at least 22 measurements per child. The sensitivity analysis dataset had 1,158 children (19% of original sample) and 25,476 total observations and had similar distributions of all key variables compared to the full dataset.

Specification of growth indicators

Age and sex standardized LAZ were calculated using the World Health Organization (WHO) Child Growth Standards macro for Stata (5, 18), and length/height-for-age differences (LAD) were calculated manually in Stata using WHO growth reference tabulated median length/height values (5). Length velocity was calculated by subtracting each month's length measurement from the previous measurement, dividing by the time gap between measurements,

and multiplying by 30.44 to get length velocity in cm/month. Our primary outcome of attained length is defined as the child's absolute length at the end of the study period, in cm.

Growth curve visualizations

We visualized children's individual growth curves to illustrate the timing of growth faltering among children in our sample using multiple methods. For each descriptive graph, we divide the sample into either quintiles or selected centiles of attained length to show how growth differs at different levels of attained length. We examine population-level shifts in LAZ among each of the attained length quintiles in our sample by plotting the distribution of LAZ at four selected ages (6,12,18, and 24 months) against a hypothetical WHO growth reference distribution curve with mean zero and standard deviation of one. To visualize what individual growth trajectories look like at different levels of attained length, we graph scatterplots of all children's length, length velocities, LAZ, and LAD using the sensitivity analysis dataset containing only full cases with no imputations. As this dataset has fewer children, we were able to plot the entirety of the sample from each selected centile of attained length. Visualizations were done in R-studio (19) and Stata 16.1 (20).

Analytic methods

To empirically assess the episodic versus continuous nature of growth faltering, we examine whether growth-curve smoothness is an important predictor of attained length using two stages of regression models. First, we regress each child's length on their age in individual linear regression models for each child, totaling 5,039 separate regression models. We extract model fit and diagnostic parameters from these models, including the R^2 and F-statistics as measures of curve fit and smoothness, constant values as a measure of initial length at 6 months, and age-term coefficients as a measure of average velocity. In the second stage, we regress the extracted

parameters on individual-level attained length at study end. The hypothesis is that if growth faltering is episodic, occurring intermittently, then a child's progress along their own growth curve will have more variance around that curve, and therefore a lower R^2 from simple regressions of their length on their age. Thus, higher values of R^2 indicate smoother growth, in which more of the variance in length is explained by age alone. Using this logic, it also follows that if higher attained length is the result of uninhibited growth spurts, a low R^2 could also be associated with the highest levels of growth.

To determine the appropriate functional form of the initial individual regressions of length on age for each child, we compared the AIC and BIC between a linear regression model with a cubic term for age, linear splines with 6 knots evenly spaced, linear splines with 4 knots, and cubic splines. We found that linear splines with 6 knots had the best fit for the data overall. Individual regressions for each child thus took the form for each child, *i*:

$Length_i = \beta_{0i} + \beta_{1i} age + \sum_{k=1}^{K} b_k (age - \xi_k) + \ ;$

where *K* is the number of knots, $(age - \xi_k)+$ refers to the k^{th} linear function with a knot at ξ_k, and $(age - \xi_k)+ = \begin{Bmatrix} age - \xi_k : if\ age - \xi_k > 0 \\ 0 : if\ age - \xi_k \leq 0 \end{Bmatrix}$.

We place six knots at 9, 12, 15, 18, 21, and 24 months; the slope of the relationship between length and age changes at each knot point based on the weight of each linear function, b_k. This regression was run separately for each child. Though we impose a common functional form on all individual's growth models, functional form may differ by child. We therefore perform sensitivity analyses to check the coefficients on R^2 when attained length is regressed on R^2 from each of the models using the candidate functional forms (**Supplemental Table 1**). We also note that since these are individual regressions of length on age, overfitting is not an issue.

After each child's growth curve was modeled separately, we extracted the model parameters and ran a second round of regressions to estimate the average association between model parameters and attained length, of the form:

$$Attained\ Length_i = \delta_{0i} + \delta_{1i}(R^2) + \delta_{2i}(Intercept) + \delta_{wi}(\sum_{k=1}^{K} b_k(age - \xi_k) +) + \varepsilon_i;$$

where for each child, i, δ_w is the coefficient for each age spline: 6-8 months, 9-11 months, 12-14 months, 15-17 months, 18-20 months, 21-23 months, and 24-28 months, the *Intercept* represents initial length, and R^2 represents the smoothness of growth from the individual model.

To check that our inferences about the biological nature of growth faltering were made irrespective of study arm, as this is a secondary analysis of data collected during an intervention trial, we checked for differences in mean R^2 by quintile, stratified by study arm, and found that in all study arms, the differences in R^2 from each quintile to the next is very similar (**Supplemental Table 2**). We can thus be confident in interpreting our findings with the assumption that provision of different types of food supplements did not influence growth trajectories over time.

Ethics

The original study from which data are derived was approved by the Tufts University Health Sciences Institutional Review Board (IRB #: 10899) and the ethics board of the Ministry of Health in Burkina Faso (#: 2013-10-090). Secondary analysis for this paper was exempt by the Tufts University Health Sciences Institutional Review Board (IRB ID: STUDY00000255).

Results

Sample anthropometric characteristics

Table 1 lays out a summary of the anthropometric characteristics of our sample by quintile of attained length. Age at both first and last measurements is similar across quintiles, affirming that attained length quintile is an appropriate indicator of growth faltering. There is a

5.3 cm difference in absolute length at first measurement between the highest and lowest quintile, which increases to 9.1 cm at last measurement. Length-for-age differences (LAD) all decrease between the first and last measurements, regardless of quintile, but the decrease is much larger in children in the lowest quintile of attained length, going from -3.6 to -8.02 (difference of -4.42), whereas in the highest quintile, LAD goes from 1.06 to 0.46 (difference of -0.59), remaining positive even at the end of the study. Characteristics are similar in the sensitivity analysis dataset.

To investigate population level shifts in linear growth faltering among children in each quintile of attained length, we examined kernel density plots of LAZ among the sample children in each quintile compared to the WHO reference at ages 6, 12, 18, and 24 months (**Figure 1**). Regardless of attained length quintile, as the children age, the LAZ distribution shifts further to the left of the WHO reference. Children in the highest quintile have a distribution that is skewed slightly to the right of the normal WHO reference curve at 6 months, but by 24 months, even these children's distribution is skewed to the left of the WHO reference.

Visualizations of individual growth curves

Given our objective of determining when growth faltering happens along children's individual growth curves, we compare individual growth trajectories in selected centiles of attained length (**Figures 2 & 3**). In lower centiles of attained length, the growth curves are flatter, and slopes appear less constant throughout the observed period (**Figure 2a**). Children with lower attained length start smaller and remain on their initial trajectories, continuously growing slower than their taller counterparts. Those in the lowest centile of attained length reach 76 cm by 28 months whereas those in the 99th centile reach the same length by 10 months of age.

Growth velocity is highly heterogeneous over time among all children, regardless of attained length rank (**Figure 2b**). To exclude the possibility that heterogeneity in growth velocities is an artifact of measurement error, we examined distributions of length velocity at each age, including the standard deviations and coefficients of variation (standard deviation/mean) and found them to be similarly normally distributed across quintiles of attained length (**Supplemental Table 3**). While there is heterogeneity in the rate of growth in all selected centiles, the amplitude of length velocities is smaller among children in the lower centiles. On average, in the lower centiles of attained length, growth velocities stay below the overall mean of 1.0 cm/month and rise above the mean in the higher centiles.

Examination of LAZ and LAD curves over time (**Figure 3**) reveal that children in the lowest selected centiles of attained length experience continuous steep declines in growth relative to the reference population as they age, while children in the highest centiles have relatively constant growth rates in relation to the reference population. The steepest declines appear to happen prior to 12 months of age, however, LAD curves (**Figure 3b**) among the lowest centiles (1^{st} and 10^{th}), show that major declines continue throughout the study period, never leveling out as in the higher centiles. If only looking at LAZ, one may conclude that declines in growth, even among the lowest centiles, level out after 12 months of age; however, LAD is likely a more appropriate indicator to evaluate changes in growth as children age (21). Though growth rates among the shortest children appear constant (and slow compared to growth rates among taller children) in relative terms over time, when compared to the reference population averages, growth becomes increasingly slower as children age among those in the lowest centiles.

<u>Growth smoothness and attained length</u>

Two-stage regressions testing the relationship between smoothness of growth and attained length reveal that the smoothness of growth curves is associated with attaining more length, but growth velocities are the most influential determinant of attained length. Regression diagnostics extracted from individual linear spline regressions of length on age are summarized by attained length quintile in **Table 2**. The higher the attained length quintile, the higher the average intercepts (initial length), R^2 (smoothness of growth), and age coefficients (average length velocities) from the individual spline regressions. Linear regressions of the parameters from individual growth curves on attained length (**Table 3**) reveal that the shortest children have statistically significantly lower R^2 from individual regressions of length on age than taller children. Without considering growth velocities, each increase of 0.01 in R^2 is associated with a 3.10 cm increase in attained length (95% confidence interval: 2.80, 3.41) (Model 1). The smoothness of the curve alone is therefore significantly associated with increased length. Sensitivity analyses using alternative functional forms for the individual regression models (linear polynomial model with cubic term for age, restricted cubic splines, linear splines with four knots) give a range of 2.44-2.83 for R^2, when attained length is regressed on R^2, with 95% confidence intervals spanning 2.39-3.09 (**Supplementary Table 1**).

As additional parameters from individual linear spline models are added into the model for attained length, the importance of R^2 decreases in relation to average growth velocities but remains statistically significant (Models 2-9). This is to be expected, since the only roughness of growth to explain once all growth velocity variables have been included occurs within the 3-month spline intervals. An increase of 1 cm in initial length, which provides the best estimate for unobserved growth prior to this study, is associated with a 0.96 cm increase in attained length (Model 9). The most influential age period for growth is between 9-11 months; during this

period, for each cm increase in length gained per month, children achieve 6.71 additional centimeters of length at the end of the study period. From 12-14 months, each additional cm increase in length increases attained length by 3.91 cm, and from 6-8 months, each cm increase in length increases attained length by 3.43 cm. Influence of growth velocity in the age periods from 15-23 months is slightly lower, ranging from 2.2 from 15-17 months to 3.06 from 21-23 months. Growth during the last age period studied, from 24-28 months, was the least influential for attained length, which increased by 0.85 cm for each additional cm of length gained during this period.

Discussion

Using multiple methods to examine individual growth curves among young children in Burkina Faso, we find that children who end up short started small at 6 months of age and stayed on their initial growth trajectories, continuously growing slower than those who ended up taller. We demonstrate the importance of smooth growth for attained length, as well as the relative influence of growth velocities at different age periods. During the period from 6-27 months of age, growth faltering manifests through consistently slower growth, especially from 9-11 months of age, as well as greater levels of heterogeneity in growth velocities; taller children have both smoother, and faster growth.

Our finding that children who end up shorter start with slower growth velocities that continue to decline as they age confirms that the timing of growth faltering among individuals closely resembles what has been concluded based on cross-sectional studies of population averages. Cross-sectional studies that have measured prevalence of growth faltering at each age have been consistent in showing that children are often born with LAZ already below zero, and that children have lower average LAZ at each increasing age (1, 3, 9, 22). Longitudinal studies of

child growth in Malawi and the Gambia, as well as a recent *Knowledge Initiative* study that combined data from 31 longitudinal cohorts, have found similarly that linear growth faltering started at birth and continued throughout the first three years of life (11, 23, 24). Looking at individual growth curves, we confirm that LAZ, LAD and length velocity decrease as children age, and show that among individuals, the lower the initial growth indicators are, the lower the ending growth indicators – children who start with larger deficits in relation to the WHO standards maintain and increase these large deficits. Among children with the most severe growth faltering, growth becomes increasingly slower compared to the standards as they age. This aligns with the *Knowledge Initiative* finding that larger deficits at younger ages informed higher incidence of later stunting (11). Thus, the addition of children to the stunted category of LAZ < -2 as they age is a function of the children who already had lower LAZ continuing to lose LAZ as they age. The comparison of LAD with LAZ in our sample corroborates important conclusions by Leroy et al. that growth faltering continues even after LAZ apparently levels out due to an artifact of increasing standard deviations as children age in the calculation of LAZ (10, 21). We find the biggest differences between LAD and LAZ to be among the shortest children, who continue their downward trajectories well after the end of the 1,000-day critical window of opportunity cut-off, highlighting the importance of using indicators other than LAZ to assess growth over time in children. For the most vulnerable children, limiting interventions to children under two may be insufficient to prevent further growth faltering.

Though we lack sufficient growth data from birth to 6 months, we identified the most influential period for growth from 6-28 months as that between 9-11 months. Length velocity in this period is associated with almost twice the increases in attained length as in the next most influential period, between 12-14 months. The longitudinal *Knowledge Initiative* study found

that in the 31 combined birth cohorts, stunting incidence was highest from birth to 3 months, and declined in subsequent age periods (11), but we demonstrate using more sensitive indicators that there are additional influential growth windows that should be considered when designing growth interventions. This specific period from 9-11 months may well be related to the transition of the child from exclusive breastfeeding to complementary feeding (9, 25). While children often begin this transition around 6 months, household complementary foods may not make up a large portion of a child's diet until around 9 months, when the WHO recommends increasing meal frequency and amount (26). In contexts such as Burkina Faso, where inadequate diets are common due to environmental conditions that make growing and trading a variety of nutrient-dense crops difficult (27), transition to complementary household foods may pose challenges to child growth. Quality of complementary foods aside, introduction of complementary foods may also be accompanied by increased exposure to pathogens new to the child's immune system (26). The combination of these factors could easily make children especially vulnerable during the period from 9-11 months.

We show for the first time that the smoothness of a child's growth along their growth curve is an important factor in relation to attained height. The finding that growth among children who end up shorter is characterized by greater variation in the amplitude of linear growth velocity (i.e., lower smoothness of the growth curve) suggests that growth may be disproportionately influenced by adverse environmental or nutritional factors in these children compared to those who end up taller. The conditions in which a child lives must lead to substantial reductions in a child's growth rate for a protracted period of time in order to lead to extreme growth faltering (28–30). If conditions are favorable to growth, meaning adequate micro- and macro- nutrient intake necessary for the biological processes that regulate bone

growth, as well as limited environmental instigators of inflammation, a child will grow to their genetic potential (30). While all children in our sample appear to live in sub-optimal conditions for linear growth, those in the bottom quintile of attained length may not only be experiencing the harshest chronic conditions that limit their growth rates all the time, but also may be less resilient to episodic insults. In addition, these children are always growing slower than children in higher quintiles, so any further decline in growth velocity is more detrimental.

In addition, the fact that children in the lowest centile of attained length reach about 76 cm by 28 months of age, while those in the 99th centile have already reached the same length by 10 months provides empirical evidence that growth tempo plays a key role in overall height attainment. Children who experienced greater levels of growth faltering may have slower growth tempos, contributing to larger growth delays. Growth delay, or the difference between a child's height-age, in which the observed height distribution would be normal, and their chronological age based on their actual height, has been proposed as a new population-level indicator of evaluating linear growth faltering that considers the importance of growth tempo in achieving height (31).

While only children in the bottom two quintiles of attained length actually fall into the category of "stunted" by the end of the observation period at 28 months, our study also confirms previous findings that growth faltering does not happen solely among the most vulnerable children in the context of low- and middle- income countries, including Burkina Faso, rather occurs in most children to some degree (30, 32). In our population, as has been seen in other studies set in low- and middle- income countries (1, 3), despite a nutrition intervention covering the entire region, the distribution of LAZ is shifted to the left of the WHO growth reference distribution, and gets further to the left as the children age. On average, children in the bottom

four attained length quintiles have LAZ below zero for the entire duration of the study period, with even those in the top quintile dropping below zero around 24 months. A recent analysis in the newest Lancet series on maternal and child undernutrition showed similar population-level shifts in the entire distribution of both HAZ and WHZ among children in 31 low-income countries (32). This is an indication that population-wide conditions are not conducive to proper growth and development (3, 33).

We note several limitations to our study design, the most flagrant being the lack of data on birth size and measurements up to 6 months of age, given the importance of fetal growth restriction and small size at birth to later length-for-age indicators (34, 35). We assume the initial length measurements in our study to be an indicator of the cumulative growth velocities in the first six months of life. In addition, we lack data on maternal height, which has been shown to be a predictor of LAZ (11), and can influence child growth by affecting fetal growth and birth size (30). We are thus unable to condition our results on genetic factors that may influence growth curves and cannot account for heterogeneity in gestational age at birth, which can impact growth in the first two years of life. We therefore cannot distinguish individuals who have lower attained height due to genetic predisposition versus those who are impacted by socioeconomic and environmental factors. In addition, as this study was not originally designed for this analysis, all children were part of the supplementary feeding intervention trial, which had no pure control group, so we cannot determine how growth faltering would have happened in the absence of the intervention program. Nonetheless, we observed that the pattern of growth faltering and the inferences related to the rate of growth and smoothness of the growth curves were consistent across supplementation groups. Lastly, the data were collected from a sample of children in one province in Burkina Faso and may not be representative of children in every low- or middle-

income country setting. However, the results align well with many other studies from low- and middle- income countries, suggesting at least some level of generalizability.

Despite the limitations to our study design, our use of longitudinal data that follows a single cohort of children each month from about 6-28 months adds important nuances to discussions of the timing of growth faltering that have implications for optimal timing and nature of interventions to limit growth faltering in children. Our findings that children who experience the most extreme levels of growth faltering have both greater heterogeneity in their growth curves, and slower growth throughout their early childhood, point to the utility of addressing the overall conditions in which children live that constrain their growth. Further, the finding that most children in the study experience some level of growth faltering underlines the importance of improving community-level, systemic factors that constrain growth among the entire population, rather than simply focusing on household or nutritional factors. There is much left to be done to fully understand the timing of growth faltering in children. Further study should use indicators appropriate for the study of longitudinal growth (i.e., LAD, length velocity, etc.) to examine the factors that contribute to slow growth periods, the duration of slow growth episodes, as well as establish the exact time points along a trajectory at which growth slows and relate specific factors to those slowdowns.

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Tables and Figures

Tables

Table 1. Sample anthropometric characteristics by quintile of attained length

	Main dataset					
	Overall (N=5,039)	Quintile 1 (n=1,028)	Quintile 2 (n=999)	Quintile 3 (n=1,010)	Quintile 4 (n=1,009)	Quintile 5 (n=993)
Total # observations	108,580	21,996	21,489	21,784	21,825	21,486
Female sex	2,484 (49.3)	610 (59.3)	522 (52.3)	505 (50.0)	465 (46.1)	382 (38.5)
Observations per child	21.55 ± 0.68	21.40 ± 0.76	21.51 ± 0.69	21.57 ± 0.65	21.63 ± 0.64	21.64 ± 0.63
Linear growth velocity (cm/month)	0.94 ± 0.59	0.85 ± 0.59	0.91 ± 0.58	0.94 ± 0.58	0.98 ± 0.58	1.02 ± 0.58
Age at first measurement	6.16 ± 0.58	6.10 ± 0.59	6.13 ± 0.58	6.13 ± 0.57	6.19 ± 0.58	6.23 ± 0.59
Age at last measurement	26.68 ± 0.75	26.48 ± 0.86	26.61 ± 0.76	26.67 ± 0.74	26.80 ± 0.66	26.86 ± 0.65
Length (cm) at first measurement	65.62 ± 2.58	63.06 ± 1.98	64.59 ± 1.71	65.64 ± 1.78	66.55 ± 1.72	68.36 ± 2.06
Length (cm) at last measurement	84.96 ± 3.25	80.43 ± 1.66	83.32 ± 0.52	85.01 ± 0.49	86.71 ± 0.51	89.49 ± 1.57
Length-for-age difference at first measurement	-1.34 ± 2.37	-3.60 ± 1.95	-2.28 ± 1.62	-1.27 ± 1.75	-0.55 ± 1.60	1.06 ± 1.89
Length-for-age difference at last measurement	-3.77 ± 3.18	-8.02 ± 1.88	-5.31 ± 1.06	-3.70 ± 1.01	-2.16 ± 0.97	0.47 ± 1.69
	Sensitivity analysis dataset					
	Overall (N=1,158)	Quintile 1 (n=236)	Quintile 2 (n=228)	Quintile 3 (n=231)	Quintile 4 (n=232)	Quintile 5 (n=231)
Total # observations	25,476	5,192	5,016	5,082	5,104	5,082
Female sex	532 (45.9)	138 (58.5)	115 (50.4)	106 (45.9)	96 (41.4)	77 (33.3)
Observations per child	22.0 ± 0.00	22.0 ± 0.00	22.0 ± 0.00	22.0 ± 0.00	22.0 ± 0.00	22.0 ± 0.00
Linear growth velocity (cm/month)	0.94 ± 0.56	0.84 ± 0.56	0.91 ± 0.55	0.94 ± 0.56	0.97 ± 0.55	1.02 ± 0.57
Age at first measurement	6.00 ± 0.38	5.94 ± 0.38	5.96 ± 0.36	5.99 ± 0.42	6.05 ± 0.36	6.07 ± 0.35
Age at last measurement	27.00 ± 0.40	26.90 ± 0.41	26.94 ± 0.43	26.95 ± 0.43	27.02 ± 0.36	27.04 ± 0.37
Length (cm) at first measurement	65.52 ± 2.50	62.98 ± 2.06	64.38 ± 1.68	65.49 ± 1.54	66.58 ± 1.67	68.18 ± 1.78
Length (cm) at last measurement	85.23 ± 3.26	80.68 ± 1.62	83.47 ± 0.54	85.36 ± 0.55	86.98 ± 0.49	89.71 ± 1.51
Length-for-age difference at first measurement	-1.27 ± 2.31	-3.47 ± 2.06	-2.26 ± 1.62	-1.28 ± 1.53	-0.37 ± 1.53	1.05 ± 1.72
Length-for-age difference at last measurement	-3.77 ± 3.20	-8.12 ± 1.79	-5.44 ± 0.89	-3.63 ± 1.01	-2.13 ± 0.87	0.51 ± 1.59

Notes: Values are mean ± SD or n (%)

Table 2. Descriptive statistics of regression diagnostics from individual linear spline regressions of length on age

	Overall	**Quintile 1**	**Quintile 2**	**Quintile 3**	**Quintile 4**	**Quintile 5**
	N=5,039	n=1,028	n=999	n=1,010	n=1,009	n=993
Intercept	57.88 ± 3.84	56.07 ± 3.46	57.12 ± 3.17	57.70 ± 3.64	58.52 ± 3.95	60.03 ± 3.71
R^2	0.9956 ± 0.003	0.9944 ± 0.004	0.9953 ± 0.003	0.9956 ± 0.002	0.9960 ± 0.002	0.9964 ± 0.002
Average velocity, 6-8 months	1.27 ± 0.40	1.16 ± 0.37	1.24 ± 0.36	1.30 ± 0.39	1.31 ± 0.44	1.35 ± 0.40
Average velocity, 9-11 months	1.02 ± 0.30	0.95 ± 0.30	1.00 ± 0.29	1.01 ± 0.29	1.06 ± 0.27	1.11 ± 0.30
Average velocity, 12-14 months	0.94 ± 0.28	0.86 ± 0.27	0.89 ± 0.27	0.94 ± 0.27	0.99 ± 0.26	1.04 ± 0.27
Average velocity, 15-17 months	0.92 ± 0.27	0.82 ± 0.28	0.89 ± 0.26	0.93 ± 0.27	0.94 ± 0.25	1.01 ± 0.26
Average velocity, 18-20 months	0.88 ± 0.26	0.77 ± 0.28	0.87 ± 0.25	0.89 ± 0.25	0.92 ± 0.25	0.97 ± 0.24
Average velocity, 21-23 months	0.82 ± 0.26	0.74 ± 0.28	0.81 ± 0.25	0.81 ± 0.25	0.86 ± 0.24	0.91 ± 0.25
Average velocity, 24-28 months	0.70 ± 0.51	0.62 ± 0.69	0.65 ± 0.49	0.71 ± 0.44	0.73 ± 0.28	0.79 ± 0.54
F-statistic	895.18 ± 539.27	742.23 ± 462.74	841.24 ± 518.16	865.44 ± 510.16	984.45 ± 576.42	1047.33 ± 568.72

Table 3. Contribution of uninterrupted growth and age-specific velocities to attained height of children at 28 months

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
R^2 (Smoothness)	3.104***	3.370***	3.300***	2.656***	2.092***	1.735***	1.168***	0.567***	0.412***
	(2.796, 3.411)	*(3.113, 3.628)*	*(3.058, 3.543)*	*(2.473, 2.839)*	*(1.938, 2.246)*	*(1.584, 1.886)*	*(1.025, 1.311)*	*(0.442, 0.692)*	*(0.295, 0.529)*
Initial length		0.610***	0.671***	0.946***	0.979***	0.957***	0.943***	0.956***	0.958***
		(0.584, 0.636)	*(0.646, 0.696)*	*(0.926, 0.967)*	*(0.962, 0.996)*	*(0.941, 0.974)*	*(0.928, 0.958)*	*(0.943, 0.969)*	*(0.946, 0.970)*
Velocity 6-8 months			2.260***	3.706***	3.677***	3.590***	3.473***	3.441***	3.433***
			(2.085, 2.435)	*(3.567, 3.845)*	*(3.561, 3.792)*	*(3.479, 3.701)*	*(3.371, 3.575)*	*(3.354, 3.529)*	*(3.352, 3.514)*
Velocity 9-11 months				6.296***	7.180***	7.015***	6.841***	6.755***	6.713***
				(6.098, 6.493)	*(7.011, 7.348)*	*(6.853, 7.177)*	*(6.693, 6.990)*	*(6.627, 6.882)*	*(6.595, 6.831)*
Velocity 12-14 months					3.860***	4.153***	4.062***	3.938***	3.906***
					(3.700, 4.020)	*(3.997, 4.308)*	*(3.919, 4.204)*	*(3.816, 4.060)*	*(3.792, 4.019)*
Velocity 15-17 months						1.760***	2.262***	2.213***	2.203***
						(1.600, 1.920)	*(2.112, 2.412)*	*(2.084, 2.341)*	*(2.084, 2.322)*
Velocity 18-20 months							2.383***	2.910***	2.900***
							(2.234, 2.533)	*(2.780, 3.041)*	*(2.779, 3.021)*
Velocity 21-23 months								2.786***	3.056***
								(2.658, 2.914)	*(2.936, 3.176)*
Velocity 24-28 months									0.852***
									(0.793, 0.911)
Observations	5,039	5,039	5,039	5,039	5,039	5,039	5,039	5,039	5,039
R-squared	0.072	0.350	0.423	0.675	0.775	0.794	0.828	0.873	0.891

95% Confidence Interval in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Sensitivity analyses using alternative functional forms for the individual regression models (linear polynomial model with cubic term for age, restricted cubic splines, linear splines with four knots) give a range of 2.44-2.83 for R^2, when attained length is regressed on R^2, with 95% confidence intervals spanning 2.39-3.09.

Figures

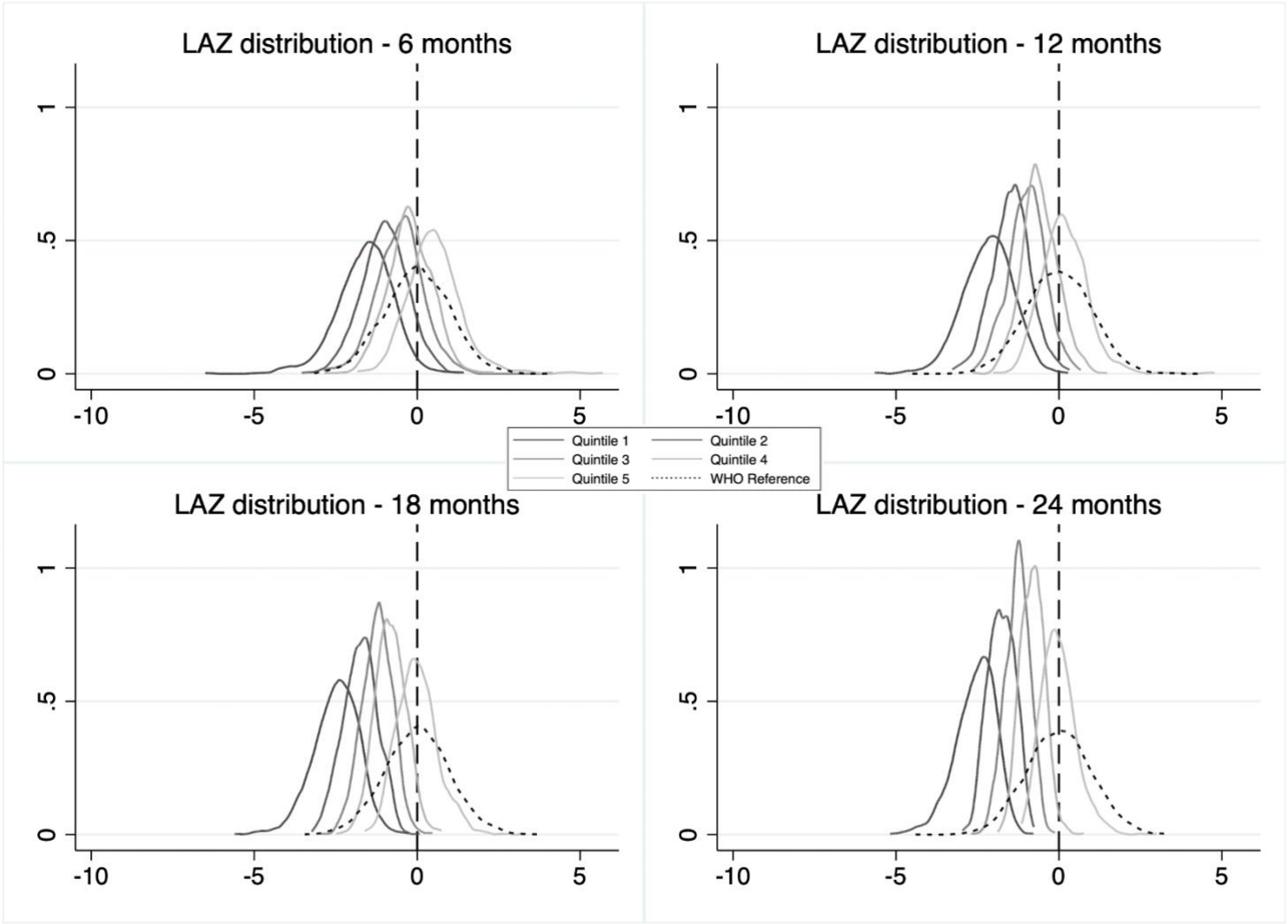

Figure 1. Kernel-density plots of length-for-age z-scores among sample children at selected ages, compared to WHO growth curve distribution.

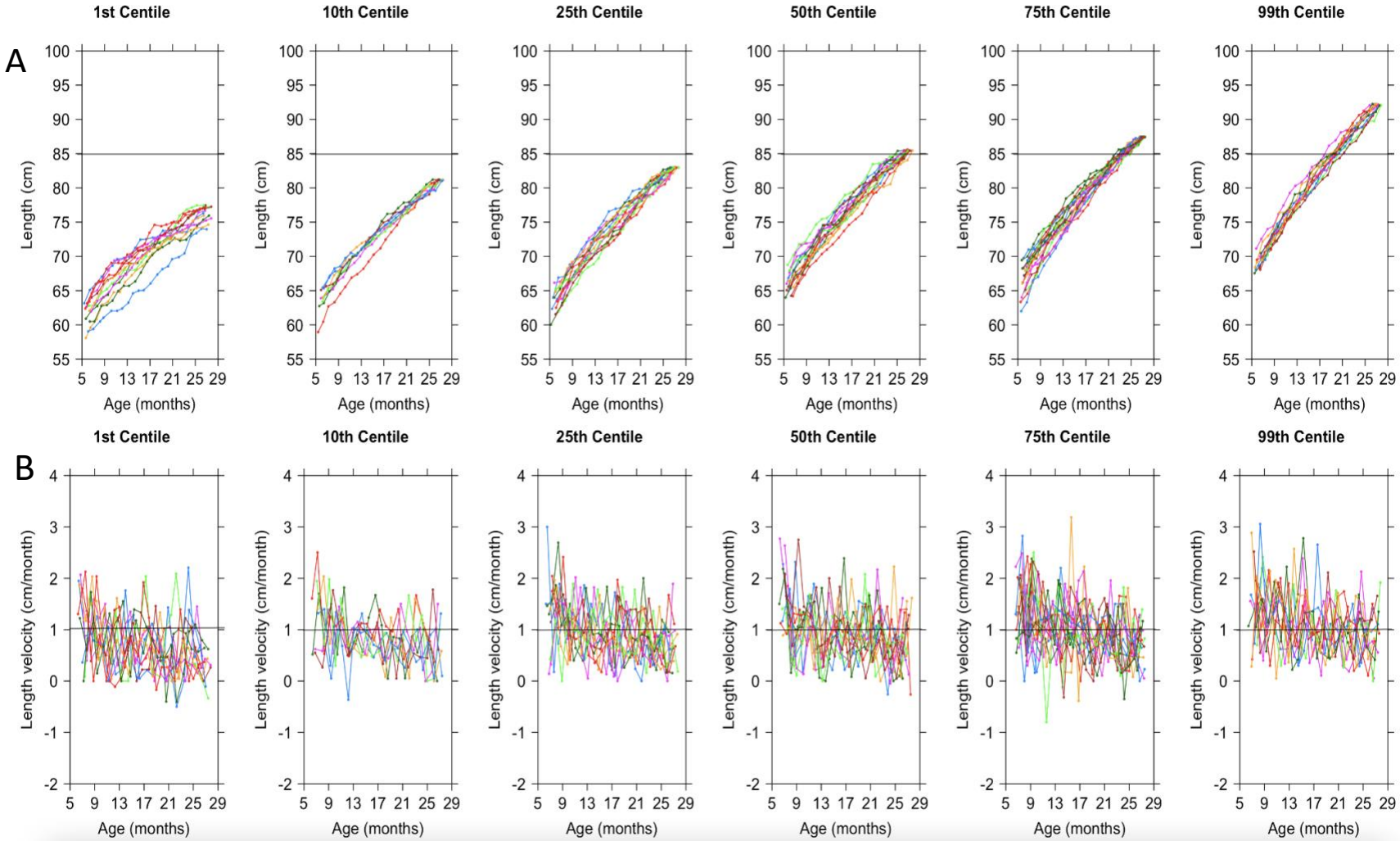

Figure 2. (A) Length (cm) and (B) Length velocity (cm/month) by age among children from selected centiles of attained length. Each colored line represents the growth curve over time of one individual child. Horizontal bars indicate average attained length (A), and average length velocity (B).

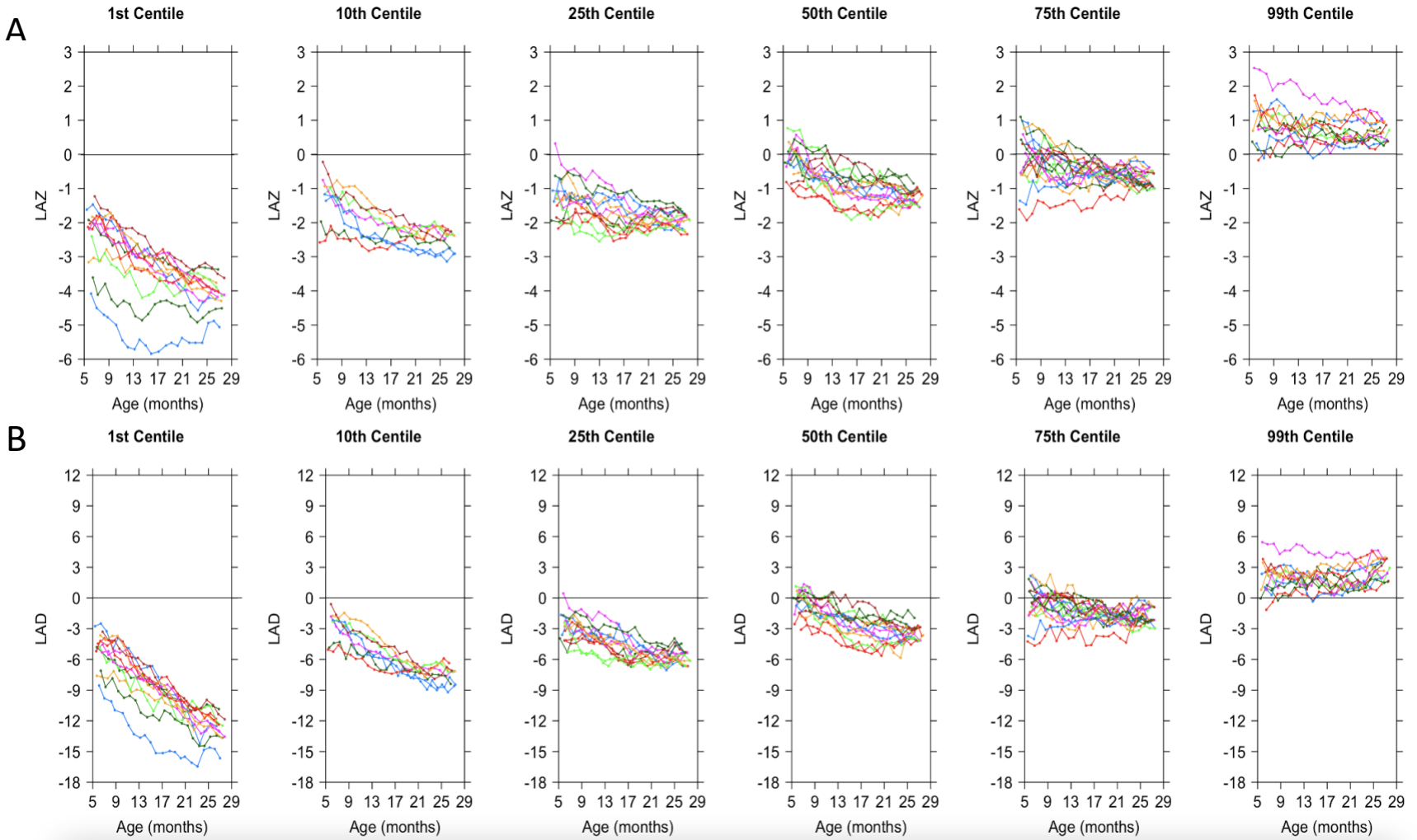

Figure 3. (A) Length-for-age z-scores and (B) Length-for-age difference by age among children from selected centiles of attained length. Each colored line represents the growth curve over time of one individual child. Horizontal bars indicate reference population z-score mean (A) and zero length-for-age difference from reference population median (B).

Supplemental Tables

Supplemental Table 1. Sensitivity analyses by functional form for age

	Cubic Polynomial	4-Knot Linear Splines	6-Knot Linear Splines	Cubic Splines
R^2 (smoothness)	2.442***	2.532***	3.108***	2.841***
	(2.394, 2.491)	*(2.480, 2.584)*	*(3.042, 3.174)*	*(2.787, 2.896)*
Observations	107,677	108,802	108,802	108,802
R-squared	0.082	0.076	0.073	0.086

95% confidence interval in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 2. Mean R^2 by quintile in each study arm

	Quintile 1	Quintile 2	Quintile 3	Quintile 4	Quintile 5
CSB+	0.9946	0.9955	0.9958	0.9964	0.9964
CSWB	0.9939	0.9953	0.9955	0.9960	0.9962
SC+	0.9948	0.9956	0.9958	0.9961	0.9965
RUSF	0.9945	0.9951	0.9952	0.9958	0.9963

Supplemental Table 3. Length velocity moments by age in each quintile

	Quintile 1				Quintile 2				Quintile 3				Quintile 4				Quintile 5			
Age	**N**	**LV**	**SD**	**CV**	**N**	**LV**	**SD**	**CV**	**N**	**LV**	**SD**	**CV**	**N**	**LV**	**SD**	**CV**	**N**	**LV**	**SD**	**CV**
6	130	1.28	0.76	0.59	88	1.63	0.69	0.42	103	1.56	0.75	0.48	63	1.58	0.81	0.51	59	1.58	0.77	0.49
7	788	1.29	0.75	0.58	771	1.39	0.72	0.52	746	1.45	0.73	0.50	728	1.50	0.74	0.49	709	1.48	0.74	0.50
8	998	1.12	0.66	0.59	976	1.20	0.66	0.55	999	1.25	0.68	0.54	990	1.27	0.66	0.52	936	1.36	0.66	0.49
9	1,009	1.06	0.61	0.58	986	1.12	0.61	0.54	1,007	1.15	0.63	0.55	980	1.21	0.62	0.51	978	1.25	0.64	0.51
10	1,008	1.01	0.59	0.58	965	1.04	0.57	0.55	974	1.11	0.59	0.53	991	1.09	0.56	0.51	967	1.14	0.57	0.50
11	1,026	0.97	0.59	0.61	1,003	1.02	0.57	0.56	1,021	1.01	0.55	0.54	1,033	1.08	0.56	0.52	1,006	1.12	0.57	0.51
12	1,026	0.89	0.57	0.64	990	0.98	0.60	0.61	982	0.97	0.55	0.57	973	1.05	0.59	0.56	992	1.11	0.57	0.51
13	1,020	0.90	0.56	0.62	1,002	0.93	0.56	0.60	1,025	0.95	0.57	0.60	1,014	1.01	0.59	0.58	982	1.04	0.57	0.55
14	1,017	0.85	0.56	0.66	984	0.87	0.57	0.66	997	0.95	0.61	0.64	1,004	0.97	0.57	0.59	983	1.04	0.56	0.54
15	1,022	0.86	0.55	0.64	983	0.90	0.54	0.60	981	0.94	0.55	0.59	995	0.99	0.55	0.56	966	1.01	0.59	0.58
16	1,036	0.82	0.56	0.68	1,024	0.88	0.55	0.63	1,029	0.92	0.54	0.59	997	0.98	0.59	0.60	1,015	1.05	0.58	0.55
17	1,007	0.85	0.51	0.60	978	0.91	0.52	0.57	1,001	0.94	0.55	0.59	1,008	0.96	0.56	0.58	974	1.02	0.58	0.57
18	1,047	0.81	0.56	0.69	1,005	0.90	0.54	0.60	1,020	0.92	0.56	0.61	1,033	0.92	0.54	0.59	1,008	1.00	0.56	0.56
19	1,020	0.79	0.58	0.73	1,000	0.87	0.54	0.62	1,001	0.93	0.54	0.58	977	0.95	0.53	0.56	981	0.95	0.51	0.54
20	1,051	0.77	0.51	0.66	1,033	0.86	0.55	0.64	1,048	0.88	0.53	0.60	1,064	0.93	0.52	0.56	1,035	0.96	0.54	0.56
21	1,031	0.77	0.52	0.68	995	0.84	0.51	0.61	987	0.87	0.53	0.61	933	0.90	0.50	0.56	984	1.00	0.52	0.52
22	1,028	0.74	0.50	0.68	997	0.85	0.52	0.61	1,020	0.84	0.50	0.60	1,011	0.90	0.50	0.56	988	0.92	0.49	0.53
23	1,042	0.76	0.52	0.68	1,034	0.81	0.48	0.59	1,042	0.81	0.49	0.60	1,041	0.85	0.48	0.56	1,026	0.89	0.47	0.53
24	1,036	0.69	0.49	0.71	995	0.73	0.46	0.63	998	0.75	0.49	0.65	1,004	0.83	0.47	0.57	980	0.89	0.47	0.53
25	1,042	0.66	0.54	0.82	1,017	0.73	0.47	0.64	1,032	0.75	0.50	0.67	1,024	0.75	0.46	0.61	1,006	0.80	0.47	0.59
26	898	0.64	0.52	0.81	923	0.68	0.52	0.76	943	0.69	0.48	0.70	977	0.75	0.50	0.67	953	0.78	0.48	0.62
27	674	0.52	0.59	1.13	706	0.61	0.52	0.85	754	0.71	0.50	0.70	830	0.72	0.50	0.69	852	0.75	0.51	0.68
28	79	0.53	0.55	1.04	83	0.50	0.63	1.26	106	0.64	0.57	0.89	118	0.67	0.48	0.72	146	0.73	0.60	0.82

Note: LV = length velocity (cm/month); SD = standard deviation; CV = coefficient of variation

Chapter 5: Temporal patterns in linear and ponderal growth velocity among young children

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Abstract

The temporal relationship between length (linear) and weight (ponderal) growth is important to understand for optimal nutrition program design. Recent studies have established that wasting often precedes stunting, but these studies use measures of attained size which incorporate past growth conditions as well as current ones. As a result, mechanisms through which temporal relationships occur remain unclear. We explore the bi-directional temporal relationships between linear and ponderal growth velocities to understand how current growth conditions influence both linear and ponderal growth, including how they relate to each other. Using measurements from a cohort of 5,039 Burkinabè children enrolled at 6 months of age and measured at monthly intervals until 28 months, we use multi-level mixed effects regression models to investigate the concurrent and lagged associations between linear and ponderal growth velocity, controlling for time trends, seasonality, and morbidity. Among individuals, faster ponderal growth is associated with faster concurrent and subsequent linear growth, while faster linear growth is associated with slower future weight gain. On average, ponderal growth slows around the same time as peaks in morbidity, followed roughly a month later by slower linear growth. Results demonstrate that the same growth-limiting conditions likely affect both length and weight velocity, that slow ponderal growth likely limits linear growth, and that linear growth spurts may not be accompanied by sufficient increases in dietary intake to avoid slowdowns in weight gain. To improve child growth, programs should combine strategies that address both weight and height.

Introduction

Malnutrition in all its forms remains a prevalent global issue, with 21.9% of children stunted (low length-for-age (LAZ) ratios compared to the WHO growth reference standards), 6.9% wasted (low weight-for-length (WLZ) ratios), and 5.6% overweight (high WLZ ratios) worldwide in 2019 (1, 2). While programs have historically focused on each form of malnutrition as a separate problem (3–6), with wasting thought to be associated with factors that have an immediate effect on health such as illness or food shortages, and stunting attributed to general underlying conditions of poverty and food insecurity (7), this approach limits the ability of the nutrition community to maximize the efficiency and effectiveness of malnutrition prevention and treatment (8).

Recently, increased attention has been paid to the relationship among the different forms of malnutrition, including how knowledge of interdependencies can be leveraged to increase program effectiveness (9). Wasting and stunting have separately been used as indicators that can predict mortality and future productivity (10), but children with concurrent stunting and wasting are at the highest risk for mortality (11, 12). The prevalence of concurrent stunting and wasting has been measured in cross-sectional studies at both the population and individual level, highlighting the co-existence of the two conditions, which in some places exceeds 5% of children (4, 8). This is concerning, and it likely underestimates the depth of the issue since measuring prevalence at a single time-point may fail to pick up associations given the transient nature of wasting and the more prolonged condition of stunting. If one condition precedes the other, for example, this would not be captured in prevalence studies of cross-sectional data (6).

Additional research has therefore focused on the temporal and causal relationships between the different forms of undernutrition, showing that stunting and wasting likely have overlapping

causal pathways (13–16). The overwhelming consensus from studies that make use of longitudinal data to investigate temporality between stunting and wasting is that sufficient ponderal (weight) growth, and thus ample energy reserves, may be necessary for linear (length) growth (13, 17, 18), so early episodes of wasting or deficits in weight gain have significant effects on attained height, and may precede the development of stunting (6, 12, 16, 19–26). While most studies have investigated temporal dependencies in only one direction, with linear growth or stunting as the outcome, and earlier wasting or ponderal growth as the independent variable, at least one study also found that the relationship may be bidirectional, with poor linear growth associated with higher wasting (27).

These studies have advanced our understanding of the temporal associations between stunting and wasting, but in many cases are limited by the rigidity of the definitions of stunting and wasting, which were established as cut-offs for assessing population levels of malnutrition but may not be appropriate for individual level assessment given the lack of biological justification for the cut-off of -2 standard deviations from a growth reference population (28). A limited number of studies have made use of the entire range of attained size z-scores (LAZ, WLZ) or investigated the connections between attained WLZ and linear growth velocities (6, 17, 26, 29), which gives a more nuanced understanding of the timing of different types of growth faltering.

We aim to add to the discussion of the temporal associations between linear and ponderal growth trajectories by exploring the bi-directional relationships between linear and ponderal growth using WHO growth reference length and weight velocity z-scores in addition to absolute length and weight velocities. Velocity indicators will allow for understanding of how changes in length and weight relate to each other and how growth in one parameter may predict growth in

the other, rather than relying on attained size indicators that reflect the cumulative effects of all environmental growth-limiting conditions up to the point of measurement (30). We determine the temporal dependencies between linear and ponderal growth velocities among a large, single cohort of children followed monthly between age 6 and 28 months. We show how when an individual child experiences increases (or decreases) in one growth velocity parameter, it affects the rates of the other parameter, and identify sensitive age ranges when the rate of growth in one parameter is more influential on the rate of growth of the other parameter. This will help determine how the types of interventions used can increase their likelihood of improving both weight and height acquisition, and aid programs in targeting precise time windows for optimal effects.

Methods

Study design and data source

Anthropometric data were collected between August 2014 and December 2016 during a longitudinal geographically clustered trial comparing the cost-effectiveness of four supplementary foods in preventing stunting and wasting in children 6-23 months in Sanmatenga Province, Burkina Faso. All children in the catchment area were eligible for enrollment on a rolling basis as they reached 6 months, except those with a mid-upper-arm circumference < 11.5 cm who were referred for treatment for severe acute malnutrition (SAM). Participating children were measured monthly (recumbent length, weight, mid-upper-arm circumference) for 18 months during the supplementary feeding intervention and for an additional 3 months post-intervention, with most measurements occurring when children were between 6-28 months. Details of the original trial, including methods and results are found elsewhere (31). Children

from all four study arms are pooled for this analysis, and study arm is controlled for as a covariate.

The original dataset includes 129,994 measurements from 6,112 children. Biologically implausible values were identified as those for which the absolute value of jackknifed residuals after regressing each child's length or weight measurements on their age was above 5, as described by Shi et al. 2018 as an appropriate method for identifying outliers in longitudinal growth data (32). Overall, 7% of data were missing or implausible. Randomness of the distribution of missing and implausible values was assessed and confirmed by regressing indicators for missing or implausible values on socio-demographic factors, as well as enumerator code. All missing and implausible values were then imputed using predicted values from simple linear regressions of the measurement on age, for each child. Finally, the dataset was restricted to children who had at least 20 repeated measurements. The final dataset used for analysis includes 108,580 measurements on 5,039 children between 5-28 months and comprises 82% of the original sample.

Variable specification

Indicators for linear and ponderal growth serve as both the dependent and independent variables; when linear growth indicators are the dependent variables, ponderal growth indicators are the independent variables, and vice versa. Indicators for absolute length and weight velocity were calculated by subtracting the current month's measurements from the previous month's measurements, dividing by the time difference between measurements and multiplying by 30.44 to obtain cm/month and kg/month. Velocity z-scores compare growth velocity among sample children to the 2009 WHO Child Growth Standards and were calculated using the Lamda-Mu-Sigma (LMS) parameters supplied by the WHO (33). Growth velocity standards are limited to 2-

month intervals among children under 24 months, so growth velocity z-scores are constant for each 2-month age period. In order to compare our results to previous studies, we also looked at temporality between attained linear versus ponderal size using LAZ and WLZ, calculated with the Stata macro developed using the 2006 WHO Child Growth Standards (2, 34).

In addition to growth indicators, we coded a dichotomous variable identifying whether or not the child's caregiver reported any type of illness in the previous two weeks on the day the child was measured. Illnesses noted included upper-respiratory symptoms (cough, difficulty breathing, rapid breathing), fever, diarrhea, confirmed malaria, accident/injury, or burn. We also descriptively examine the temporal relationship between reported fever or diarrhea on the day of measurement and growth indicators. Last, the original trial was geographically clustered, so by controlling for study arm, we are also controlling for geographic region.

Data analysis

To estimate the relationship between linear and ponderal growth indicators, we used multi-level mixed effects linear regression models with child-level random intercepts. To control for the effects of seasonality and overall time trends on child growth, we included trigonometric terms, and a continuous daily time indicator, centered at zero to represent the first day the study was initiated (35, 36). We investigated multiple functional forms to control for age in our models, and ultimately decided for ease of interpretation to stratify the models by narrow age categories, as well as by sex of the child, since our sample size is large enough to handle relatively fine stratifications. Age categories were set in three-month intervals, with separate models for children 6-8 months, 9-11, 12-14, 15-17, 18-20, 21-23, and 24-28 months. Models were specified for the entire sample, as well as each age and sex category as follows:

$$Y_{id} = \beta_{0i} + \beta_{1id}G + \beta_{2id}PG + \beta_{3id}I + \beta_{4i}S + \beta_{5i}d + \beta_{6i}\sin(2\pi\omega d) + \beta_{7i}\cos(2\pi\omega d) + \beta_{8i}\sin(4\pi\omega d) + \beta_{9i}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{id};$$

where Y_{id} is the growth outcome for child *i* on study day *d*. Growth indicators for linear and ponderal growth are paired together by type (absolute velocity, velocity z-scores, attained size indicators) and serve as each other's outcomes and primary explanatory variables in separate models. Pairs include length and weight velocity, length velocity z-scores (LVZ) and weight velocity z-scores (WVZ), and LAZ and WLZ. The coefficient β_1 represents the explanatory growth variable, *G*, which is the opposing linear or ponderal growth indicator to the outcome (e.g., when the outcome is length velocity, the explanatory growth variable is weight velocity). The relationship between the previous month's measurement and the current measurement for the outcome is represented by the coefficient β_2, where *PG* is the previous month's measurement for the outcome variable. The effect of the explanatory growth variable on the outcome growth variable is therefore conditional on the previous growth trajectory of the outcome variable. Morbidity in the previous two weeks is controlled for by coefficient β_3, where *I* is a dichotomous indicator for any self-reported (by the caregiver) illness in the previous two weeks, and study arm, *S*, is controlled for by β_4. The coefficient β_5 represents a control for the overall time trend of the model. Seasonality is controlled for by the coefficients of the sine and cosine terms where ω is a constant equal to 1/365.25, representing the frequency of the annual cycle in days accounting for the 2016 leap year. Individual child level random effects are accounted for by α_i, and ε_{id} is the time-varying error term.

Each model was fit with concurrent indicators from the same month for both the outcome and explanatory growth indicators, as well as a lagged explanatory variable, with growth indicators from the previous month in relation to the outcome indicator. For LVZ and WVZ models, in which growth indicators are constant for two-month periods of time, lagged growth indicators were those from two months ago in chronological time. In addition to these models,

we ran harmonic regression models with each of the growth and morbidity indicators as outcomes and only the trigonometric and time indicator terms as the predictors, to investigate overall seasonal and time trends for each indicator.

Last, as a secondary analysis, we fit ordinary least squares regression models to examine the relationship between LAZ or WLZ at the end of the study and total months of wasting or stunting measurements throughout the study period, respectively. We fit these models to increase generalizability of our analyses and be able to compare our results with those from previous studies that examined the relationships between early episodes of wasting (between 0-17 months) and later stunting or LAZ (after 18 months) and to expand on those findings by also looking at the reverse (how early stunting effects later WLZ). These models took the form:

$$Y_i = \beta_0 + \beta_1 N + \beta_2 SA + \beta_3 StudyArm + \beta_4 Illness + \beta_5 Month + \mu_i;$$

where Y_i is end (~27 months of age) LAZ or WLZ for child *i*, the primary independent variable, *N*, is total number of wasted or stunted months throughout the study period, *SA* represents starting anthropometric z-scores, *StudyArm* indicates dummy variables for the original study arm, *Illness* is an indicator of the total number months in which an episode of illness was reported, and *Month* is an indicator from 1-12 for calendar month at the end of the study.

Ethics

The Tufts University Health Sciences Institutional Review Board (IRB #: 10899) and the ethics board of the Ministry of Health in Burkina Faso (#: 2013-10-090) approved the original study in which anthropometric data were collected. Secondary analysis of the same anthropometric data for this paper was exempt by the Tufts University Health Sciences Institutional Review Board (IRB ID: STUDY00000255).

Results

Description of growth and morbidity indicators

Descriptive analysis of growth and morbidity indicators reveals stark differences by both sex and age category (**Table 1**). For almost all growth and morbidity indicators, males are worse-off than females. Males experience 3-4 percentage point increases in prevalence of concurrent stunting and wasting, regardless of age category, which in some cases amounts to more than double the prevalence of concurrent stunting and wasting than their female counterparts. Males also have lower LAZ, WLZ, WVZ, and absolute length and weight velocity, as well as higher prevalence of any reported illness including fever and diarrhea at the time of measurement. The only metric by which males are not systematically worse-off than females is LVZ.

Patterns by age category depend on the indicator. Average LAZ declines as children age, as does absolute length velocity. Absolute weight velocity remains relatively constant as children age, and weight-for-length z-scores fluctuate from age block to age block with no apparent overall age trend over time. Both WVZ and LVZ increase once children are older. LVZ remains relatively constant until children reach the 15–17-month age block, at which point it increases. WVZ starts off lowest between 6-8 months, increases slightly at 9-11 months, and then increases drastically and remains relatively constant from 12-14 months onwards. Instances of morbidity also decrease as children age, with the highest prevalence for all morbidities when children are 6-8 months and decreasing prevalence thereafter.

We visualized these patterns along with their seasonality components using graphs of predicted growth indicators from harmonic regression models of each indicator over time. We overlaid each pair of corresponding linear and ponderal growth indicators to look at the average timing of peaks and nadirs in the indicators in relation to each other (**Figure 1**). Seasonality of each indicator did not differ by child sex, so we display a single curve for each indicator,

showing the averages over time for the entire sample. Each anthropometric indicator shows two peaks and nadirs per year. Peak timing of length and weight velocity occur at almost exactly the same time, at the beginning of January (cooler, dry season), and again near the end of July (near the peak of the rainy season). The slowest points for weight velocity in mid-April (hot, dry season) and again in mid-October (hot, dry season) are followed slightly over a month later (39-42 days) by the slowest points in length velocity at the end of May (hot, pre-rainy season) and the end of November (hot, dry season). Similar relationships are seen with regard to WVZ and LVZ, with WVZ hitting its nadir about a month before the nadir of LVZ, each time. LAZ did not reveal seasonal trends like the other indicators, so its average temporal relationship with WLZ is harder to establish. Peaks in fever and diarrhea prevalence happen within 19 days of the nadirs in ponderal growth indicators, though they sometimes occur before, and sometimes right after the periods of slowest ponderal growth.

Relationship between linear and ponderal growth

Figure 2 shows the Pearson Correlation Coefficients between each combination of corresponding linear and ponderal growth indicators at different lag periods. Each lag period is a one-month time interval between the current month's measurement and the lagged measurement. For example, lag 1 occurs the month prior to the current measurement, lag 2 occurs two months prior, etc. Current length is highly correlated with previous weight, even after 9 lag periods. Similarly, current weight is highly correlated with previous length, but to a slightly lesser degree, with decreasing correlation as the lag periods increase. When previous weight or length increase, current length or weight also increase. Current LAZ remains significantly positively correlated with previous WLZ at roughly the same level, regardless of lag period, with extremely slight increases in the magnitude of correlation with lags 3-4 of WLZ. Current WLZ is also

significantly positively correlated with previous LAZ, with very small declines as the lag periods increase. Velocity indicators have much lower correlations with each other than attained size indicators, and less consistent relationships. Nevertheless, current LVZ is significantly positively correlated with past WVZ until lag 7, with the largest correlations after one lag period. Correlations are not statistically significant between current LVZ and previous WVZ after lag 7. WVZ is significantly negatively correlated with LVZ from the previous period; at lags 1 and 2, if LVZ increased in the previous period, then current WVZ decreases. There is no significant correlation at lags 3 or 4. At the 5^{th} lag period, the direction of this relationship reverses so that an increase in LVZ five months ago corresponds with an increase in WVZ, but is only significant at lag 5, and not thereafter. These correlations are all small in magnitude, at times very close to zero. Similar correlations are observed between absolute length and weight velocity, with very slightly significant positive correlations between current length velocity and previous weight velocity until lag 7, and very small significant negative correlations between current weight velocity and previous length velocity until lag 3.

Figure 3 reveals how individual children's linear and ponderal growth velocity indicators relate to each other in each age category, stratified by sex. To be able to compare changes in length and weight velocity to each other, we calculated the percent change from the average for each indicator after a one percent change in the corresponding indicator. For example, among male children 6-8 months, weight velocity increases by 0.68% if the average length velocity for children 6-8 months increases by 1% during the same time period, but it decreases by 0.8% if average length velocity increases by 1% in the previous time period. Overall, length velocity increases modestly (0.2-0.6% above average) if weight velocity increases either concurrently, or in the previous time period, with the highest increases in the two youngest age categories, and

higher increases among females than males. Weight velocity increases greatly (0.35-0.68%) if average length velocity doubles in the same month, with increases generally decreasing as children age. However, current weight velocity decreases slightly if length velocity doubled in the previous month. In other words, faster linear growth is associated with slightly slower ponderal growth in the subsequent month. This relationship is strongest among females 9-14 months, and males 6-8 months and 24-28 months. Similar relationships are observed between LVZ and WVZ, which are expressed as changes in z-scores with 1-unit increases in the opposing z-scores. Increases in WVZ have a larger effect on LVZ than increases in LVZ have on WVZ. Here again, prior increases in LVZ are associated with very slight (mostly non-significant) decreases in WVZ in the current month. The only significant coefficients for the relationship between WVZ and previous LVZ were those for females 9-11 months, and for males 9-14 months. Across all age and sex groups, all coefficients for concurrent linear and ponderal growth velocities were significant at the 1% level, as were all coefficients from models in which linear growth velocity (absolute or standardized) was the outcome and lagged ponderal velocity was the predictor.

Results from LAZ/WLZ models reveal very small but statistically significant increases in LAZ after concurrent and previous increases in WLZ, as well as small but significant increases in WLZ after concurrent or previous increases in LAZ (**Figure 4**). Among children over 21 months, these relationships lose their statistical significance. Full results from all models that make up Figures 3 and 4 are available in Supplemental Tables 1-24.

Ordinary least squares regression of LAZ and WLZ at study end on total number of wasted or stunted months, respectively, show significant decreases in both LAZ and WLZ at the end of the study period with an increased number of previously wasted or stunted months (**Table**

2). Conditional on starting z-scores, month of measurement, study arm, and total episodes of illness, each additional wasted month throughout the study period is associated with a 0.023 decrease in LAZ at study end, and each additional stunted month is associated with a 0.015 decrease in WLZ at study end.

Discussion

In recent years, the Wasting-Stunting Technical Interest Group (WaSt TIG) has produced several articles and policy briefs outlining the important connections between stunting and wasting, making the case for aggregating interventions that address both forms of undernutrition (37). These papers and reports, which largely describe findings related to the associations between attained size indicators (LAZ, WLZ), have begun to change the paradigms for addressing undernutrition (38). While they present ample, convincing evidence that there is a significant relationship between earlier episodes of wasting and later linear growth faltering (6, 12, 26, 16, 19–25), the focus on attained size indicators limits interpretation of temporality between linear and ponderal growth. A key feature of attained size indicators is that they incorporate all growth up until the point of measurement, making it difficult to decipher how current growth-limiting conditions affect each growth parameter. Our study, in which we demonstrate temporal dependencies between linear and ponderal growth velocities, allows for novel understanding of how conditions at or around the time of measurement influence both linear and ponderal growth and how growth in the different anthropometric parameters responds to these conditions in relation to each other. We find that episodes of faster ponderal growth are associated with concurrent and subsequent faster linear growth, but that episodes of faster linear growth are associated with slower subsequent ponderal growth. At the same time, our analyses of attained size indicators reveal similar findings to previous studies, that more episodes of wasting

are associated with lower LAZ at the end of the study, and greater number of months with stunting indicated is associated with lower WLZ, to a lesser extent. These findings permit new theories of the fundamental growth processes that contribute to the previously established associations between WLZ and LAZ.

The significant association between linear and ponderal growth velocities in the same month at the individual level suggests that conditions that affect one type of growth affect the other at roughly the same time. Many have suggested based on attained size findings that reveal that linear growth faltering often happens following ponderal growth faltering, that linear growth faltering is partially a biological response to being wasted (25, 38). We do not negate this idea; rather we offer evidence of its biological plausibility. Since stunting is a slower process than wasting, in that the body loses mass relatively quickly in growth-limiting conditions, in contrast to the lag period between growth-limiting conditions and a lower LAZ (13), the 2-3 month temporal delay observed between low WLZ and low LAZ may be an artifact of the relative speed of these two processes. Our investigation into the overall time trends and seasonality patterns of growth in different anthropometric parameters also supports the idea that the same growth-limiting conditions, whether they be food or disease related, affect both length and weight velocity. Comparison of the slowest average ponderal growth period to the slowest average linear growth period among all children in our sample separates the two by about one month, whereas previous studies that have looked at this question in terms of attained size indicators have found that LAZ declines roughly 2-3 months after declines in WLZ (19, 29, 39).

We find that on average, fever and diarrhea prevalence peak around the same time as the slowest ponderal growth velocity, which is followed shortly by the period of slowest linear growth velocity. While we cannot establish directionality of effect between fever or diarrhea and

slow ponderal growth in this analysis, the close temporal proximity of the slowest ponderal growth velocity to peaks in fever and diarrhea demonstrates the effects of the well-accepted cycle of undernutrition and infection, whereby illness leads to nutrient loss, malabsorption and loss of appetite, which leads to growth faltering and compromised immunity (40–42). Often-cited theories related to the importance of fat mass for production of leptin, and the importance of leptin for both immune response and bone growth (13, 43) may help explain how conditions lead first to ponderal growth velocity slow-downs and then to linear growth velocity slow-downs shortly thereafter. The most likely cause of initial slow-downs in ponderal growth is infection, as evidenced by the significant relationships between both linear and ponderal growth velocity and illness in our models, and the temporal proximity of fever and diarrhea to slow ponderal growth (which are followed a month later by slowdowns in linear growth). Multiple insults to ponderal growth velocity perpetuated by the vicious cycle of infection and lowered immunity will continuously lead to slower linear growth velocity, eventually manifesting as low LAZ.

We also find that faster linear growth is associated with slower future ponderal growth. When dietary intake is inadequate to maintain metabolic processes, the body is forced to draw on nutritional reserves in fat and muscle tissues to ensure that organs have enough energy (44). In addition, linear growth increases energy requirements through the association with accretion of lean tissue (45). Growth spurts among children in the context of Burkina Faso may not be accompanied by sufficient increases in dietary intake to avoid slowdowns in weight gain due to these physiological adjustments. If faster linear growth is associated with slower future weight gain, then slower linear growth may be associated with faster future ponderal growth in some cases. Recent fears by nutrition programmers that treatment for wasted children could lead to excess fat in children with low LAZ, since treatment for wasting often increases weight gain

without spurring linear growth right away, could be supported by this finding (46). However, since studies have shown that the weight gained during treatment for severe wasting appears to be lean tissue and not fat mass (47), it is unlikely that the implications of slower linear growth being associated with higher future weight gain is an issue. More likely is that programmers need to consider the effects that linear growth spurts may have on weight gain in contexts where dietary intake is insufficient.

Last, we find, as have other studies before this one, that male children are more vulnerable to growth insults than female children and are more likely to experience linear and ponderal growth faltering concurrently (37). While changes in weight velocity in response to increased length velocity are larger among males, the opposite is true among females – increases in length velocity associated with increased weight velocity are larger among females. In addition, the temporal relationships between linear and ponderal growth are strongest among the youngest children, Males and younger children also experience higher prevalence of illness, further bolstering the likelihood that the morbidity pathway has a strong influence on linear and ponderal growth trajectories and their temporal dependencies.

A key limitation of this study is the lack of longitudinal data on food security and diet diversity, which may be important exposures that influence growth velocity in addition to morbidity. Future studies should collect high-frequency data on such exposures to further explain the potential underlying pathways leading to slow ponderal and linear growth. In addition, given the strong association between LAZ at the beginning and end of the study, which indicates the continued effects of early growth faltering, it would be beneficial to have data on maternal characteristics, as well as gestational age and birth size of the infants, to be able to examine intergenerational growth faltering. Last, all of the children in this study were receiving a

supplemental food, which may have influenced linear and ponderal growth trajectories. Any influence of the supplemental foods on growth would likely have been protective of slowdowns, which would make our results underestimations of the true relationship between linear and ponderal growth. We may have seen relationships of higher magnitude in the absence of the supplementary feeding program. Regardless, the results of our study along with previous studies make clear the importance of programs that combine strategies that address the underlying risk factors affecting both linear and ponderal growth. Such programs should take care to avoid episodes of slower ponderal growth after linear growth spurts by addressing the multiple mechanisms through which ponderal growth can decrease, including both infection and dietary intake.

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Tables and Figures

Tables

Table 1. Characteristics of study children, Sanmatenga Province, Burkina Faso, 2014-2016

		Age Block						
	Overall	6-8 months	9-11 months	12-14 months	15-17 months	18-20 months	21-23 months	24-28 months
Observations	108,580	16,539	14,491	15,010	15,230	15,177	15,198	16,452
				Outcomes				
Concurrent stunting[1] and wasting[2]	4,490 (4.14)	313 (1.89)	564 (3.77)	809 (5.39)	799 (5.25)	786 (5.18)	607 (3.99)	611 (3.71)
Females	1,288 (2.40)	58 (0.71)	148 (2.01)	240 (3.24)	231 (3.08)	225 (3.01)	173 (2.31)	213 (2.60)
Males	3,215 (5.82)	255 (3.03)	416 (5.48)	569 (7.49)	568 (7.35)	561 (7.29)	434 (5.64)	411 (4.84)
Length-for-age z-score	-1.11 ± 1.04	-0.66 ± 1.06	-0.90 ± 1.04	-1.11 ± 1.02	-1.23 ± 1.02	-1.27 ± 1.01	-1.28 ± 0.99	-1.32 ± 0.98
Females	-1.00 ± 0.98	-0.55 ± 0.98	-0.79 ± 0.96	-0.99 ± 0.95	-1.11 ± 0.95	-1.15 ± 0.94	-1.17 ± 0.94	-1.22 ± 0.93
Males	-1.22 ± 1.09	-0.77 ± 1.11	-1.02 ± 1.09	-1.23 ± 1.08	-1.35 ± 1.07	-1.39 ± 1.06	-1.39 ± 1.03	-1.42 ± 1.01
Weight-for-length z-score	-0.86 ± 0.97	-0.71 ± 1.05	-0.95 ± 1.01	-1.03 ± 0.98	-0.91 ± 0.94	-0.85 ± 0.94	-0.78 ± 0.91	-0.80 ± 0.91
Females	-0.77 ± 0.92	-0.66 ± 0.98	-0.86 ± 0.96	-0.91 ± 0.93	-0.80 ± 0.90	-0.74 ± 0.90	-0.70 ± 0.87	-0.76 ± 0.89
Males	-0.94 ± 1.01	-0.76 ± 1.11	-1.05 ± 1.06	-1.14 ± 1.01	-1.02 ± 0.97	-0.96 ± 0.96	-0.86 ± 0.93	-0.85 ± 0.94
Length velocity z-score	-0.37 ± 0.92	-0.50 ± 1.05	-0.55 ± 0.96	-0.50 ± 0.91	-0.27 ± 0.86	-0.20 ± 0.82	-0.16 ± 0.79	NA
Females	-0.38 ± 0.94	-0.51 ± 1.07	-0.57 ± 0.98	-0.50 ± 0.93	-0.27 ± 0.86	-0.21 ± 0.84	-0.17 ± 0.82	NA
Males	-0.36 ± 0.90	-0.50 ± 1.04	-0.53 ± 0.95	-0.50 ± 0.89	-0.26 ± 0.85	-0.19 ± 0.80	-0.15 ± 0.77	NA
Weight velocity z-score	-0.10 ± .42	-0.27 ± 0.49	-0.13 ± 0.43	-0.05 ± 0.39	-0.04 ± 0.38	-0.03 ± 0.38	-0.05 ± 0.37	NA
Females	-0.09 ± .41	-0.23 ± 0.46	-0.12 ± 0.42	-0.04 ± 0.40	-0.05 ± 0.38	-0.04 ± 0.37	-0.05 ± 0.36	NA
Males	-0.11 ± .43	-0.30 ± 0.51	-0.15 ± 0.44	-0.05 ± 0.39	-0.03 ± 0.38	-0.02 ± 0.38	-0.05 ± 0.38	NA
Length velocity (cm/month)	0.94 ± 0.59	1.29 ± 0.70	1.07 ± 0.58	0.95 ± 0.57	0.93 ± 0.56	0.89 ± 0.54	0.83 ± 0.50	0.72 ± 0.51
Females	0.95 ± 0.59	1.30 ± 0.70	1.08 ± 0.59	0.97 ± 0.57	0.96 ± 0.57	0.90 ± 0.55	0.84 ± 0.50	0.73 ± 0.51
Males	0.92 ± 0.58	1.29 ± 0.69	1.05 ± 0.58	0.94 ± 0.58	0.91 ± 0.55	0.87 ± 0.53	0.82 ± 0.49	0.70 ± 0.50
Weight velocity (kg/month)	0.18 ± 0.34	0.19 ± 0.30	0.18 ± 0.31	0.18 ± 0.33	0.20 ± 0.33	0.18 ± 0.35	0.17 ± 0.35	0.15 ± 0.39
Females	0.18 ± 0.33	0.20 ± 0.29	0.19 ± 0.30	0.18 ± 0.32	0.19 ± 0.32	0.18 ± 0.34	0.17 ± 0.34	0.15 ± 0.38

Males	0.18 ± 0.35	0.18 ± 0.31	0.18 ± 0.33	0.17 ± 0.33	0.20 ± 0.33	0.17 ± 0.35	0.18 ± 0.35	0.16 ± 0.39
Illness in last two weeks	33,389 (32.74)	6,615 (41.42)	5,389 (38.23)	4,710 (33.42)	4,526 (32.32)	4,288 (30.88)	3,776 (26.55)	4,081 (25.98)
Females	15,940 (31.74)	3,124 (39.89)	2,542 (36.77)	2,266 (32.59)	2,181 (31.77)	2,061 (30.09)	1,826 (26.04)	1,938 (24.86)
Males	17,493 (33.65)	3,491 (42.89)	2,847 (39.64)	2,444 (34.23)	2,345 (32.85)	2,227 (31.64)	1,950 (27.03)	2,187 (26.94)
Current fever	5,483 (5.38)	1,306 (8.18)	854 (6.06)	769 (5.46)	712 (5.08)	641 (4.62)	509 (3.58)	692 (4.41)
Females	2,549 (5.08)	595 (7.60)	382 (5.53)	355 (5.11)	346 (5.04)	297 (4.34)	242 (3.45)	332 (4.26)
Males	2,945 (5.67)	711 (8.74)	472 (6.57)	414 (5.80)	366 (5.13)	344 (4.89)	267 (3.70)	371 (4.57)
Current diarrhea	4,265 (4.18)	942 (5.90)	853 (6.05)	730 (5.18)	567 (4.05)	445 (3.20)	341 (2.40)	386 (2.46)
Females	1,859 (3.70)	383 (4.89)	374 (5.41)	316 (4.55)	245 (3.57)	192 (2.80)	164 (2.34)	185 (2.37)
Males	2,416 (4.65)	559 (6.87)	479 (6.67)	414 (5.80)	322 (4.51)	253 (3.59)	177 (2.45)	210 (2.59)

Notes: Values are mean ± sd or n (%)

[1]Stunting defined as length-for-age z-score < -2

[2]Wasting defined as weight-for-length z-score < -2

Table 2. Relationship between attained size at study end and total number of wasted or stunted months

	End LAZ	Adjusted End LAZ	End WLZ	Adjusted End WLZ
Total # wasted months	-0.060***	-0.023***		
	(-0.061, -0.059)	*(-0.024, -0.022)*		
Start LAZ		0.672***		
		(0.669, 0.676)		
Total # stunted months			-0.025***	-0.015***
			(-0.026, -0.024)	*(-0.016, -0.014)*
Start WLZ				0.475***
				(0.470, 0.479)
Study arm (ref=CSB+)				
CSWB		-0.154***		-0.059***
		(-0.165, -0.143)		*(-0.073, -0.046)*
SC+		0.062***		-0.086***
		(0.052, 0.073)		*(-0.100, -0.073)*
RUSF		-0.024***		-0.013*
		(-0.035, -0.013)		*(-0.026, 0.001)*
Total # illness episodes		-0.008***		-0.018***
		(-0.009, -0.007)		*(-0.019, -0.017)*
End month (ref=March)				
April		-0.180**		-0.129
		(-0.324, -0.037)		*(-0.304, 0.046)*
May		0.014		-0.318***
		(-0.121, 0.149)		*(-0.483, -0.153)*
June		0.100		-0.285***
		(-0.034, 0.235)		*(-0.450, -0.120)*
July		0.024		-0.042
		(-0.111, 0.159)		*(-0.206, 0.123)*
August		0.089		0.044
		(-0.046, 0.224)		*(-0.121, 0.208)*
September		0.159**		-0.007
		(0.024, 0.294)		*(-0.171, 0.158)*
October		0.170**		-0.168**
		(0.035, 0.304)		*(-0.333, -0.003)*

November		0.215***		-0.183**
		(0.081, 0.350)		*(-0.347, -0.018)*
December		0.264***		-0.026
		(0.129, 0.399)		*(-0.190, 0.139)*
Constant	-1.206***	-0.966***	-0.688***	-0.196**
	(-1.212, -1.200)	*(-1.101, -0.831)*	*(-0.694, -0.682)*	*(-0.361, -0.031)*
Observations	108,802	108,012	108,802	108,012
R-squared	0.076	0.590	0.032	0.330

Notes: Values are coefficients (95% confidence intervals) from ordinary least squares regression models; *** p<0.01, ** p<0.05, * p<0.1. LAZ = length-for-age z-scores, WLZ = weight-for-length z-scores

Figures

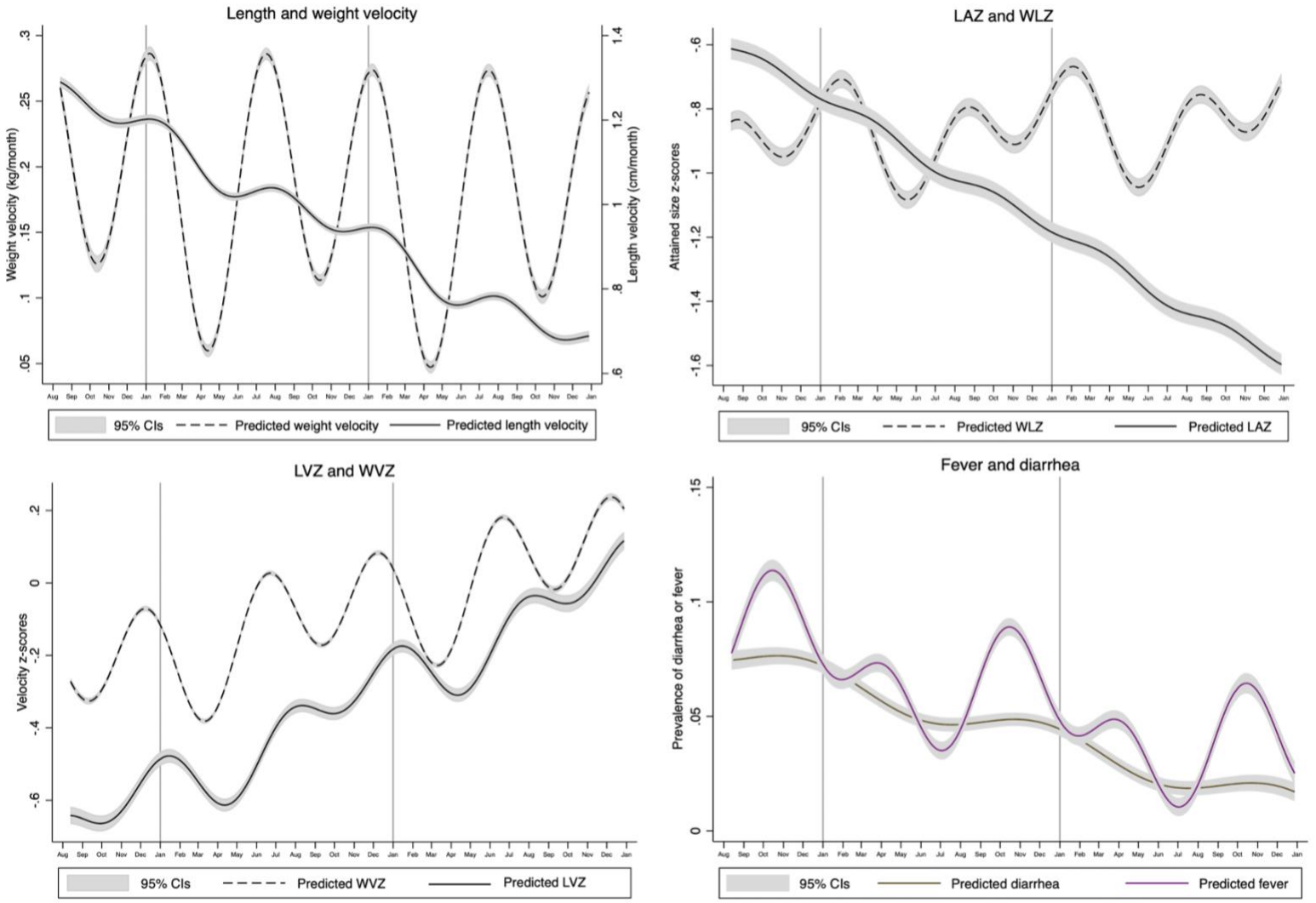

Figure 1. Seasonality of linear and ponderal growth indicators and morbidity indicators based on model predictions from harmonic regression models

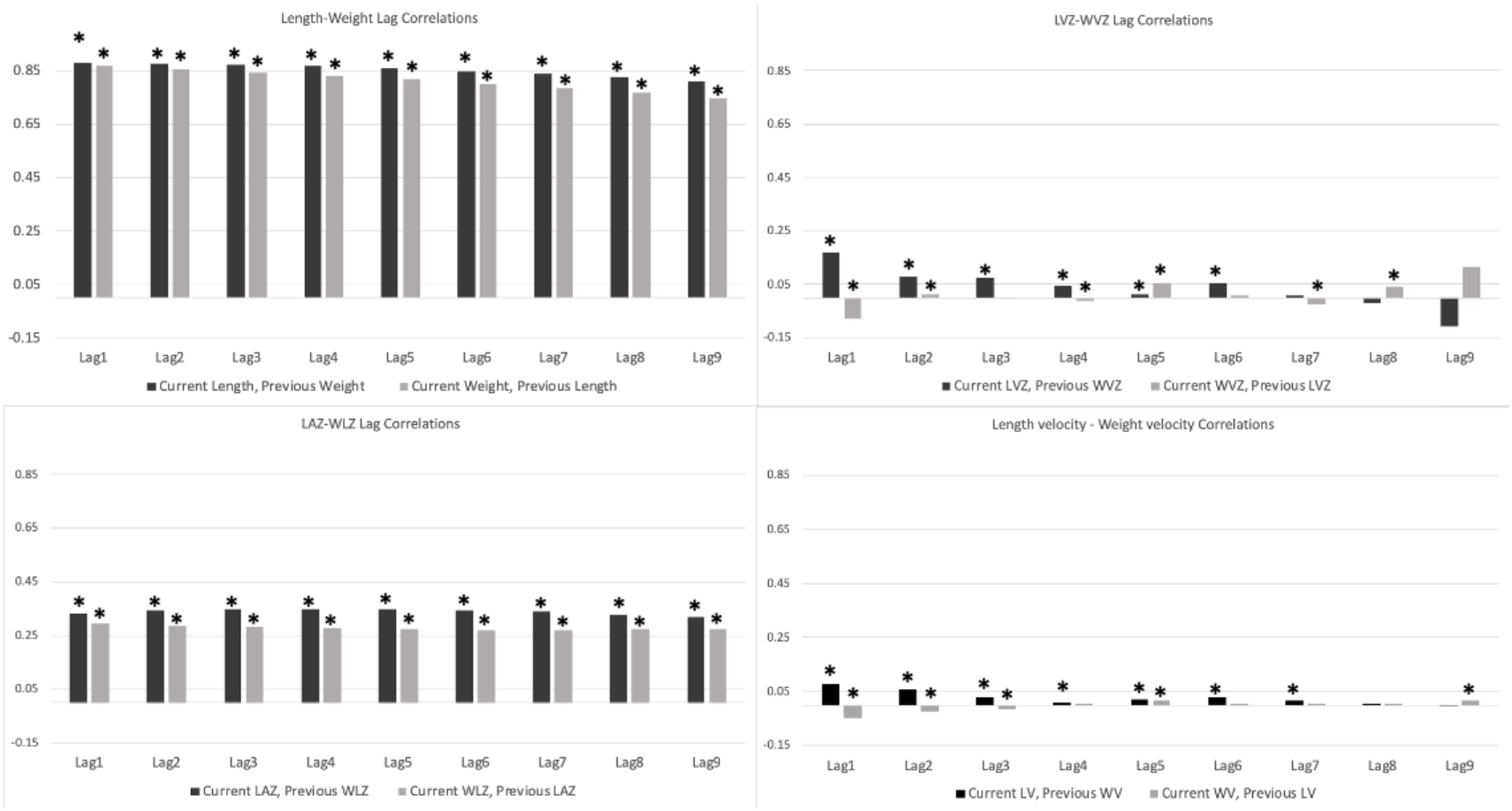

Figure 2. Correlations between length and weight indicators at different lag periods. Values are Pearson Correlation Coefficients. LAZ = length-for-age z-score; WLZ = weight-for-length z-score; LVZ = length velocity z-score; WVZ = weight velocity z-score. *p<0.05.

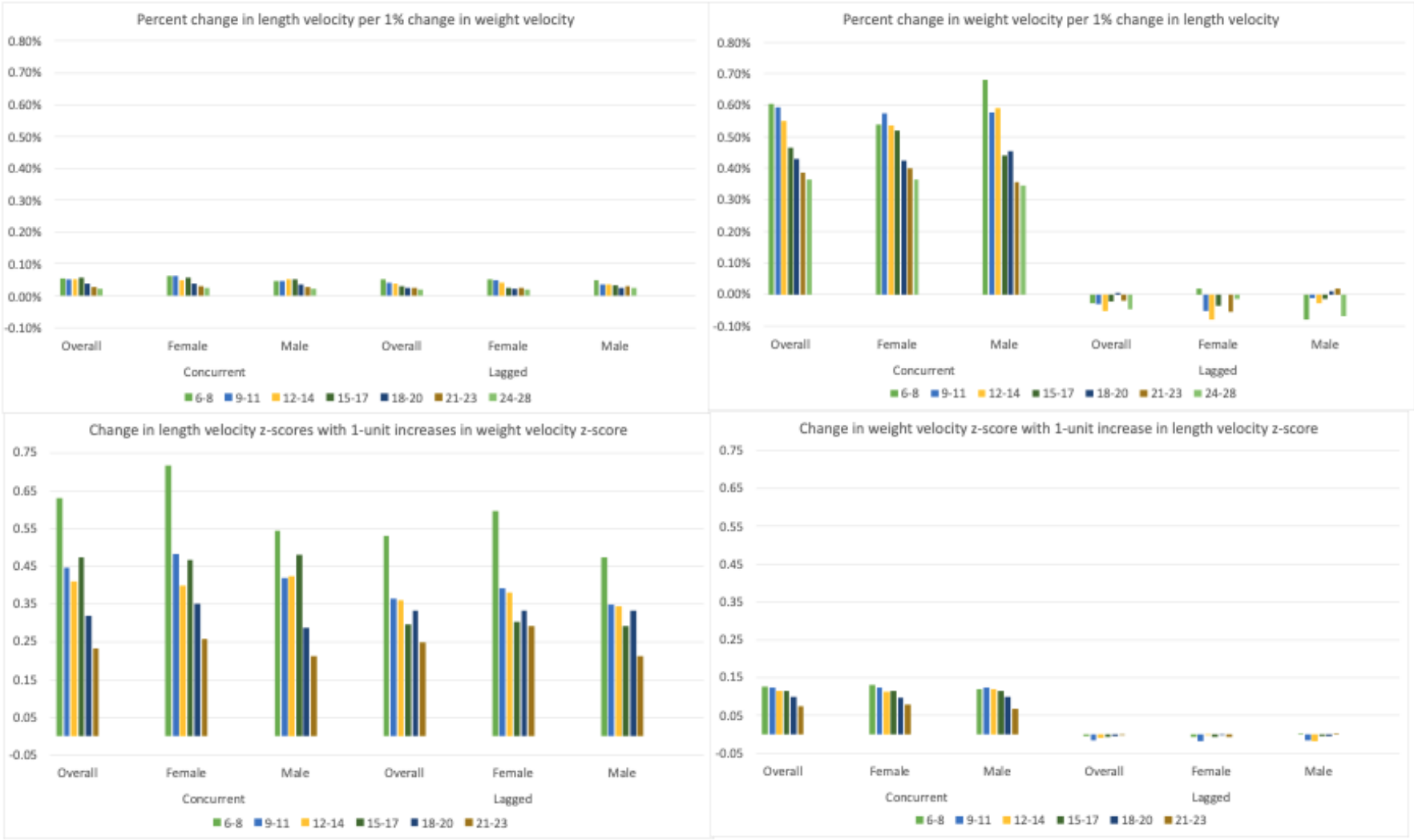

Figure 3. Relationships between linear and ponderal growth velocity by age and sex

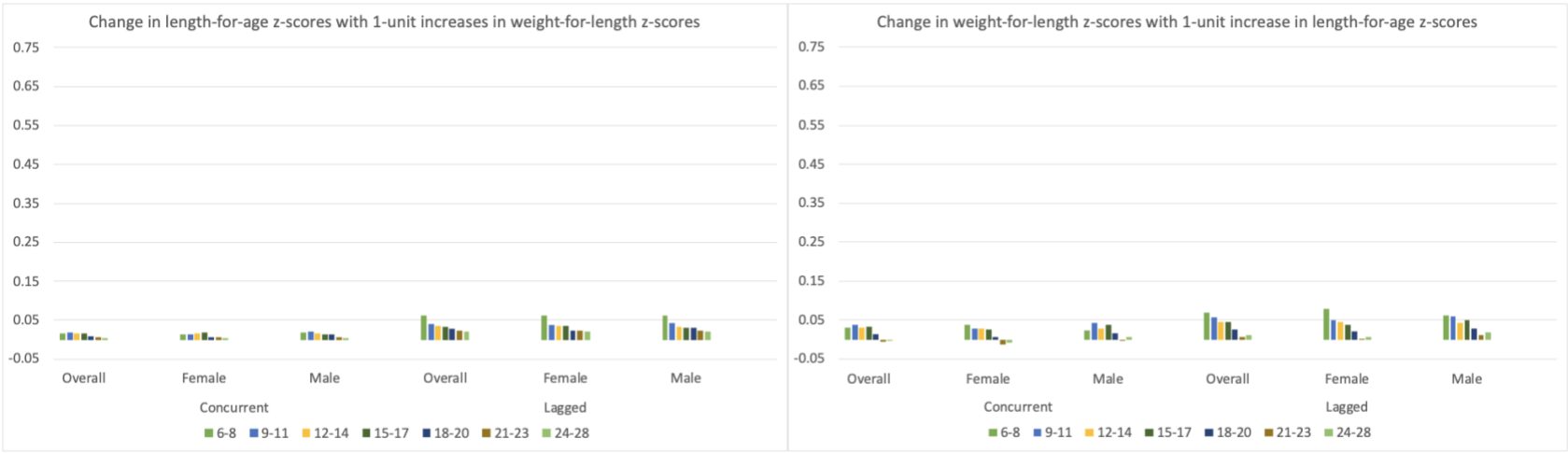

Figure 4. Relationships between linear and ponderal attained size indicators by age and sex

Supplemental Tables

Supplemental Table 1. Length velocity as predictor, concurrent weight velocity as outcome

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23	Concurrent 24-28
Weight velocity (kg/month)	0.207***	0.365***	0.308***	0.277***	0.259***	0.185***	0.134***	0.103***
	(0.00542)	(0.0277)	(0.0160)	(0.0149)	(0.0144)	(0.0133)	(0.0123)	(0.0104)
Length velocity lag 1	-0.151***	-0.190***	-0.155***	-0.157***	-0.174***	-0.182***	-0.141***	-0.134***
	(0.00311)	(0.0112)	(0.00784)	(0.00803)	(0.00801)	(0.00802)	(0.00791)	(0.00792)
Time (days)	-0.000769***	-0.00172***	-4.84e-05	-0.000697***	9.41e-05	0.000116	-0.000220	0.000370
	(9.94e-06)	(0.000542)	(0.000162)	(0.000158)	(0.000151)	(0.000149)	(0.000141)	(0.000245)
Sin(2π(day/365.25))	-0.00541**	0.00499	-0.00717	-0.0552***	0.00544	-0.00256	-0.0279**	0.0475*
	(0.00254)	(0.0266)	(0.0136)	(0.0149)	(0.0126)	(0.0137)	(0.0117)	(0.0244)
Cos(2π(day/365.25))	0.0342***	-0.163***	0.0119	0.132***	0.0168	0.0345***	-0.0233*	0.0363***
	(0.00252)	(0.0531)	(0.0154)	(0.0131)	(0.0142)	(0.0126)	(0.0132)	(0.0130)
Sin(4π(day/365.25))	0.0269***	0.129***	0.0693***	0.0354***	0.000794	-0.00519	0.0230***	0.0450***
	(0.00246)	(0.0193)	(0.00748)	(0.00732)	(0.00701)	(0.00692)	(0.00640)	(0.00900)
Cos(4π(day/365.25))	-0.00573**	-0.118***	-0.0458***	0.0112	0.000939	-0.00729	0.0155*	0.0309***
	(0.00258)	(0.0192)	(0.00982)	(0.00940)	(0.00913)	(0.00885)	(0.00834)	(0.00921)
CSWB arm	-0.0616***	-0.117***	-0.0212	-0.0320**	-0.00643	-0.0229*	-0.0320***	-0.0807***
	(0.00578)	(0.0233)	(0.0136)	(0.0132)	(0.0128)	(0.0126)	(0.0117)	(0.0112)
SC+ arm	-0.0213***	-0.00986	0.0280**	-0.0345***	0.0121	0.0154	0.0285**	-0.0195*
	(0.00565)	(0.0219)	(0.0133)	(0.0129)	(0.0125)	(0.0123)	(0.0114)	(0.0111)
RUSF arm	-0.0161***	-0.0142	0.00810	-0.0126	0.0181	-0.00310	0.00913	-0.0675***
	(0.00587)	(0.0215)	(0.0137)	(0.0132)	(0.0128)	(0.0126)	(0.0117)	(0.0118)
Illness in previous 2 weeks	-0.0472***	-0.0340**	-0.0483***	-0.0470***	-0.0414***	-0.0471***	-0.0434***	-0.0328***
	(0.00400)	(0.0169)	(0.0103)	(0.0101)	(0.00985)	(0.00985)	(0.00952)	(0.00921)
Constant	1.444***	1.853***	1.216***	1.399***	1.037***	0.991***	1.080***	0.591***
	(0.00784)	(0.116)	(0.0478)	(0.0597)	(0.0704)	(0.0831)	(0.0914)	(0.175)
Observations	92,369	6,216	14,015	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,432	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 2. Length velocity as outcome, concurrent weight velocity as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23	Concurrent Girls 24-28
Weight velocity (kg/month)	0.223***	0.397***	0.355***	0.269***	0.287***	0.192***	0.149***	0.114***
	(0.00796)	(0.0415)	(0.0242)	(0.0216)	(0.0209)	(0.0193)	(0.0180)	(0.0154)
Length velocity lag 1	-0.153***	-0.187***	-0.161***	-0.154***	-0.180***	-0.195***	-0.140***	-0.141***
	(0.00443)	(0.0163)	(0.0112)	(0.0113)	(0.0114)	(0.0114)	(0.0112)	(0.0113)
Time (days)	-0.000762***	-0.00168**	-0.000336	-0.000442**	0.000114	-0.000173	-0.000164	0.000429
	(1.43e-05)	(0.000764)	(0.000229)	(0.000220)	(0.000215)	(0.000211)	(0.000202)	(0.000361)
Sin(2π(day/365.25))	-0.00658*	0.0167	-0.0156	-0.0428**	-0.0111	0.0206	-0.0306*	0.0562
	(0.00366)	(0.0370)	(0.0195)	(0.0207)	(0.0182)	(0.0194)	(0.0170)	(0.0359)
Cos(2π(day/365.25))	0.0320***	-0.166**	-0.00469	0.108***	0.0236	0.000848	-0.0287	0.0256
	(0.00363)	(0.0756)	(0.0216)	(0.0186)	(0.0201)	(0.0182)	(0.0188)	(0.0193)
Sin(4π(day/365.25))	0.0310***	0.123***	0.0826***	0.0345***	0.0121	0.00343	0.0250***	0.0434***
	(0.00354)	(0.0281)	(0.0107)	(0.0103)	(0.0100)	(0.00991)	(0.00920)	(0.0131)
Cos(4π(day/365.25))	-0.00664*	-0.105***	-0.0652***	-0.00370	-0.00236	0.00694	0.0165	0.0388***
	(0.00372)	(0.0273)	(0.0141)	(0.0133)	(0.0131)	(0.0127)	(0.0120)	(0.0135)
CSWB arm	-0.0627***	-0.110***	-0.0323*	-0.0137	-0.0137	-0.0292	-0.0441***	-0.0723***
	(0.00818)	(0.0335)	(0.0196)	(0.0187)	(0.0184)	(0.0181)	(0.0169)	(0.0161)
SC+ arm	-0.0151*	0.0470	0.0282	-0.0305*	0.0152	0.0224	0.0419**	-0.0240
	(0.00803)	(0.0319)	(0.0192)	(0.0184)	(0.0181)	(0.0179)	(0.0165)	(0.0160)
RUSF arm	-0.0162*	-0.00868	-0.00211	0.00260	0.0111	-0.00749	0.00369	-0.0503***
	(0.00827)	(0.0310)	(0.0196)	(0.0187)	(0.0183)	(0.0181)	(0.0168)	(0.0169)
Illness in previous 2 weeks	-0.0489***	-0.0496**	-0.0457***	-0.0504***	-0.0448***	-0.0524***	-0.0462***	-0.0234*
	(0.00579)	(0.0246)	(0.0149)	(0.0144)	(0.0142)	(0.0143)	(0.0138)	(0.0135)
Constant	1.458***	1.816***	1.311***	1.311***	1.057***	1.191***	1.058***	0.556**
	(0.0113)	(0.164)	(0.0677)	(0.0835)	(0.100)	(0.118)	(0.131)	(0.258)
Observations	45,393	3,045	6,868	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,176	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 3. Length velocity as outcome, concurrent weight velocity as predictor, males

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23	Concurrent Boys 24-28
Weight velocity (kg/month)	0.194***	0.339***	0.270***	0.284***	0.233***	0.178***	0.122***	0.0946***
	(0.00739)	(0.0372)	(0.0212)	(0.0205)	(0.0198)	(0.0182)	(0.0168)	(0.0142)
Length velocity lag 1	-0.148***	-0.193***	-0.151***	-0.162***	-0.172***	-0.172***	-0.143***	-0.127***
	(0.00435)	(0.0155)	(0.0109)	(0.0114)	(0.0112)	(0.0113)	(0.0111)	(0.0111)
Time (days)	-0.000770***	-0.00171**	0.000261	-0.000969***	9.13e-05	0.000375*	-0.000275	0.000313
	(1.38e-05)	(0.000771)	(0.000230)	(0.000226)	(0.000211)	(0.000209)	(0.000197)	(0.000332)
Sin(2π(day/365.25))	-0.00472	-0.00687	0.00238	-0.0703***	0.0200	-0.0242	-0.0251	0.0387
	(0.00353)	(0.0384)	(0.0189)	(0.0215)	(0.0174)	(0.0194)	(0.0161)	(0.0333)
Cos(2π(day/365.25))	0.0361***	-0.155**	0.0311	0.156***	0.00846	0.0655***	-0.0179	0.0461***
	(0.00349)	(0.0749)	(0.0219)	(0.0185)	(0.0199)	(0.0174)	(0.0185)	(0.0176)
Sin(4π(day/365.25))	0.0228***	0.133***	0.0559***	0.0355***	-0.00923	-0.0133	0.0216**	0.0460***
	(0.00341)	(0.0267)	(0.0105)	(0.0104)	(0.00978)	(0.00964)	(0.00889)	(0.0124)
Cos(4π(day/365.25))	-0.00502	-0.131***	-0.0264*	0.0263**	0.00547	-0.0211*	0.0150	0.0229*
	(0.00359)	(0.0270)	(0.0137)	(0.0133)	(0.0127)	(0.0123)	(0.0116)	(0.0126)
CSWB arm	-0.0602***	-0.125***	-0.0122	-0.0504***	0.000973	-0.0166	-0.0199	-0.0895***
	(0.00800)	(0.0323)	(0.0189)	(0.0185)	(0.0178)	(0.0174)	(0.0161)	(0.0155)
SC+ arm	-0.0263***	-0.0614**	0.0281	-0.0385**	0.0101	0.00966	0.0163	-0.0152
	(0.00779)	(0.0300)	(0.0184)	(0.0181)	(0.0173)	(0.0170)	(0.0157)	(0.0153)
RUSF arm	-0.0167**	-0.0188	0.0170	-0.0286	0.0242	0.000273	0.0144	-0.0854***
	(0.00818)	(0.0298)	(0.0190)	(0.0187)	(0.0179)	(0.0175)	(0.0162)	(0.0164)
Illness in previous 2 weeks	-0.0444***	-0.0203	-0.0478***	-0.0423***	-0.0370***	-0.0415***	-0.0403***	-0.0396***
	(0.00552)	(0.0234)	(0.0142)	(0.0142)	(0.0136)	(0.0135)	(0.0131)	(0.0126)
Constant	1.427***	1.876***	1.117***	1.495***	1.013***	0.812***	1.103***	0.623***
	(0.0108)	(0.165)	(0.0676)	(0.0854)	(0.0984)	(0.116)	(0.127)	(0.237)
Observations	46,976	3,171	7,147	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,256	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 4. Length velocity as outcome, lagged weight velocity as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23	Lag 1 24-28
Weight velocity lag 1	0.155***	0.343***	0.244***	0.206***	0.138***	0.121***	0.124***	0.0962***
	(0.00545)	(0.0283)	(0.0160)	(0.0151)	(0.0142)	(0.0134)	(0.0121)	(0.0108)
Length velocity lag 1	-0.173***	-0.222***	-0.187***	-0.187***	-0.198***	-0.200***	-0.155***	-0.147***
	(0.00315)	(0.0114)	(0.00801)	(0.00819)	(0.00820)	(0.00816)	(0.00796)	(0.00796)
Time (days)	-0.000802***	-0.00111**	-0.000216	-0.000817***	0.000201	0.000129	-0.000276*	0.000346
	(9.98e-06)	(0.000543)	(0.000163)	(0.000159)	(0.000152)	(0.000149)	(0.000141)	(0.000245)
Sin(2π(day/365.25))	-0.00732***	-0.0184	-0.0153	-0.0662***	-0.00722	-0.00716	-0.0330***	0.0459*
	(0.00255)	(0.0266)	(0.0137)	(0.0150)	(0.0127)	(0.0138)	(0.0117)	(0.0244)
Cos(2π(day/365.25))	0.0363***	-0.102*	-0.00265	0.148***	0.0117	0.0404***	-0.0289**	0.0374***
	(0.00252)	(0.0532)	(0.0154)	(0.0132)	(0.0143)	(0.0126)	(0.0132)	(0.0130)
Sin(4π(day/365.25))	0.0214***	0.102***	0.0654***	0.0283***	-0.00465	-0.0118*	0.0175***	0.0419***
	(0.00250)	(0.0196)	(0.00760)	(0.00747)	(0.00718)	(0.00704)	(0.00646)	(0.00903)
Cos(4π(day/365.25))	0.0100***	-0.100***	-0.0286***	0.0374***	0.0272***	0.00758	0.0212**	0.0389***
	(0.00255)	(0.0191)	(0.00982)	(0.00935)	(0.00907)	(0.00879)	(0.00831)	(0.00916)
CSWB arm	-0.0637***	-0.109***	-0.0244*	-0.0343***	-0.00582	-0.0255**	-0.0327***	-0.0809***
	(0.00594)	(0.0233)	(0.0137)	(0.0132)	(0.0129)	(0.0126)	(0.0117)	(0.0112)
SC+ arm	-0.0216***	0.00165	0.0252*	-0.0315**	0.0140	0.0154	0.0287**	-0.0196*
	(0.00581)	(0.0219)	(0.0134)	(0.0130)	(0.0126)	(0.0124)	(0.0114)	(0.0111)
RUSF arm	-0.0162***	-0.0176	0.00780	-0.0104	0.0216*	-0.00332	0.00929	-0.0678***
	(0.00603)	(0.0215)	(0.0137)	(0.0133)	(0.0129)	(0.0127)	(0.0117)	(0.0118)
Illness in previous 2 weeks	-0.0828***	-0.0810***	-0.0960***	-0.0947***	-0.0813***	-0.0790***	-0.0640***	-0.0538***
	(0.00390)	(0.0165)	(0.0100)	(0.00983)	(0.00965)	(0.00962)	(0.00931)	(0.00895)
Constant	1.503***	1.781***	1.328***	1.503***	1.044***	1.023***	1.135***	0.625***
	(0.00775)	(0.117)	(0.0476)	(0.0598)	(0.0709)	(0.0834)	(0.0912)	(0.174)
Observations	92,369	6,216	14,015	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,432	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 5. Length velocity as outcome, lagged weight velocity as predictor, females

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23	Lag 1 Girls 24-28
Weight velocity lag 1	0.154***	0.341***	0.284***	0.218***	0.121***	0.112***	0.117***	0.0902***
	(0.00804)	(0.0430)	(0.0246)	(0.0216)	(0.0210)	(0.0196)	(0.0179)	(0.0158)
Length velocity lag 1	-0.177***	-0.218***	-0.197***	-0.187***	-0.206***	-0.214***	-0.156***	-0.154***
	(0.00451)	(0.0166)	(0.0115)	(0.0115)	(0.0118)	(0.0116)	(0.0113)	(0.0114)
Time (days)	-0.000798***	-0.000964	-0.000481**	-0.000581***	0.000215	-0.000153	-0.000218	0.000400
	(1.44e-05)	(0.000768)	(0.000230)	(0.000221)	(0.000217)	(0.000212)	(0.000202)	(0.000361)
Sin(2π(day/365.25))	-0.00882**	-0.00764	-0.0250	-0.0550***	-0.0233	0.0153	-0.0365**	0.0536
	(0.00367)	(0.0371)	(0.0196)	(0.0208)	(0.0184)	(0.0195)	(0.0170)	(0.0359)
Cos(2π(day/365.25))	0.0350***	-0.0956	-0.0130	0.125***	0.0222	0.00781	-0.0337*	0.0275
	(0.00364)	(0.0759)	(0.0217)	(0.0187)	(0.0203)	(0.0183)	(0.0188)	(0.0193)
Sin(4π(day/365.25))	0.0267***	0.0963***	0.0745***	0.0272***	0.00952	-0.00149	0.0211**	0.0418***
	(0.00361)	(0.0286)	(0.0109)	(0.0105)	(0.0103)	(0.0101)	(0.00931)	(0.0131)
Cos(4π(day/365.25))	0.0101***	-0.0867***	-0.0452***	0.0228*	0.0265**	0.0206	0.0246**	0.0474***
	(0.00367)	(0.0274)	(0.0141)	(0.0132)	(0.0131)	(0.0127)	(0.0120)	(0.0135)
CSWB arm	-0.0650***	-0.0902***	-0.0363*	-0.0169	-0.0158	-0.0303*	-0.0453***	-0.0724***
	(0.00845)	(0.0338)	(0.0197)	(0.0188)	(0.0186)	(0.0182)	(0.0169)	(0.0162)
SC+ arm	-0.0154*	0.0554*	0.0260	-0.0278	0.0178	0.0236	0.0420**	-0.0245
	(0.00829)	(0.0320)	(0.0194)	(0.0185)	(0.0183)	(0.0179)	(0.0166)	(0.0161)
RUSF arm	-0.0155*	-0.0122	-0.00120	0.00450	0.0171	-0.00747	0.00450	-0.0498***
	(0.00854)	(0.0311)	(0.0197)	(0.0188)	(0.0185)	(0.0182)	(0.0168)	(0.0170)
Illness in previous 2 weeks	-0.0846***	-0.0921***	-0.0958***	-0.0937***	-0.0871***	-0.0837***	-0.0664***	-0.0463***
	(0.00566)	(0.0242)	(0.0145)	(0.0140)	(0.0140)	(0.0140)	(0.0136)	(0.0131)
Constant	1.523***	1.722***	1.423***	1.421***	1.078***	1.221***	1.116***	0.597**
	(0.0111)	(0.165)	(0.0675)	(0.0835)	(0.102)	(0.119)	(0.131)	(0.258)
Observations	45,393	3,045	6,868	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,176	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 6. Length velocity as outcome, lagged weight velocity as predictor, males

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23	Lag 1 Boys 24-28
Weight velocity lag 1	0.156***	0.343***	0.212***	0.195***	0.154***	0.129***	0.133***	0.103***
	(0.00741)	(0.0375)	(0.0210)	(0.0209)	(0.0191)	(0.0184)	(0.0164)	(0.0148)
Length velocity lag 1	-0.169***	-0.226***	-0.181***	-0.189***	-0.195***	-0.191***	-0.155***	-0.141***
	(0.00440)	(0.0157)	(0.0112)	(0.0116)	(0.0114)	(0.0114)	(0.0112)	(0.0111)
Time (days)	-0.000801***	-0.00121	6.85e-05	-0.00107***	0.000205	0.000382*	-0.000336*	0.000293
	(1.38e-05)	(0.000770)	(0.000231)	(0.000228)	(0.000212)	(0.000210)	(0.000197)	(0.000332)
Sin(2π(day/365.25))	-0.00618*	-0.0283	-0.00522	-0.0802***	0.00711	-0.0278	-0.0294*	0.0380
	(0.00354)	(0.0383)	(0.0190)	(0.0216)	(0.0175)	(0.0194)	(0.0161)	(0.0332)
Cos(2π(day/365.25))	0.0375***	-0.105	0.0113	0.171***	0.000109	0.0704***	-0.0243	0.0467***
	(0.00350)	(0.0748)	(0.0220)	(0.0186)	(0.0201)	(0.0175)	(0.0185)	(0.0176)
Sin(4π(day/365.25))	0.0162***	0.108***	0.0555***	0.0284***	-0.0173*	-0.0216**	0.0146	0.0415***
	(0.00347)	(0.0270)	(0.0106)	(0.0106)	(0.00999)	(0.00982)	(0.00897)	(0.0124)
Cos(4π(day/365.25))	0.00997***	-0.113***	-0.0117	0.0522***	0.0295**	-0.00517	0.0181	0.0306**
	(0.00353)	(0.0269)	(0.0137)	(0.0133)	(0.0125)	(0.0122)	(0.0115)	(0.0125)
CSWB arm	-0.0623***	-0.128***	-0.0149	-0.0516***	0.00347	-0.0206	-0.0202	-0.0899***
	(0.00821)	(0.0323)	(0.0190)	(0.0186)	(0.0179)	(0.0174)	(0.0161)	(0.0155)
SC+ arm	-0.0266***	-0.0473	0.0250	-0.0351*	0.0112	0.00856	0.0167	-0.0151
	(0.00800)	(0.0300)	(0.0184)	(0.0182)	(0.0174)	(0.0170)	(0.0157)	(0.0153)
RUSF arm	-0.0175**	-0.0218	0.0155	-0.0260	0.0251	1.81e-05	0.0141	-0.0866***
	(0.00839)	(0.0298)	(0.0191)	(0.0189)	(0.0180)	(0.0176)	(0.0162)	(0.0164)
Illness in previous 2 weeks	-0.0801***	-0.0716***	-0.0932***	-0.0941***	-0.0745***	-0.0739***	-0.0614***	-0.0597***
	(0.00537)	(0.0227)	(0.0138)	(0.0138)	(0.0133)	(0.0132)	(0.0128)	(0.0122)
Constant	1.481***	1.829***	1.230***	1.594***	1.009***	0.845***	1.156***	0.653***
	(0.0107)	(0.165)	(0.0673)	(0.0857)	(0.0990)	(0.117)	(0.127)	(0.236)
Observations	46,976	3,171	7,147	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,256	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 7. Weight velocity as outcome, concurrent length velocity as predictor

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23	Concurrent 24-28
Length velocity (cm/month)	0.0927***	0.0888***	0.1000***	0.104***	0.0998***	0.0867***	0.0791***	0.0764***
	(0.00184)	(0.00533)	(0.00412)	(0.00440)	(0.00450)	(0.00495)	(0.00533)	(0.00562)
Weight velocity lag 1	-0.308***	-0.271***	-0.281***	-0.289***	-0.314***	-0.330***	-0.313***	-0.334***
	(0.00308)	(0.0121)	(0.00784)	(0.00791)	(0.00758)	(0.00789)	(0.00776)	(0.00770)
Time (days)	-1.92e-05***	0.000934***	-0.000384***	-2.31e-05	0.000324***	-2.80e-05	-0.000362***	-0.000234
	(5.58e-06)	(0.000235)	(8.08e-05)	(8.47e-05)	(8.26e-05)	(8.89e-05)	(9.07e-05)	(0.000175)
Sin(2π(day/365.25))	-0.0379***	-0.0642***	-0.0607***	-0.0297***	-0.0652***	-0.0331***	-0.0781***	-0.0606***
	(0.00145)	(0.0115)	(0.00678)	(0.00798)	(0.00691)	(0.00819)	(0.00752)	(0.0175)
Cos(2π(day/365.25))	0.0235***	0.0950***	-0.0322***	0.0300***	0.0138*	0.0427***	0.00518	0.00667
	(0.00144)	(0.0230)	(0.00766)	(0.00704)	(0.00777)	(0.00753)	(0.00850)	(0.00932)
Sin(4π(day/365.25))	0.0680***	0.0529***	0.0754***	0.0681***	0.0604***	0.0533***	0.0589***	0.0752***
	(0.00143)	(0.00851)	(0.00378)	(0.00398)	(0.00390)	(0.00420)	(0.00416)	(0.00648)
Cos(4π(day/365.25))	0.0908***	0.0604***	0.0621***	0.0835***	0.110***	0.111***	0.0785***	0.0816***
	(0.00146)	(0.00825)	(0.00486)	(0.00498)	(0.00494)	(0.00524)	(0.00535)	(0.00657)
CSWB arm	-0.00909***	-0.0303***	-0.0136**	-0.00894	0.0171**	-0.00169	-0.0304***	-0.00210
	(0.00286)	(0.0101)	(0.00680)	(0.00704)	(0.00703)	(0.00751)	(0.00752)	(0.00797)
SC+ arm	-0.00317	0.0136	-0.00542	-0.00787	0.0113	0.0137*	-0.0148**	-0.0123
	(0.00279)	(0.00949)	(0.00664)	(0.00692)	(0.00686)	(0.00737)	(0.00734)	(0.00788)
RUSF arm	-0.00210	-0.000848	0.00164	0.00166	0.0218***	0.00665	-0.0310***	-0.0109
	(0.00291)	(0.00933)	(0.00682)	(0.00709)	(0.00703)	(0.00755)	(0.00753)	(0.00840)
Illness in previous 2 weeks	-0.169***	-0.137***	-0.157***	-0.169***	-0.157***	-0.167***	-0.165***	-0.213***
	(0.00220)	(0.00717)	(0.00499)	(0.00525)	(0.00526)	(0.00574)	(0.00600)	(0.00640)
Constant	0.218***	0.000801	0.296***	0.207***	0.0336	0.227***	0.468***	0.388***
	(0.00422)	(0.0512)	(0.0234)	(0.0321)	(0.0386)	(0.0496)	(0.0588)	(0.125)
Observations	92,369	6,216	14,015	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,432	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 8. Weight velocity as outcome, concurrent length velocity as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23	Concurrent Girls 24-28
Length velocity (cm/month)	0.0925***	0.0834***	0.101***	0.0996***	0.103***	0.0845***	0.0810***	0.0750***
	(0.00255)	(0.00732)	(0.00556)	(0.00614)	(0.00629)	(0.00685)	(0.00736)	(0.00780)
Weight velocity lag 1	-0.305***	-0.245***	-0.262***	-0.295***	-0.321***	-0.339***	-0.313***	-0.317***
	(0.00441)	(0.0176)	(0.0114)	(0.0111)	(0.0110)	(0.0112)	(0.0111)	(0.0109)
Time (days)	-3.89e-05***	0.000878***	-0.000333***	4.44e-05	0.000268**	6.02e-05	-0.000414***	-0.000301
	(7.80e-06)	(0.000318)	(0.000108)	(0.000116)	(0.000116)	(0.000123)	(0.000126)	(0.000252)
Sin(2π(day/365.25))	-0.0315***	-0.0557***	-0.0510***	-0.0220**	-0.0543***	-0.0274**	-0.0757***	-0.0571**
	(0.00203)	(0.0154)	(0.00923)	(0.0108)	(0.00981)	(0.0113)	(0.0106)	(0.0251)
Cos(2π(day/365.25))	0.0263***	0.0905***	-0.0227**	0.0246**	0.0201*	0.0529***	0.00295	0.0183
	(0.00202)	(0.0315)	(0.0102)	(0.00977)	(0.0108)	(0.0106)	(0.0117)	(0.0134)
Sin(4π(day/365.25))	0.0664***	0.0488***	0.0676***	0.0708***	0.0587***	0.0525***	0.0620***	0.0729***
	(0.00200)	(0.0119)	(0.00516)	(0.00548)	(0.00549)	(0.00586)	(0.00582)	(0.00915)
Cos(4π(day/365.25))	0.0887***	0.0638***	0.0655***	0.0795***	0.108***	0.0984***	0.0731***	0.0824***
	(0.00204)	(0.0112)	(0.00660)	(0.00687)	(0.00698)	(0.00736)	(0.00749)	(0.00941)
CSWB arm	-0.0113***	-0.0195	0.00117	-0.0145	0.00355	0.00285	-0.0347***	-0.0109
	(0.00400)	(0.0141)	(0.00928)	(0.00978)	(0.00991)	(0.0106)	(0.0106)	(0.0112)
SC+ arm	-0.00448	0.0103	-0.000868	-0.0132	0.00929	0.0167	-0.0143	-0.0174
	(0.00392)	(0.0133)	(0.00911)	(0.00963)	(0.00974)	(0.0104)	(0.0103)	(0.0111)
RUSF arm	0.00105	-0.00172	0.00871	-0.00437	0.0223**	0.0158	-0.0235**	-0.00681
	(0.00404)	(0.0129)	(0.00927)	(0.00979)	(0.00987)	(0.0106)	(0.0105)	(0.0118)
Illness in previous 2 weeks	-0.163***	-0.120***	-0.147***	-0.156***	-0.152***	-0.165***	-0.156***	-0.218***
	(0.00310)	(0.0101)	(0.00685)	(0.00734)	(0.00747)	(0.00815)	(0.00848)	(0.00914)
Constant	0.223***	0.0111	0.269***	0.190***	0.0577	0.177**	0.488***	0.432**
	(0.00592)	(0.0695)	(0.0316)	(0.0438)	(0.0541)	(0.0690)	(0.0818)	(0.180)
Observations	45,393	3,045	6,868	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,176	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 9. Weight velocity as outcome, concurrent length velocity as predictor, males

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23	Concurrent Boys 24-28
Length velocity (cm/month)	0.0933***	0.0946***	0.0985***	0.107***	0.0966***	0.0887***	0.0783***	0.0788***
	(0.00266)	(0.00775)	(0.00607)	(0.00631)	(0.00645)	(0.00716)	(0.00771)	(0.00807)
Weight velocity lag 1	-0.312***	-0.293***	-0.296***	-0.284***	-0.308***	-0.322***	-0.314***	-0.351***
	(0.00432)	(0.0168)	(0.0108)	(0.0112)	(0.0105)	(0.0111)	(0.0109)	(0.0108)
Time (days)	2.26e-07	0.00101***	-0.000443***	-8.46e-05	0.000383***	-0.000109	-0.000297**	-0.000171
	(7.96e-06)	(0.000347)	(0.000120)	(0.000124)	(0.000118)	(0.000128)	(0.000131)	(0.000244)
Sin(2π(day/365.25))	-0.0440***	-0.0733***	-0.0709***	-0.0367***	-0.0757***	-0.0384***	-0.0797***	-0.0642***
	(0.00208)	(0.0172)	(0.00990)	(0.0118)	(0.00972)	(0.0119)	(0.0107)	(0.0244)
Cos(2π(day/365.25))	0.0209***	0.101***	-0.0422***	0.0345***	0.00714	0.0332***	0.00867	-0.00426
	(0.00206)	(0.0336)	(0.0115)	(0.0101)	(0.0112)	(0.0107)	(0.0123)	(0.0129)
Sin(4π(day/365.25))	0.0696***	0.0562***	0.0829***	0.0655***	0.0620***	0.0540***	0.0559***	0.0778***
	(0.00204)	(0.0122)	(0.00553)	(0.00577)	(0.00556)	(0.00601)	(0.00595)	(0.00915)
Cos(4π(day/365.25))	0.0929***	0.0566***	0.0584***	0.0871***	0.112***	0.122***	0.0840***	0.0809***
	(0.00208)	(0.0121)	(0.00711)	(0.00721)	(0.00698)	(0.00746)	(0.00763)	(0.00918)
CSWB arm	-0.00704*	-0.0393***	-0.0284***	-0.00336	0.0306***	-0.00557	-0.0263**	0.00605
	(0.00408)	(0.0145)	(0.00990)	(0.0101)	(0.00996)	(0.0107)	(0.0107)	(0.0113)
SC+ arm	-0.00212	0.0169	-0.0103	-0.00292	0.0133	0.0111	-0.0157	-0.00783
	(0.00397)	(0.0135)	(0.00963)	(0.00991)	(0.00967)	(0.0104)	(0.0104)	(0.0112)
RUSF arm	-0.00545	9.16e-05	-0.00597	0.00717	0.0213**	-0.00173	-0.0384***	-0.0146
	(0.00417)	(0.0134)	(0.00998)	(0.0103)	(0.01000)	(0.0108)	(0.0108)	(0.0120)
Illness in previous 2 weeks	-0.175***	-0.151***	-0.166***	-0.180***	-0.161***	-0.170***	-0.174***	-0.208***
	(0.00311)	(0.0102)	(0.00722)	(0.00750)	(0.00740)	(0.00809)	(0.00848)	(0.00896)
Constant	0.212***	-0.0152	0.325***	0.222***	0.00763	0.273***	0.439***	0.347**
	(0.00600)	(0.0753)	(0.0346)	(0.0470)	(0.0551)	(0.0714)	(0.0845)	(0.174)
Observations	46,976	3,171	7,147	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,256	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 10. Weight velocity as outcome, lagged length velocity as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23	Lag 1 24-28
Length velocity lag 1	-0.00190	-0.00427	-0.00500	-0.00989**	-0.00510	0.000994	-0.00444	-0.0100*
	(0.00182)	(0.00505)	(0.00406)	(0.00445)	(0.00453)	(0.00492)	(0.00517)	(0.00573)
Weight velocity lag 1	-0.297***	-0.248***	-0.262***	-0.271***	-0.305***	-0.324***	-0.305***	-0.326***
	(0.00316)	(0.0125)	(0.00812)	(0.00817)	(0.00784)	(0.00809)	(0.00787)	(0.00777)
Time (days)	-7.94e-05***	0.000794***	-0.000390***	-0.000107	0.000342***	-1.16e-05	-0.000383***	-0.000208
	(5.66e-06)	(0.000240)	(8.26e-05)	(8.62e-05)	(8.40e-05)	(8.99e-05)	(9.14e-05)	(0.000176)
Sin(2π(day/365.25))	-0.0390***	-0.0649***	-0.0610***	-0.0368***	-0.0658***	-0.0344***	-0.0805***	-0.0572***
	(0.00147)	(0.0118)	(0.00693)	(0.00813)	(0.00703)	(0.00829)	(0.00758)	(0.0176)
Cos(2π(day/365.25))	0.0265***	0.0807***	-0.0313***	0.0447***	0.0150*	0.0468***	0.00288	0.00952
	(0.00146)	(0.0236)	(0.00783)	(0.00716)	(0.00790)	(0.00761)	(0.00857)	(0.00937)
Sin(4π(day/365.25))	0.0698***	0.0641***	0.0821***	0.0708***	0.0598***	0.0522***	0.0603***	0.0784***
	(0.00145)	(0.00869)	(0.00385)	(0.00405)	(0.00397)	(0.00424)	(0.00419)	(0.00651)
Cos(4π(day/365.25))	0.0921***	0.0544***	0.0609***	0.0879***	0.113***	0.111***	0.0802***	0.0846***
	(0.00148)	(0.00848)	(0.00498)	(0.00508)	(0.00502)	(0.00530)	(0.00539)	(0.00661)
CSWB arm	-0.0142***	-0.0386***	-0.0157**	-0.0124*	0.0167**	-0.00363	-0.0329***	-0.00820
	(0.00290)	(0.0103)	(0.00694)	(0.00718)	(0.00715)	(0.00760)	(0.00757)	(0.00801)
SC+ arm	-0.00483*	0.0139	-0.00308	-0.0112	0.0127*	0.0148**	-0.0127*	-0.0138*
	(0.00283)	(0.00970)	(0.00678)	(0.00705)	(0.00698)	(0.00745)	(0.00740)	(0.00793)
RUSF arm	-0.00348	-0.00234	0.00261	0.000555	0.0238***	0.00615	-0.0304***	-0.0161*
	(0.00295)	(0.00954)	(0.00696)	(0.00723)	(0.00715)	(0.00763)	(0.00758)	(0.00844)
Illness in previous 2 weeks	-0.177***	-0.144***	-0.166***	-0.178***	-0.165***	-0.173***	-0.170***	-0.217***
	(0.00222)	(0.00732)	(0.00507)	(0.00533)	(0.00534)	(0.00579)	(0.00604)	(0.00643)
Constant	0.337***	0.148***	0.410***	0.353***	0.126***	0.297***	0.551***	0.435***
	(0.00423)	(0.0517)	(0.0242)	(0.0324)	(0.0392)	(0.0502)	(0.0592)	(0.126)
Observations	92,369	6,216	14,015	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,432	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 11. Weight velocity as outcome, lagged length velocity as predictor, females

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23	Lag 1 Girls 24-28
Length velocity lag 1	-0.00286	0.00273	-0.00858	-0.0146**	-0.00703	-0.000245	-0.0111	-0.00271
	(0.00253)	(0.00705)	(0.00553)	(0.00613)	(0.00640)	(0.00683)	(0.00714)	(0.00801)
Weight velocity lag 1	-0.294***	-0.228***	-0.238***	-0.275***	-0.313***	-0.335***	-0.304***	-0.311***
	(0.00453)	(0.0183)	(0.0118)	(0.0115)	(0.0114)	(0.0115)	(0.0113)	(0.0111)
Time (days)	-9.95e-05***	0.000736**	-0.000370***	-1.33e-05	0.000291**	5.74e-05	-0.000431***	-0.000270
	(7.93e-06)	(0.000325)	(0.000111)	(0.000118)	(0.000118)	(0.000125)	(0.000127)	(0.000253)
Sin(2π(day/365.25))	-0.0328***	-0.0547***	-0.0528***	-0.0275**	-0.0568***	-0.0270**	-0.0786***	-0.0529**
	(0.00206)	(0.0157)	(0.00946)	(0.0110)	(0.0100)	(0.0114)	(0.0107)	(0.0252)
Cos(2π(day/365.25))	0.0292***	0.0750**	-0.0232**	0.0369***	0.0220**	0.0548***	0.000227	0.0203
	(0.00205)	(0.0322)	(0.0104)	(0.00993)	(0.0110)	(0.0107)	(0.0118)	(0.0135)
Sin(4π(day/365.25))	0.0687***	0.0604***	0.0751***	0.0735***	0.0596***	0.0521***	0.0637***	0.0757***
	(0.00203)	(0.0121)	(0.00526)	(0.00558)	(0.00559)	(0.00592)	(0.00586)	(0.00920)
Cos(4π(day/365.25))	0.0901***	0.0617***	0.0622***	0.0821***	0.111***	0.0999***	0.0751***	0.0860***
	(0.00207)	(0.0116)	(0.00678)	(0.00700)	(0.00711)	(0.00744)	(0.00755)	(0.00946)
CSWB arm	-0.0165***	-0.0256*	-0.00209	-0.0163	0.00227	0.000706	-0.0383***	-0.0159
	(0.00406)	(0.0144)	(0.00950)	(0.00996)	(0.0101)	(0.0107)	(0.0106)	(0.0113)
SC+ arm	-0.00566	0.0148	0.00140	-0.0160	0.0114	0.0184*	-0.0109	-0.0194*
	(0.00398)	(0.0136)	(0.00933)	(0.00981)	(0.00992)	(0.0105)	(0.0104)	(0.0112)
RUSF arm	-0.000191	-0.00260	0.00887	-0.00399	0.0238**	0.0151	-0.0232**	-0.0103
	(0.00410)	(0.0132)	(0.00949)	(0.00997)	(0.0101)	(0.0107)	(0.0106)	(0.0118)
Illness in previous 2 weeks	-0.170***	-0.127***	-0.156***	-0.165***	-0.161***	-0.171***	-0.161***	-0.222***
	(0.00314)	(0.0102)	(0.00699)	(0.00745)	(0.00760)	(0.00823)	(0.00855)	(0.00919)
Constant	0.345***	0.141**	0.398***	0.328***	0.156***	0.259***	0.577***	0.468***
	(0.00593)	(0.0702)	(0.0325)	(0.0443)	(0.0552)	(0.0699)	(0.0824)	(0.181)
Observations	45,393	3,045	6,868	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,176	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 12. Weight velocity as outcome, lagged length velocity as predictor, males

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23	Lag 1 Boys 24-28
Length velocity lag 1	-0.000787	-0.0109	-0.00177	-0.00529	-0.00321	0.00201	0.00353	-0.0162**
	(0.00261)	(0.00722)	(0.00594)	(0.00644)	(0.00644)	(0.00708)	(0.00748)	(0.00819)
Weight velocity lag 1	-0.301***	-0.265***	-0.281***	-0.268***	-0.298***	-0.316***	-0.306***	-0.342***
	(0.00441)	(0.0173)	(0.0112)	(0.0116)	(0.0108)	(0.0114)	(0.0110)	(0.0109)
Time (days)	-5.99e-05***	0.000864**	-0.000414***	-0.000199	0.000397***	-7.46e-05	-0.000322**	-0.000144
	(8.08e-06)	(0.000355)	(0.000123)	(0.000126)	(0.000120)	(0.000130)	(0.000131)	(0.000245)
Sin(2π(day/365.25))	-0.0451***	-0.0755***	-0.0697***	-0.0459***	-0.0748***	-0.0414***	-0.0817***	-0.0608**
	(0.00210)	(0.0176)	(0.0101)	(0.0120)	(0.00987)	(0.0120)	(0.0107)	(0.0246)
Cos(2π(day/365.25))	0.0239***	0.0870**	-0.0396***	0.0516***	0.00757	0.0392***	0.00663	-0.000715
	(0.00208)	(0.0344)	(0.0117)	(0.0103)	(0.0113)	(0.0108)	(0.0124)	(0.0130)
Sin(4π(day/365.25))	0.0710***	0.0675***	0.0887***	0.0680***	0.0602***	0.0522***	0.0570***	0.0813***
	(0.00207)	(0.0124)	(0.00563)	(0.00589)	(0.00564)	(0.00608)	(0.00600)	(0.00920)
Cos(4π(day/365.25))	0.0942***	0.0472***	0.0592***	0.0934***	0.115***	0.122***	0.0854***	0.0831***
	(0.00211)	(0.0124)	(0.00728)	(0.00735)	(0.00708)	(0.00754)	(0.00769)	(0.00923)
CSWB arm	-0.0120***	-0.0504***	-0.0296***	-0.00828	0.0310***	-0.00728	-0.0277***	-0.00127
	(0.00413)	(0.0149)	(0.0101)	(0.0103)	(0.0101)	(0.0108)	(0.0108)	(0.0114)
SC+ arm	-0.00418	0.0128	-0.00774	-0.00669	0.0143	0.0118	-0.0147	-0.00904
	(0.00402)	(0.0138)	(0.00981)	(0.0101)	(0.00982)	(0.0105)	(0.0105)	(0.0112)
RUSF arm	-0.00702*	-0.00195	-0.00440	0.00450	0.0236**	-0.00208	-0.0378***	-0.0216*
	(0.00422)	(0.0137)	(0.0102)	(0.0105)	(0.0102)	(0.0109)	(0.0108)	(0.0120)
Illness in previous 2 weeks	-0.183***	-0.158***	-0.175***	-0.190***	-0.168***	-0.176***	-0.178***	-0.213***
	(0.00315)	(0.0104)	(0.00732)	(0.00763)	(0.00750)	(0.00816)	(0.00853)	(0.00900)
Constant	0.329***	0.150**	0.423***	0.378***	0.0942*	0.331***	0.516***	0.399**
	(0.00602)	(0.0761)	(0.0358)	(0.0475)	(0.0559)	(0.0723)	(0.0850)	(0.175)
Observations	46,976	3,171	7,147	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,256	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 13. Length velocity z-score as outcome, concurrent weight velocity z-score as predictor

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23
Weight velocity z-score	0.453***	0.629***	0.446***	0.410***	0.472***	0.318***	0.232***
	(0.00863)	(0.0328)	(0.0190)	(0.0192)	(0.0196)	(0.0190)	(0.0204)
Length velocity z-score lag 1	-0.196***	-0.0956***	-0.323***	-0.330***	-0.257***	-0.285***	-0.267***
	(0.00365)	(0.0131)	(0.00794)	(0.00790)	(0.00829)	(0.00823)	(0.00911)
Time (days)	0.00107***	-0.00112**	0.000703***	4.30e-05	0.000832***	0.00125***	-0.000385
	(2.23e-05)	(0.000528)	(0.000266)	(0.000252)	(0.000235)	(0.000226)	(0.000256)
Sin(2π(day/365.25))	-0.00220	0.0752***	-0.0639***	-0.0651***	-0.00914	-0.0486**	-0.0663***
	(0.00476)	(0.0284)	(0.0221)	(0.0239)	(0.0200)	(0.0211)	(0.0190)
Cos(2π(day/365.25))	0.0400***	-0.0782	0.0906***	0.0568***	-0.0195	0.0374*	-0.0555**
	(0.00463)	(0.0525)	(0.0252)	(0.0209)	(0.0222)	(0.0194)	(0.0248)
Sin(4π(day/365.25))	0.0688***	0.140***	0.106***	0.0611***	0.0571***	0.0209**	2.30e-05
	(0.00461)	(0.0214)	(0.0119)	(0.0115)	(0.0109)	(0.0107)	(0.0108)
Cos(4π(day/365.25))	-0.00218	0.0361*	0.0216	-0.00199	-0.0112	-0.0386***	0.000190
	(0.00474)	(0.0193)	(0.0151)	(0.0141)	(0.0137)	(0.0128)	(0.0129)
CSWB arm	-0.0483***	-0.0698	0.00132	-0.0970***	-0.0417	-0.0672**	-0.0814***
	(0.0137)	(0.0470)	(0.0311)	(0.0293)	(0.0275)	(0.0272)	(0.0307)
SC+ arm	0.0557***	-0.0182	0.0517*	-0.0336	0.0633**	0.105***	0.0638**
	(0.0132)	(0.0426)	(0.0302)	(0.0289)	(0.0267)	(0.0262)	(0.0296)
RUSF arm	0.0313**	-0.0616	0.0759**	0.00952	0.0478*	0.0552**	0.00139
	(0.0137)	(0.0430)	(0.0312)	(0.0297)	(0.0273)	(0.0271)	(0.0307)
Illness in previous 2 weeks	-0.121***	0.00298	-0.0744***	-0.101***	-0.0999***	-0.103***	-0.0553***
	(0.00729)	(0.0177)	(0.0161)	(0.0154)	(0.0153)	(0.0151)	(0.0147)
Constant	-0.835***	-0.264**	-0.848***	-0.600***	-0.723***	-0.953***	0.0798
	(0.0143)	(0.117)	(0.0771)	(0.0953)	(0.110)	(0.127)	(0.164)
Observations	62,750	4,717	11,966	12,011	11,967	11,958	10,131
Number of groups	4,989	3,363	4,489	4,448	4,445	4,474	4,370

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 14. Length velocity z-score as outcome, concurrent weight velocity z-score as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23
Weight velocity z-score	0.478***	0.717***	0.481***	0.397***	0.465***	0.350***	0.257***
	(0.0126)	(0.0481)	(0.0279)	(0.0272)	(0.0281)	(0.0279)	(0.0303)
Length velocity z-score lag 1	-0.197***	-0.169***	-0.321***	-0.344***	-0.241***	-0.296***	-0.265***
	(0.00518)	(0.0193)	(0.0112)	(0.0111)	(0.0118)	(0.0118)	(0.0129)
Time (days)	0.00108***	-0.000621	0.000319	6.90e-05	0.00102***	0.00116***	3.94e-05
	(3.21e-05)	(0.000716)	(0.000374)	(0.000355)	(0.000330)	(0.000321)	(0.000367)
Sin(2π(day/365.25))	-0.00141	0.0841**	-0.0727**	-0.0656*	-0.0443	-0.0184	-0.0436
	(0.00685)	(0.0384)	(0.0317)	(0.0336)	(0.0284)	(0.0299)	(0.0276)
Cos(2π(day/365.25))	0.0330***	0.0109	0.0457	0.0675**	-0.0296	0.00819	-0.0450
	(0.00670)	(0.0723)	(0.0353)	(0.0299)	(0.0311)	(0.0280)	(0.0355)
Sin(4π(day/365.25))	0.0696***	0.109***	0.132***	0.0736***	0.0604***	0.0349**	-0.00524
	(0.00665)	(0.0303)	(0.0169)	(0.0163)	(0.0155)	(0.0153)	(0.0156)
Cos(4π(day/365.25))	0.00219	0.0473*	0.0186	-0.00845	0.00869	-0.0348*	0.0208
	(0.00685)	(0.0266)	(0.0216)	(0.0199)	(0.0195)	(0.0185)	(0.0187)
CSWB arm	-0.0396**	-0.0888	0.0269	-0.0481	-0.0401	-0.0677*	-0.108**
	(0.0195)	(0.0671)	(0.0444)	(0.0433)	(0.0386)	(0.0392)	(0.0455)
SC+ arm	0.0739***	0.0171	0.0806*	-0.0214	0.0827**	0.116***	0.0963**
	(0.0190)	(0.0615)	(0.0435)	(0.0430)	(0.0378)	(0.0380)	(0.0440)
RUSF arm	0.0311	-0.0696	0.0429	0.0582	0.0428	0.0531	0.00419
	(0.0194)	(0.0610)	(0.0444)	(0.0435)	(0.0382)	(0.0390)	(0.0450)
Illness in previous 2 weeks	-0.125***	-0.0106	-0.0912***	-0.0898***	-0.0946***	-0.115***	-0.0679***
	(0.0106)	(0.0258)	(0.0234)	(0.0222)	(0.0219)	(0.0220)	(0.0213)
Constant	-0.852***	-0.385**	-0.773***	-0.655***	-0.816***	-0.911***	-0.199
	(0.0205)	(0.160)	(0.109)	(0.135)	(0.155)	(0.180)	(0.236)
Observations	30,886	2,287	5,855	5,945	5,920	5,923	4,956
Number of groups	2,456	1,635	2,215	2,195	2,203	2,220	2,138

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 15. Length velocity z-score as outcome, concurrent weight velocity z-score as predictor, males

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23
Weight velocity z-score	0.430***	0.544***	0.418***	0.424***	0.479***	0.286***	0.212***
	(0.0118)	(0.0450)	(0.0260)	(0.0270)	(0.0275)	(0.0258)	(0.0275)
Length velocity z-score lag 1	-0.195***	-0.0313*	-0.322***	-0.315***	-0.273***	-0.275***	-0.269***
	(0.00513)	(0.0178)	(0.0113)	(0.0112)	(0.0116)	(0.0115)	(0.0128)
Time (days)	0.00107***	-0.00155**	0.00116***	1.65e-05	0.000668**	0.00135***	-0.000779**
	(3.09e-05)	(0.000771)	(0.000380)	(0.000357)	(0.000336)	(0.000319)	(0.000356)
Sin(2π(day/365.25))	-0.00333	0.0658	-0.0522*	-0.0645*	0.0251	-0.0790***	-0.0878***
	(0.00661)	(0.0419)	(0.0309)	(0.0339)	(0.0282)	(0.0298)	(0.0260)
Cos(2π(day/365.25))	0.0466***	-0.161**	0.142***	0.0491*	-0.0107	0.0654**	-0.0642*
	(0.00642)	(0.0756)	(0.0361)	(0.0293)	(0.0317)	(0.0270)	(0.0346)
Sin(4π(day/365.25))	0.0680***	0.167***	0.0778***	0.0502***	0.0535***	0.00697	0.00547
	(0.00638)	(0.0298)	(0.0166)	(0.0161)	(0.0154)	(0.0149)	(0.0150)
Cos(4π(day/365.25))	-0.00687	0.0264	0.0263	0.00378	-0.0301	-0.0425**	-0.0179
	(0.00655)	(0.0277)	(0.0211)	(0.0199)	(0.0192)	(0.0178)	(0.0178)
CSWB arm	-0.0563***	-0.0624	-0.0237	-0.143***	-0.0446	-0.0651*	-0.0564
	(0.0191)	(0.0656)	(0.0434)	(0.0397)	(0.0392)	(0.0377)	(0.0412)
SC+ arm	0.0382**	-0.0361	0.0224	-0.0466	0.0450	0.0948***	0.0343
	(0.0184)	(0.0587)	(0.0418)	(0.0388)	(0.0376)	(0.0361)	(0.0397)
RUSF arm	0.0325*	-0.0526	0.109**	-0.0398	0.0527	0.0586	-0.00150
	(0.0193)	(0.0604)	(0.0436)	(0.0406)	(0.0392)	(0.0377)	(0.0418)
Illness in previous 2 weeks	-0.117***	0.0141	-0.0608***	-0.110***	-0.104***	-0.0907***	-0.0423**
	(0.0100)	(0.0241)	(0.0222)	(0.0215)	(0.0214)	(0.0207)	(0.0201)
Constant	-0.820***	-0.175	-0.940***	-0.545***	-0.638***	-0.997***	0.339
	(0.0199)	(0.170)	(0.109)	(0.135)	(0.157)	(0.179)	(0.228)
Observations	31,864	2,430	6,111	6,066	6,047	6,035	5,175
Number of groups	2,533	1,728	2,274	2,253	2,242	2,254	2,232

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 16. Length velocity z-score as outcome, lagged weight velocity z-score as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23
Weight velocity z-score lag 1	0.375***	0.530***	0.365***	0.360***	0.295***	0.333***	0.249***
	(0.00848)	(0.0341)	(0.0178)	(0.0186)	(0.0199)	(0.0192)	(0.0202)
Length velocity z-score lag 1	-0.258***	-0.183***	-0.390***	-0.396***	-0.312***	-0.335***	-0.291***
	(0.00374)	(0.0139)	(0.00811)	(0.00806)	(0.00855)	(0.00838)	(0.00920)
Time (days)	0.00106***	-0.000583	0.000787***	-0.000282	0.00109***	0.00146***	-0.000538**
	(2.26e-05)	(0.000536)	(0.000267)	(0.000252)	(0.000238)	(0.000226)	(0.000256)
Sin(2π(day/365.25))	-0.00670	0.00752	-0.0506**	-0.110***	-0.0389*	-0.0652***	-0.0670***
	(0.00478)	(0.0287)	(0.0222)	(0.0238)	(0.0202)	(0.0210)	(0.0189)
Cos(2π(day/365.25))	0.0123***	-0.0859	0.0802***	0.0633***	-0.0619***	0.0261	-0.0903***
	(0.00466)	(0.0534)	(0.0253)	(0.0209)	(0.0225)	(0.0194)	(0.0247)
Sin(4π(day/365.25))	-0.0243***	0.0752***	0.0223*	-0.0326***	-0.0294***	-0.0554***	-0.0371***
	(0.00470)	(0.0218)	(0.0121)	(0.0117)	(0.0112)	(0.0107)	(0.0110)
Cos(4π(day/365.25))	0.0369***	0.0416**	0.0725***	0.0490***	0.0330**	-0.0247*	0.0176
	(0.00467)	(0.0196)	(0.0149)	(0.0138)	(0.0136)	(0.0127)	(0.0128)
CSWB arm	-0.0575***	-0.0525	-0.00369	-0.0890***	-0.0557*	-0.0712***	-0.0902***
	(0.0143)	(0.0476)	(0.0317)	(0.0300)	(0.0284)	(0.0274)	(0.0305)
SC+ arm	0.0543***	-0.0267	0.0384	-0.0219	0.0665**	0.109***	0.0614**
	(0.0138)	(0.0430)	(0.0308)	(0.0296)	(0.0275)	(0.0264)	(0.0295)
RUSF arm	0.0318**	-0.0604	0.0739**	0.0239	0.0584**	0.0409	0.00363
	(0.0143)	(0.0435)	(0.0318)	(0.0304)	(0.0282)	(0.0274)	(0.0306)
Illness in previous 2 weeks	-0.0815***	0.0283	-0.0380**	-0.0660***	-0.0584***	-0.0735***	-0.0501***
	(0.00737)	(0.0181)	(0.0162)	(0.0155)	(0.0155)	(0.0151)	(0.0147)
Constant	-0.860***	-0.333***	-0.899***	-0.534***	-0.879***	-1.081***	0.163
	(0.0147)	(0.119)	(0.0773)	(0.0956)	(0.112)	(0.126)	(0.164)
Observations	62,750	4,717	11,966	12,011	11,967	11,958	10,131
Number of groups	4,989	3,363	4,489	4,448	4,445	4,474	4,370

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 17. Length velocity z-scores as outcome, lagged weight velocity z-scores as predictor, females

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23
Weight velocity z-score lag 1	0.389***	0.595***	0.391***	0.380***	0.302***	0.331***	0.292***
	(0.0126)	(0.0519)	(0.0269)	(0.0269)	(0.0284)	(0.0280)	(0.0302)
Length velocity z-score lag 1	-0.260***	-0.267***	-0.399***	-0.411***	-0.290***	-0.343***	-0.292***
	(0.00533)	(0.0206)	(0.0115)	(0.0113)	(0.0121)	(0.0120)	(0.0130)
Time (days)	0.00107***	-0.000296	0.000322	-0.000293	0.00128***	0.00134***	-5.98e-05
	(3.26e-05)	(0.000728)	(0.000375)	(0.000356)	(0.000333)	(0.000321)	(0.000367)
Sin(2π(day/365.25))	-0.00777	0.0290	-0.0739**	-0.116***	-0.0647**	-0.0396	-0.0392
	(0.00688)	(0.0388)	(0.0318)	(0.0335)	(0.0287)	(0.0298)	(0.0276)
Cos(2π(day/365.25))	0.00827	0.00158	0.0358	0.0739**	-0.0671**	-0.00299	-0.0765**
	(0.00674)	(0.0735)	(0.0354)	(0.0298)	(0.0315)	(0.0280)	(0.0354)
Sin(4π(day/365.25))	-0.0237***	0.0444	0.0404**	-0.0229	-0.0268*	-0.0392**	-0.0454***
	(0.00681)	(0.0310)	(0.0173)	(0.0166)	(0.0158)	(0.0154)	(0.0159)
Cos(4π(day/365.25))	0.0454***	0.0481*	0.0648***	0.0490**	0.0515***	-0.0174	0.0429**
	(0.00676)	(0.0271)	(0.0213)	(0.0195)	(0.0195)	(0.0183)	(0.0185)
CSWB arm	-0.0519**	-0.0233	0.0134	-0.0456	-0.0467	-0.0789**	-0.123***
	(0.0204)	(0.0686)	(0.0457)	(0.0443)	(0.0396)	(0.0395)	(0.0452)
SC+ arm	0.0739***	0.000181	0.0788*	-0.00950	0.0936**	0.121***	0.0889**
	(0.0199)	(0.0627)	(0.0448)	(0.0441)	(0.0388)	(0.0383)	(0.0437)
RUSF arm	0.0326	-0.0793	0.0511	0.0639	0.0574	0.0357	0.00966
	(0.0203)	(0.0622)	(0.0457)	(0.0445)	(0.0392)	(0.0394)	(0.0447)
Illness in previous 2 weeks	-0.0814***	0.0139	-0.0496**	-0.0467**	-0.0541**	-0.0891***	-0.0593***
	(0.0107)	(0.0263)	(0.0235)	(0.0221)	(0.0222)	(0.0221)	(0.0214)
Constant	-0.883***	-0.416**	-0.811***	-0.576***	-0.982***	-1.022***	-0.148
	(0.0210)	(0.163)	(0.109)	(0.135)	(0.157)	(0.180)	(0.235)
Observations	30,886	2,287	5,855	5,945	5,920	5,923	4,956
Number of groups	2,456	1,635	2,215	2,195	2,203	2,220	2,138

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 18. Length velocity z-scores as outcome, lagged weight velocity z-scores as predictor, males

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23
Weight velocity z-score lag 1	0.365***	0.473***	0.347***	0.343***	0.292***	0.333***	0.211***
	(0.0115)	(0.0454)	(0.0237)	(0.0258)	(0.0279)	(0.0263)	(0.0272)
Length velocity z-score lag 1	-0.255***	-0.109***	-0.381***	-0.381***	-0.333***	-0.326***	-0.290***
	(0.00524)	(0.0188)	(0.0115)	(0.0115)	(0.0120)	(0.0117)	(0.0130)
Time (days)	0.00106***	-0.000837	0.00130***	-0.000264	0.000906***	0.00158***	-0.000973***
	(3.14e-05)	(0.000783)	(0.000380)	(0.000359)	(0.000339)	(0.000317)	(0.000356)
Sin(2π(day/365.25))	-0.00594	-0.0100	-0.0276	-0.102***	-0.0141	-0.0904***	-0.0927***
	(0.00663)	(0.0422)	(0.0310)	(0.0340)	(0.0284)	(0.0296)	(0.0260)
Cos(2π(day/365.25))	0.0162**	-0.164**	0.131***	0.0553*	-0.0575*	0.0544**	-0.101***
	(0.00644)	(0.0767)	(0.0362)	(0.0294)	(0.0320)	(0.0269)	(0.0345)
Sin(4π(day/365.25))	-0.0253***	0.104***	0.000217	-0.0410**	-0.0327**	-0.0704***	-0.0286*
	(0.00650)	(0.0304)	(0.0169)	(0.0164)	(0.0157)	(0.0149)	(0.0152)
Cos(4π(day/365.25))	0.0286***	0.0333	0.0810***	0.0488**	0.0153	-0.0319*	-0.00419
	(0.00646)	(0.0281)	(0.0208)	(0.0196)	(0.0191)	(0.0176)	(0.0177)
CSWB arm	-0.0629***	-0.0800	-0.0214	-0.128***	-0.0657	-0.0628*	-0.0600
	(0.0200)	(0.0658)	(0.0438)	(0.0406)	(0.0407)	(0.0380)	(0.0412)
SC+ arm	0.0357*	-0.0410	0.000149	-0.0349	0.0406	0.0981***	0.0355
	(0.0193)	(0.0589)	(0.0422)	(0.0397)	(0.0391)	(0.0364)	(0.0396)
RUSF arm	0.0323	-0.0448	0.0988**	-0.0169	0.0594	0.0471	-0.00252
	(0.0202)	(0.0605)	(0.0440)	(0.0415)	(0.0407)	(0.0380)	(0.0417)
Illness in previous 2 weeks	-0.0816***	0.0371	-0.0288	-0.0845***	-0.0618***	-0.0600***	-0.0399**
	(0.0101)	(0.0245)	(0.0223)	(0.0216)	(0.0217)	(0.0206)	(0.0201)
Constant	-0.839***	-0.270	-1.000***	-0.495***	-0.782***	-1.140***	0.448**
	(0.0204)	(0.172)	(0.109)	(0.135)	(0.159)	(0.177)	(0.228)
Observations	31,864	2,430	6,111	6,066	6,047	6,035	5,175
Number of groups	2,533	1,728	2,274	2,253	2,242	2,254	2,232

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 19. Weight velocity z-score as outcome, concurrent length velocity z-score as predictor

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23
Length velocity z-score	0.120***	0.126***	0.123***	0.115***	0.115***	0.0983***	0.0745***
	(0.00163)	(0.00549)	(0.00355)	(0.00350)	(0.00355)	(0.00370)	(0.00417)
Weight velocity z-score lag 1	-0.300***	-0.272***	-0.373***	-0.400***	-0.385***	-0.408***	-0.404***
	(0.00354)	(0.0142)	(0.00737)	(0.00765)	(0.00800)	(0.00813)	(0.00881)
Time (days)	0.000297***	0.000443***	0.000960***	0.000283***	0.000402***	0.000352***	-0.000242**
	(9.32e-06)	(0.000169)	(0.000114)	(0.000106)	(9.76e-05)	(9.78e-05)	(0.000113)
Sin(2π(day/365.25))	-0.0828***	-0.0628***	-0.0159*	-0.0608***	-0.108***	-0.0943***	-0.0773***
	(0.00204)	(0.00929)	(0.00941)	(0.0100)	(0.00827)	(0.00910)	(0.00836)
Cos(2π(day/365.25))	-0.0182***	-0.0192	0.0140	-0.00526	-0.0218**	0.0126	-0.0428***
	(0.00199)	(0.0169)	(0.0108)	(0.00878)	(0.00923)	(0.00838)	(0.0110)
Sin(4π(day/365.25))	-0.0523***	-0.0242***	-0.0181***	-0.0329***	-0.0513***	-0.0492***	-0.00497
	(0.00203)	(0.00700)	(0.00517)	(0.00494)	(0.00461)	(0.00468)	(0.00488)
Cos(4π(day/365.25))	0.100***	0.0266***	0.124***	0.105***	0.113***	0.0998***	0.0960***
	(0.00201)	(0.00614)	(0.00638)	(0.00593)	(0.00567)	(0.00558)	(0.00566)
CSWB arm	-0.00739	-0.0320	-0.0250**	0.00740	0.0152	-0.0161	-0.0553***
	(0.00464)	(0.0210)	(0.0126)	(0.0112)	(0.0109)	(0.0108)	(0.0131)
SC+ arm	0.000873	0.00305	-0.0242**	-0.00595	0.0158	0.0231**	-0.0141
	(0.00449)	(0.0190)	(0.0123)	(0.0111)	(0.0105)	(0.0104)	(0.0127)
RUSF arm	0.00758	0.0279	-0.00246	0.0247**	0.0443***	-0.00432	-0.0444***
	(0.00464)	(0.0193)	(0.0127)	(0.0114)	(0.0108)	(0.0108)	(0.0131)
Illness in previous 2 weeks	-0.00494	-0.00138	-0.00341	0.00231	0.0241***	0.00295	-0.00932
	(0.00310)	(0.00569)	(0.00691)	(0.00655)	(0.00640)	(0.00654)	(0.00649)
Constant	-0.176***	-0.274***	-0.373***	-0.150***	-0.239***	-0.218***	0.145**
	(0.00550)	(0.0388)	(0.0328)	(0.0399)	(0.0457)	(0.0547)	(0.0725)
Observations	62,959	4,720	11,984	12,057	12,011	12,010	10,177
Number of groups	4,989	3,366	4,496	4,463	4,463	4,489	4,392

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 20. Weight velocity z-score as outcome, concurrent length velocity z-score as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23
Length velocity z-score	0.118***	0.131***	0.124***	0.112***	0.114***	0.0965***	0.0799***
	(0.00226)	(0.00743)	(0.00495)	(0.00493)	(0.00505)	(0.00504)	(0.00567)
Weight velocity z-score lag 1	-0.303***	-0.260***	-0.365***	-0.420***	-0.398***	-0.407***	-0.414***
	(0.00509)	(0.0208)	(0.0109)	(0.0110)	(0.0114)	(0.0114)	(0.0126)
Time (days)	0.000216***	0.000171	0.000882***	0.000405***	0.000296**	0.000302**	-0.000141
	(1.30e-05)	(0.000217)	(0.000156)	(0.000149)	(0.000136)	(0.000133)	(0.000156)
Sin(2π(day/365.25))	-0.0716***	-0.0458***	-0.0118	-0.0541***	-0.0790***	-0.0784***	-0.0540***
	(0.00286)	(0.0119)	(0.0132)	(0.0141)	(0.0117)	(0.0124)	(0.0117)
Cos(2π(day/365.25))	-0.0109***	-0.0319	0.0168	-0.0148	-0.00388	0.0171	-0.0305**
	(0.00280)	(0.0219)	(0.0148)	(0.0125)	(0.0128)	(0.0116)	(0.0151)
Sin(4π(day/365.25))	-0.0481***	-0.0175*	-0.0179**	-0.0293***	-0.0521***	-0.0398***	0.000146
	(0.00285)	(0.00930)	(0.00728)	(0.00704)	(0.00647)	(0.00646)	(0.00679)
Cos(4π(day/365.25))	0.100***	0.0214***	0.124***	0.0983***	0.105***	0.0995***	0.0906***
	(0.00283)	(0.00799)	(0.00897)	(0.00839)	(0.00798)	(0.00773)	(0.00790)
CSWB arm	-0.0132**	0.00148	-0.00271	-0.0124	0.0136	-0.0233	-0.0733***
	(0.00646)	(0.0294)	(0.0175)	(0.0163)	(0.0156)	(0.0151)	(0.0180)
SC+ arm	-0.000565	-0.00722	-0.00918	-0.0103	0.0206	0.0305**	-0.0195
	(0.00629)	(0.0270)	(0.0171)	(0.0162)	(0.0153)	(0.0147)	(0.0174)
RUSF arm	0.00657	-0.00671	0.00783	0.0164	0.0439***	-0.00291	-0.0257
	(0.00642)	(0.0268)	(0.0174)	(0.0163)	(0.0155)	(0.0150)	(0.0177)
Illness in previous 2 weeks	-0.00421	-0.00986	0.000901	0.0145	0.0198**	-0.0162*	-0.00375
	(0.00439)	(0.00780)	(0.00984)	(0.00939)	(0.00908)	(0.00919)	(0.00911)
Constant	-0.134***	-0.162***	-0.334***	-0.184***	-0.191***	-0.197***	0.0736
	(0.00768)	(0.0506)	(0.0454)	(0.0562)	(0.0638)	(0.0747)	(0.100)
Observations	30,984	2,290	5,866	5,964	5,943	5,944	4,977
Number of groups	2,456	1,638	2,219	2,198	2,213	2,227	2,148

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 20. Weight velocity z-score as outcome, concurrent length velocity z-score as predictor, females

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23
Length velocity z-score	0.121***	0.120***	0.124***	0.119***	0.116***	0.0992***	0.0687***
	(0.00235)	(0.00801)	(0.00509)	(0.00496)	(0.00499)	(0.00542)	(0.00609)
Weight velocity z-score lag 1	-0.300***	-0.291***	-0.383***	-0.382***	-0.372***	-0.411***	-0.395***
	(0.00494)	(0.0193)	(0.0100)	(0.0106)	(0.0113)	(0.0116)	(0.0123)
Time (days)	0.000376***	0.000741***	0.00102***	0.000180	0.000506***	0.000406***	-0.000345**
	(1.33e-05)	(0.000261)	(0.000165)	(0.000151)	(0.000140)	(0.000143)	(0.000164)
Sin(2π(day/365.25))	-0.0938***	-0.0813***	-0.0206	-0.0656***	-0.137***	-0.111***	-0.100***
	(0.00291)	(0.0144)	(0.0134)	(0.0143)	(0.0117)	(0.0133)	(0.0119)
Cos(2π(day/365.25))	-0.0250***	-0.00483	0.0106	0.00243	-0.0396***	0.00851	-0.0546***
	(0.00282)	(0.0257)	(0.0157)	(0.0123)	(0.0133)	(0.0121)	(0.0159)
Sin(4π(day/365.25))	-0.0559***	-0.0292***	-0.0176**	-0.0360***	-0.0508***	-0.0576***	-0.00955
	(0.00287)	(0.0104)	(0.00735)	(0.00694)	(0.00657)	(0.00677)	(0.00698)
Cos(4π(day/365.25))	0.100***	0.0299***	0.125***	0.109***	0.121***	0.0994***	0.101***
	(0.00286)	(0.00935)	(0.00906)	(0.00838)	(0.00804)	(0.00804)	(0.00809)
CSWB arm	-0.00173	-0.0633**	-0.0482***	0.0274*	0.0180	-0.00849	-0.0391**
	(0.00665)	(0.0295)	(0.0180)	(0.0155)	(0.0150)	(0.0154)	(0.0190)
SC+ arm	0.00254	0.0142	-0.0380**	-0.000332	0.0120	0.0160	-0.0106
	(0.00639)	(0.0265)	(0.0174)	(0.0152)	(0.0144)	(0.0147)	(0.0183)
RUSF arm	0.00807	0.0603**	-0.0139	0.0330**	0.0453***	-0.00501	-0.0651***
	(0.00670)	(0.0274)	(0.0182)	(0.0158)	(0.0150)	(0.0154)	(0.0193)
Illness in previous 2 weeks	-0.00507	0.00636	-0.00533	-0.00920	0.0281***	0.0199**	-0.0141
	(0.00438)	(0.00820)	(0.00967)	(0.00913)	(0.00899)	(0.00929)	(0.00922)
Constant	-0.218***	-0.393***	-0.407***	-0.123**	-0.286***	-0.243***	0.217**
	(0.00787)	(0.0589)	(0.0474)	(0.0565)	(0.0654)	(0.0799)	(0.105)
Observations	31,975	2,430	6,118	6,093	6,068	6,066	5,200
Number of groups	2,533	1,728	2,277	2,265	2,250	2,262	2,244

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 21. Weight velocity z-scores as outcome, lagged length velocity z-score as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23
Length velocity z-score lag 1	-0.0163***	-0.00381	-0.0166***	-0.00950***	-0.00589	-0.00330	-0.00270
	(0.00165)	(0.00592)	(0.00360)	(0.00352)	(0.00365)	(0.00372)	(0.00413)
Weight velocity z-score lag 1	-0.266***	-0.213***	-0.353***	-0.381***	-0.372***	-0.397***	-0.392***
	(0.00377)	(0.0158)	(0.00791)	(0.00817)	(0.00853)	(0.00856)	(0.00907)
Time (days)	0.000423***	0.000317*	0.00115***	0.000238**	0.000526***	0.000488***	-0.000282**
	(9.81e-06)	(0.000175)	(0.000119)	(0.000110)	(0.000102)	(0.000100)	(0.000115)
Sin(2π(day/365.25))	-0.0847***	-0.0555***	-0.0167*	-0.0749***	-0.115***	-0.102***	-0.0806***
	(0.00212)	(0.00962)	(0.00986)	(0.0104)	(0.00863)	(0.00935)	(0.00852)
Cos(2π(day/365.25))	-0.0178***	-0.0272	0.0273**	0.000332	-0.0309***	0.0163*	-0.0500***
	(0.00207)	(0.0174)	(0.0113)	(0.00911)	(0.00962)	(0.00860)	(0.0111)
Sin(4π(day/365.25))	-0.0539***	-0.0129*	-0.0107**	-0.0376***	-0.0533***	-0.0530***	-0.00675
	(0.00210)	(0.00722)	(0.00540)	(0.00512)	(0.00480)	(0.00480)	(0.00496)
Cos(4π(day/365.25))	0.107***	0.0293***	0.141***	0.114***	0.121***	0.0976***	0.0983***
	(0.00209)	(0.00635)	(0.00665)	(0.00612)	(0.00587)	(0.00571)	(0.00577)
CSWB arm	-0.0132**	-0.0412*	-0.0227*	-0.00283	0.0112	-0.0247**	-0.0578***
	(0.00537)	(0.0226)	(0.0137)	(0.0121)	(0.0117)	(0.0114)	(0.0134)
SC+ arm	0.00937*	-0.000777	-0.0161	-0.00855	0.0282**	0.0316***	-0.00812
	(0.00520)	(0.0205)	(0.0133)	(0.0119)	(0.0113)	(0.0110)	(0.0130)
RUSF arm	0.0124**	0.0219	0.00896	0.0257**	0.0539***	-0.00210	-0.0431***
	(0.00538)	(0.0208)	(0.0137)	(0.0122)	(0.0116)	(0.0114)	(0.0134)
Illness in previous 2 weeks	-0.0143***	0.00194	-0.00726	-0.00642	0.0163**	-0.00314	-0.0131**
	(0.00325)	(0.00587)	(0.00721)	(0.00679)	(0.00665)	(0.00672)	(0.00661)
Constant	-0.277***	-0.302***	-0.503***	-0.192***	-0.333***	-0.314***	0.155**
	(0.00598)	(0.0403)	(0.0343)	(0.0414)	(0.0477)	(0.0561)	(0.0737)
Observations	63,028	4,724	12,000	12,065	12,026	12,020	10,193
Number of groups	4,991	3,368	4,497	4,470	4,462	4,490	4,396

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 22. Weight velocity z-scores as outcome, lagged length velocity z-score as predictor, females

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23
Length velocity z-score lag 1	-0.0138***	-0.00572	-0.0182***	-0.00186	-0.00747	-0.00231	-0.00759
	(0.00230)	(0.00890)	(0.00499)	(0.00494)	(0.00515)	(0.00513)	(0.00560)
Weight velocity z-score lag 1	-0.267***	-0.190***	-0.342***	-0.404***	-0.378***	-0.397***	-0.396***
	(0.00543)	(0.0233)	(0.0117)	(0.0118)	(0.0120)	(0.0120)	(0.0130)
Time (days)	0.000331***	7.16e-05	0.00101***	0.000350**	0.000437***	0.000417***	-0.000165
	(1.37e-05)	(0.000227)	(0.000164)	(0.000154)	(0.000142)	(0.000137)	(0.000159)
Sin(2π(day/365.25))	-0.0737***	-0.0364***	-0.0168	-0.0670***	-0.0893***	-0.0808***	-0.0578***
	(0.00298)	(0.0125)	(0.0138)	(0.0146)	(0.0122)	(0.0128)	(0.0119)
Cos(2π(day/365.25))	-0.0109***	-0.0300	0.0244	-0.00847	-0.0143	0.0195	-0.0379**
	(0.00291)	(0.0230)	(0.0155)	(0.0129)	(0.0134)	(0.0120)	(0.0153)
Sin(4π(day/365.25))	-0.0503***	-0.00984	-0.00885	-0.0335***	-0.0547***	-0.0423***	-0.00243
	(0.00296)	(0.00972)	(0.00759)	(0.00727)	(0.00672)	(0.00664)	(0.00689)
Cos(4π(day/365.25))	0.107***	0.0255***	0.139***	0.107***	0.115***	0.0977***	0.0942***
	(0.00294)	(0.00836)	(0.00936)	(0.00864)	(0.00826)	(0.00793)	(0.00804)
CSWB arm	-0.0175**	0.00359	0.00368	-0.0179	0.00944	-0.0315**	-0.0834***
	(0.00746)	(0.0317)	(0.0191)	(0.0175)	(0.0169)	(0.0159)	(0.0185)
SC+ arm	0.00978	-0.0107	0.00222	-0.0119	0.0359**	0.0382**	-0.0136
	(0.00727)	(0.0290)	(0.0188)	(0.0174)	(0.0165)	(0.0155)	(0.0180)
RUSF arm	0.0111	-0.0153	0.0146	0.0259	0.0521***	-0.00190	-0.0304*
	(0.00743)	(0.0288)	(0.0191)	(0.0175)	(0.0167)	(0.0158)	(0.0183)
Illness in previous 2 weeks	-0.0141***	-0.00954	-0.00499	0.00820	0.0118	-0.0246***	-0.00998
	(0.00460)	(0.00816)	(0.0103)	(0.00969)	(0.00943)	(0.00946)	(0.00927)
Constant	-0.230***	-0.194***	-0.450***	-0.221***	-0.295***	-0.280***	0.0757
	(0.00835)	(0.0532)	(0.0475)	(0.0584)	(0.0665)	(0.0769)	(0.102)
Observations	31,013	2,291	5,875	5,966	5,943	5,954	4,984
Number of groups	2,457	1,638	2,220	2,201	2,209	2,226	2,153

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 23. Weight velocity z-scores as outcome, lagged length velocity z-score as predictor, males

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23
Length velocity z-score lag 1	-0.0184***	0.00112	-0.0154***	-0.0168***	-0.00508	-0.00437	0.00340
	(0.00238)	(0.00797)	(0.00519)	(0.00502)	(0.00516)	(0.00538)	(0.00606)
Weight velocity z-score lag 1	-0.269***	-0.246***	-0.365***	-0.361***	-0.365***	-0.400***	-0.390***
	(0.00523)	(0.0214)	(0.0107)	(0.0113)	(0.0121)	(0.0122)	(0.0127)
Time (days)	0.000512***	0.000609**	0.00129***	0.000141	0.000622***	0.000566***	-0.000389**
	(1.40e-05)	(0.000267)	(0.000172)	(0.000157)	(0.000146)	(0.000146)	(0.000166)
Sin(2π(day/365.25))	-0.0956***	-0.0754***	-0.0172	-0.0809***	-0.140***	-0.123***	-0.103***
	(0.00302)	(0.0148)	(0.0140)	(0.0148)	(0.0122)	(0.0137)	(0.0121)
Cos(2π(day/365.25))	-0.0242***	-0.0195	0.0305*	0.00813	-0.0480***	0.0135	-0.0610***
	(0.00293)	(0.0263)	(0.0164)	(0.0128)	(0.0138)	(0.0123)	(0.0161)
Sin(4π(day/365.25))	-0.0569***	-0.0149	-0.0123	-0.0410***	-0.0522***	-0.0625***	-0.0109
	(0.00298)	(0.0106)	(0.00767)	(0.00721)	(0.00684)	(0.00692)	(0.00710)
Cos(4π(day/365.25))	0.106***	0.0315***	0.143***	0.120***	0.127***	0.0970***	0.103***
	(0.00296)	(0.00959)	(0.00945)	(0.00867)	(0.00834)	(0.00819)	(0.00826)
CSWB arm	-0.00911	-0.0810**	-0.0498**	0.0117	0.0143	-0.0172	-0.0342*
	(0.00772)	(0.0317)	(0.0195)	(0.0167)	(0.0162)	(0.0162)	(0.0193)
SC+ arm	0.00911	0.0108	-0.0327*	-0.00454	0.0217	0.0251	-0.00444
	(0.00744)	(0.0285)	(0.0188)	(0.0163)	(0.0155)	(0.0156)	(0.0186)
RUSF arm	0.0132*	0.0565*	0.00284	0.0254	0.0567***	-0.00155	-0.0576***
	(0.00779)	(0.0294)	(0.0196)	(0.0170)	(0.0161)	(0.0163)	(0.0196)
Illness in previous 2 weeks	-0.0140***	0.0117	-0.00749	-0.0207**	0.0205**	0.0160*	-0.0158*
	(0.00458)	(0.00837)	(0.0101)	(0.00950)	(0.00935)	(0.00952)	(0.00940)
Constant	-0.323***	-0.421***	-0.554***	-0.168***	-0.375***	-0.351***	0.229**
	(0.00856)	(0.0607)	(0.0495)	(0.0588)	(0.0684)	(0.0816)	(0.107)
Observations	32,015	2,433	6,125	6,099	6,083	6,066	5,209
Number of groups	2,534	1,730	2,277	2,269	2,253	2,264	2,243

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 24. Length-for-age z-score as outcome, concurrent weight-for-length z-score as predictor

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23	Concurrent 24-28
Weight-for-length z-score	0.0129***	0.0166***	0.0180***	0.0158***	0.0164***	0.00975***	0.00530***	0.00399***
	(0.000741)	(0.00287)	(0.00216)	(0.00203)	(0.00191)	(0.00177)	(0.00156)	(0.00136)
Length-for-age z-score lag 1	0.971***	0.951***	0.962***	0.970***	0.976***	0.980***	0.980***	0.980***
	(0.000694)	(0.00280)	(0.00209)	(0.00193)	(0.00176)	(0.00162)	(0.00141)	(0.00126)
Time (days)	8.61e-05***	0.000331**	8.62e-05	-0.000203***	0.000169***	0.000130**	-1.43e-05	0.000181**
	(3.58e-06)	(0.000135)	(6.90e-05)	(6.36e-05)	(5.62e-05)	(5.16e-05)	(4.63e-05)	(7.58e-05)
Sin(2π(day/365.25))	-0.000403	-0.0390***	0.00731	-0.0193***	-0.00762	-0.00705	-0.00725*	0.0165**
	(0.000962)	(0.0101)	(0.00578)	(0.00600)	(0.00470)	(0.00476)	(0.00384)	(0.00757)
Cos(2π(day/365.25))	0.0142***	0.0453***	0.00334	0.0446***	-0.00639	0.0171***	-0.00736*	0.00708*
	(0.000969)	(0.0121)	(0.00658)	(0.00529)	(0.00528)	(0.00438)	(0.00434)	(0.00403)
Sin(4π(day/365.25))	0.0126***	0.0371***	0.0338***	0.0134***	0.000139	-0.00247	0.00747***	0.0117***
	(0.000940)	(0.00492)	(0.00322)	(0.00294)	(0.00262)	(0.00241)	(0.00211)	(0.00279)
Cos(4π(day/365.25))	0.00246**	-0.0475***	-0.00804*	0.0225***	0.0116***	0.00252	0.00675**	0.0135***
	(0.000970)	(0.00679)	(0.00417)	(0.00374)	(0.00336)	(0.00304)	(0.00273)	(0.00284)
CSWB arm	-0.00943***	-0.0253***	-0.00181	-0.00585	0.00125	-0.00983**	-0.00958**	-0.0188***
	(0.00191)	(0.00821)	(0.00588)	(0.00530)	(0.00478)	(0.00437)	(0.00384)	(0.00344)
SC+ arm	0.00521***	0.00533	0.0171***	-0.00956*	0.00783*	0.00648	0.0105***	-0.00368
	(0.00187)	(0.00788)	(0.00576)	(0.00521)	(0.00468)	(0.00429)	(0.00376)	(0.00342)
RUSF arm	-0.00127	0.000746	0.00909	-0.00455	0.00740	-0.00334	0.00267	-0.0189***
	(0.00194)	(0.00794)	(0.00590)	(0.00533)	(0.00478)	(0.00439)	(0.00385)	(0.00363)
Illness in previous 2 weeks	-0.0282***	-0.0347***	-0.0378***	-0.0334***	-0.0269***	-0.0242***	-0.0179***	-0.0146***
	(0.00147)	(0.00594)	(0.00434)	(0.00398)	(0.00360)	(0.00336)	(0.00308)	(0.00279)
Constant	-0.0829***	-0.129***	-0.108***	0.0305	-0.105***	-0.0803***	-0.0103	-0.157***
	(0.00231)	(0.0272)	(0.0197)	(0.0238)	(0.0262)	(0.0288)	(0.0300)	(0.0541)
Observations	97,168	10,935	14,095	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,908	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 26. Length-for-age z-score as outcome, concurrent weight-for-length z-score as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23	Concurrent Girls 24-28
Weight-for-length z-score	0.0118***	0.0140***	0.0131***	0.0165***	0.0185***	0.00531**	0.00565**	0.00432**
	(0.00107)	(0.00424)	(0.00315)	(0.00287)	(0.00271)	(0.00252)	(0.00225)	(0.00196)
Length-for-age z-score lag 1	0.970***	0.944***	0.958***	0.968***	0.977***	0.982***	0.982***	0.982***
	(0.00102)	(0.00413)	(0.00309)	(0.00281)	(0.00257)	(0.00240)	(0.00207)	(0.00186)
Time (days)	7.94e-05***	6.90e-05	-5.09e-05	-0.000108	0.000186**	5.50e-05	6.92e-06	0.000215**
	(4.98e-06)	(0.000183)	(9.36e-05)	(8.52e-05)	(7.65e-05)	(7.10e-05)	(6.44e-05)	(0.000109)
Sin(2π(day/365.25))	-0.000344	-0.0247*	0.00205	-0.0145*	-0.0145**	-0.000184	-0.00718	0.0215**
	(0.00133)	(0.0136)	(0.00800)	(0.00799)	(0.00649)	(0.00651)	(0.00542)	(0.0108)
Cos(2π(day/365.25))	0.0132***	0.0178	-0.00243	0.0348***	-0.00533	0.00876	-0.00865	0.00351
	(0.00134)	(0.0166)	(0.00888)	(0.00721)	(0.00716)	(0.00611)	(0.00599)	(0.00581)
Sin(4π(day/365.25))	0.0145***	0.0487***	0.0357***	0.0138***	0.00374	7.90e-05	0.00835***	0.0119***
	(0.00130)	(0.00681)	(0.00443)	(0.00398)	(0.00357)	(0.00334)	(0.00295)	(0.00394)
Cos(4π(day/365.25))	0.00149	-0.0403***	-0.0148***	0.0160***	0.0118**	0.00629	0.00758**	0.0151***
	(0.00135)	(0.00928)	(0.00574)	(0.00507)	(0.00461)	(0.00424)	(0.00382)	(0.00406)
CSWB arm	-0.00873***	-0.0236**	-0.00604	-0.000264	1.32e-05	-0.00886	-0.0129**	-0.0159***
	(0.00265)	(0.0114)	(0.00815)	(0.00723)	(0.00656)	(0.00609)	(0.00539)	(0.00484)
SC+ arm	0.00789***	0.0170	0.0153*	-0.00788	0.00926	0.00999*	0.0153***	-0.00580
	(0.00260)	(0.0110)	(0.00802)	(0.00713)	(0.00645)	(0.00602)	(0.00528)	(0.00482)
RUSF arm	-0.00140	-0.00527	0.00485	-0.00103	0.00494	-0.00235	0.00225	-0.0140***
	(0.00268)	(0.0109)	(0.00814)	(0.00723)	(0.00653)	(0.00609)	(0.00537)	(0.00508)
Illness in previous 2 weeks	-0.0292***	-0.0480***	-0.0367***	-0.0313***	-0.0264***	-0.0247***	-0.0178***	-0.0129***
	(0.00206)	(0.00826)	(0.00608)	(0.00545)	(0.00497)	(0.00475)	(0.00435)	(0.00399)
Constant	-0.0808***	-0.0767**	-0.0712***	-0.00734	-0.108***	-0.0403	-0.0240	-0.182**
	(0.00318)	(0.0368)	(0.0268)	(0.0320)	(0.0356)	(0.0396)	(0.0416)	(0.0777)
Observations	47,742	5,349	6,913	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,409	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 27. Length-for-age z-score as outcome, concurrent weight-for-length z-score as predictor, males

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23	Concurrent Boys 24-28
Weight-for-length z-score	0.0137***	0.0184***	0.0213***	0.0147***	0.0143***	0.0135***	0.00523**	0.00375**
	(0.00104)	(0.00392)	(0.00298)	(0.00288)	(0.00270)	(0.00249)	(0.00217)	(0.00190)
Length-for-age z-score lag 1	0.971***	0.955***	0.965***	0.971***	0.974***	0.978***	0.979***	0.979***
	(0.000960)	(0.00386)	(0.00287)	(0.00269)	(0.00244)	(0.00223)	(0.00194)	(0.00174)
Time (days)	9.20e-05***	0.000580***	0.000224**	-0.000302***	0.000163**	0.000202***	-3.09e-05	0.000152
	(5.14e-06)	(0.000200)	(0.000102)	(9.46e-05)	(8.23e-05)	(7.51e-05)	(6.67e-05)	(0.000106)
Sin(2π(day/365.25))	-0.000445	-0.0522***	0.0127	-0.0249***	-0.00164	-0.0136**	-0.00705	0.0120
	(0.00138)	(0.0151)	(0.00835)	(0.00898)	(0.00678)	(0.00696)	(0.00545)	(0.0106)
Cos(2π(day/365.25))	0.0153***	0.0715***	0.00974	0.0543***	-0.00850	0.0247***	-0.00571	0.0103*
	(0.00140)	(0.0176)	(0.00973)	(0.00772)	(0.00778)	(0.00627)	(0.00630)	(0.00560)
Sin(4π(day/365.25))	0.0108***	0.0261***	0.0319***	0.0128***	-0.00336	-0.00479	0.00668**	0.0115***
	(0.00135)	(0.00707)	(0.00466)	(0.00433)	(0.00382)	(0.00348)	(0.00302)	(0.00394)
Cos(4π(day/365.25))	0.00339**	-0.0544***	-0.00112	0.0290***	0.0118**	-0.00116	0.00606	0.0118***
	(0.00139)	(0.00991)	(0.00602)	(0.00550)	(0.00486)	(0.00436)	(0.00390)	(0.00397)
CSWB arm	-0.0101***	-0.0266**	0.00251	-0.0113	0.00230	-0.0105*	-0.00624	-0.0219***
	(0.00275)	(0.0118)	(0.00845)	(0.00774)	(0.00695)	(0.00625)	(0.00547)	(0.00489)
SC+ arm	0.00268	-0.00630	0.0191**	-0.0111	0.00676	0.00307	0.00592	-0.00200
	(0.00268)	(0.0113)	(0.00824)	(0.00759)	(0.00676)	(0.00611)	(0.00534)	(0.00484)
RUSF arm	-0.00115	0.00688	0.0130	-0.00815	0.00985	-0.00418	0.00326	-0.0239***
	(0.00281)	(0.0115)	(0.00853)	(0.00784)	(0.00698)	(0.00631)	(0.00551)	(0.00518)
Illness in previous 2 weeks	-0.0273***	-0.0222***	-0.0385***	-0.0353***	-0.0272***	-0.0242***	-0.0179***	-0.0162***
	(0.00210)	(0.00851)	(0.00619)	(0.00578)	(0.00519)	(0.00476)	(0.00437)	(0.00391)
Constant	-0.0852***	-0.180***	-0.146***	0.0681*	-0.108***	-0.119***	0.000933	-0.134*
	(0.00334)	(0.0400)	(0.0289)	(0.0354)	(0.0384)	(0.0418)	(0.0431)	(0.0753)
Observations	49,426	5,586	7,182	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,499	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 28. Length-for-age z-score as outcome, lagged weight-for-length z-score as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23	Lag 1 24-28
Weight-for-length z-score lag 1	0.0946***	0.0616***	0.0410***	0.0346***	0.0323***	0.0270***	0.0226***	0.0207***
	(0.00118)	(0.00276)	(0.00208)	(0.00198)	(0.00186)	(0.00176)	(0.00154)	(0.00136)
Length-for-age z-score lag 1	0.841***	0.944***	0.956***	0.964***	0.970***	0.974***	0.975***	0.976***
	(0.00150)	(0.00272)	(0.00206)	(0.00191)	(0.00174)	(0.00162)	(0.00141)	(0.00126)
Time (days)	-6.86e-05***	0.000386***	7.05e-05	-0.000210***	0.000179***	0.000125**	-2.21e-05	0.000176**
	(3.87e-06)	(0.000132)	(6.83e-05)	(6.30e-05)	(5.57e-05)	(5.13e-05)	(4.60e-05)	(7.53e-05)
Sin(2π(day/365.25))	-0.00244***	-0.0392***	0.00736	-0.0204***	-0.0106**	-0.00856*	-0.00798**	0.0162**
	(0.000899)	(0.00993)	(0.00572)	(0.00595)	(0.00466)	(0.00473)	(0.00381)	(0.00752)
Cos(2π(day/365.25))	0.00686***	0.0447***	-0.00125	0.0433***	-0.00841	0.0167***	-0.00854**	0.00601
	(0.000906)	(0.0118)	(0.00651)	(0.00524)	(0.00524)	(0.00434)	(0.00431)	(0.00400)
Sin(4π(day/365.25))	0.00563***	0.0334***	0.0334***	0.0127***	-0.000646	-0.00380	0.00623***	0.0106***
	(0.000874)	(0.00480)	(0.00317)	(0.00291)	(0.00259)	(0.00239)	(0.00209)	(0.00277)
Cos(4π(day/365.25))	0.0101***	-0.0398***	-0.00360	0.0264***	0.0159***	0.00499*	0.00891***	0.0152***
	(0.000908)	(0.00666)	(0.00413)	(0.00371)	(0.00334)	(0.00302)	(0.00271)	(0.00282)
CSWB arm	-0.000708	-0.0210***	-2.65e-06	-0.00361	0.00243	-0.00909**	-0.00855**	-0.0174***
	(0.00594)	(0.00804)	(0.00581)	(0.00526)	(0.00474)	(0.00433)	(0.00381)	(0.00342)
SC+ arm	0.0243***	0.00464	0.0163***	-0.00832	0.00866*	0.00693	0.0107***	-0.00285
	(0.00582)	(0.00772)	(0.00569)	(0.00517)	(0.00464)	(0.00426)	(0.00373)	(0.00339)
RUSF arm	0.0128**	0.00508	0.0106*	-0.00302	0.00805*	-0.00382	0.00242	-0.0185***
	(0.00604)	(0.00777)	(0.00584)	(0.00529)	(0.00474)	(0.00436)	(0.00382)	(0.00360)
Illness in previous 2 weeks	-0.0303***	-0.0339***	-0.0401***	-0.0361***	-0.0294***	-0.0251***	-0.0180***	-0.0147***
	(0.00143)	(0.00576)	(0.00425)	(0.00390)	(0.00354)	(0.00331)	(0.00304)	(0.00275)
Constant	-0.0940***	-0.120***	-0.0890***	0.0442*	-0.101***	-0.0704**	0.00151	-0.146***
	(0.00474)	(0.0266)	(0.0195)	(0.0236)	(0.0260)	(0.0286)	(0.0298)	(0.0537)
Observations	97,168	10,935	14,095	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,908	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 29. Length-for-age z-score as outcome, lagged weight-for-length z-score as predictor, females

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23	Lag 1 Girls 24-28
Weight-for-length z-score lag 1	0.0959***	0.0607***	0.0374***	0.0359***	0.0342***	0.0231***	0.0229***	0.0214***
	(0.00173)	(0.00405)	(0.00308)	(0.00280)	(0.00265)	(0.00252)	(0.00222)	(0.00195)
Length-for-age z-score lag 1	0.836***	0.938***	0.952***	0.962***	0.972***	0.976***	0.977***	0.979***
	(0.00218)	(0.00401)	(0.00305)	(0.00278)	(0.00255)	(0.00240)	(0.00208)	(0.00185)
Time (days)	-8.30e-05***	0.000124	-5.18e-05	-0.000113	0.000201***	5.80e-05	5.52e-06	0.000211*
	(5.43e-06)	(0.000179)	(9.27e-05)	(8.45e-05)	(7.58e-05)	(7.06e-05)	(6.39e-05)	(0.000108)
Sin(2π(day/365.25))	-0.00310**	-0.0246*	0.00320	-0.0154*	-0.0179***	-0.00217	-0.00729	0.0209*
	(0.00125)	(0.0133)	(0.00791)	(0.00792)	(0.00644)	(0.00648)	(0.00537)	(0.0107)
Cos(2π(day/365.25))	0.00679***	0.0182	-0.00532	0.0331***	-0.00740	0.00941	-0.00893	0.00211
	(0.00125)	(0.0163)	(0.00880)	(0.00714)	(0.00709)	(0.00607)	(0.00595)	(0.00577)
Sin(4π(day/365.25))	0.00739***	0.0456***	0.0341***	0.0133***	0.00294	-0.00134	0.00693**	0.0109***
	(0.00121)	(0.00666)	(0.00437)	(0.00393)	(0.00353)	(0.00332)	(0.00292)	(0.00390)
Cos(4π(day/365.25))	0.00878***	-0.0330***	-0.0107*	0.0200***	0.0164***	0.00776*	0.0101***	0.0166***
	(0.00126)	(0.00911)	(0.00570)	(0.00503)	(0.00458)	(0.00421)	(0.00380)	(0.00404)
CSWB arm	-0.000602	-0.0199*	-0.00421	0.00126	0.000583	-0.00772	-0.0118**	-0.0140***
	(0.00834)	(0.0112)	(0.00808)	(0.00717)	(0.00650)	(0.00606)	(0.00535)	(0.00481)
SC+ arm	0.0234***	0.0144	0.0141*	-0.00683	0.0101	0.0108*	0.0155***	-0.00442
	(0.00819)	(0.0107)	(0.00794)	(0.00706)	(0.00639)	(0.00599)	(0.00525)	(0.00478)
RUSF arm	0.00921	-0.00253	0.00592	7.35e-05	0.00585	-0.00262	0.00184	-0.0137***
	(0.00843)	(0.0107)	(0.00807)	(0.00717)	(0.00648)	(0.00606)	(0.00533)	(0.00504)
Illness in previous 2 weeks	-0.0300***	-0.0455***	-0.0367***	-0.0339***	-0.0287***	-0.0239***	-0.0177***	-0.0130***
	(0.00200)	(0.00804)	(0.00595)	(0.00535)	(0.00489)	(0.00467)	(0.00429)	(0.00392)
Constant	-0.0807***	-0.0657*	-0.0567**	0.00555	-0.107***	-0.0359	-0.0166	-0.172**
	(0.00659)	(0.0361)	(0.0265)	(0.0317)	(0.0353)	(0.0394)	(0.0413)	(0.0771)
Observations	47,742	5,349	6,913	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,409	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 30. Length-for-age z-score as outcome, lagged weight-for-length z-score as predictor, males

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23	Lag 1 Boys 24-28
Weight-for-length z-score lag 1	0.0935***	0.0620***	0.0434***	0.0333***	0.0307***	0.0307***	0.0228***	0.0201***
	(0.00163)	(0.00377)	(0.00285)	(0.00282)	(0.00261)	(0.00248)	(0.00216)	(0.00190)
Length-for-age z-score lag 1	0.843***	0.948***	0.959***	0.965***	0.968***	0.972***	0.974***	0.975***
	(0.00208)	(0.00375)	(0.00281)	(0.00267)	(0.00241)	(0.00223)	(0.00195)	(0.00174)
Time (days)	-5.72e-05***	0.000639***	0.000193*	-0.000308***	0.000170**	0.000190**	-4.48e-05	0.000146
	(5.53e-06)	(0.000196)	(0.000100)	(9.38e-05)	(8.17e-05)	(7.44e-05)	(6.63e-05)	(0.000105)
Sin(2π(day/365.25))	-0.00181	-0.0532***	0.0116	-0.0260***	-0.00416	-0.0149**	-0.00841	0.0120
	(0.00129)	(0.0148)	(0.00824)	(0.00891)	(0.00673)	(0.00690)	(0.00541)	(0.0105)
Cos(2π(day/365.25))	0.00698***	0.0703***	0.00327	0.0532***	-0.0105	0.0232***	-0.00774	0.00956*
	(0.00131)	(0.0172)	(0.00963)	(0.00765)	(0.00772)	(0.00621)	(0.00625)	(0.00556)
Sin(4π(day/365.25))	0.00390***	0.0220***	0.0327***	0.0119***	-0.00418	-0.00605*	0.00559*	0.0103***
	(0.00126)	(0.00689)	(0.00459)	(0.00428)	(0.00378)	(0.00344)	(0.00299)	(0.00391)
Cos(4π(day/365.25))	0.0114***	-0.0465***	0.00340	0.0327***	0.0159***	0.00244	0.00791**	0.0136***
	(0.00131)	(0.00971)	(0.00596)	(0.00546)	(0.00484)	(0.00433)	(0.00387)	(0.00395)
CSWB arm	-0.000723	-0.0215*	0.00411	-0.00837	0.00401	-0.0101	-0.00535	-0.0210***
	(0.00849)	(0.0115)	(0.00834)	(0.00768)	(0.00690)	(0.00619)	(0.00543)	(0.00486)
SC+ arm	0.0255***	-0.00512	0.0184**	-0.00981	0.00749	0.00305	0.00609	-0.00170
	(0.00830)	(0.0111)	(0.00814)	(0.00753)	(0.00671)	(0.00606)	(0.00530)	(0.00481)
RUSF arm	0.0160*	0.0126	0.0147*	-0.00620	0.0102	-0.00496	0.00315	-0.0234***
	(0.00869)	(0.0112)	(0.00842)	(0.00778)	(0.00692)	(0.00626)	(0.00547)	(0.00515)
Illness in previous 2 weeks	-0.0304***	-0.0230***	-0.0428***	-0.0380***	-0.0298***	-0.0268***	-0.0183***	-0.0164***
	(0.00205)	(0.00824)	(0.00606)	(0.00567)	(0.00511)	(0.00468)	(0.00430)	(0.00385)
Constant	-0.107***	-0.173***	-0.122***	0.0827**	-0.101***	-0.103**	0.0173	-0.123*
	(0.00683)	(0.0392)	(0.0286)	(0.0351)	(0.0381)	(0.0414)	(0.0428)	(0.0748)
Observations	49,426	5,586	7,182	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,499	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 31. Weight-for-length z-score as outcome, concurrent length-for-age z-score as predictor

VARIABLES	Concurrent	Concurrent 6-8	Concurrent 9-11	Concurrent 12-14	Concurrent 15-17	Concurrent 18-20	Concurrent 21-23	Concurrent 24-28
Length-for-age z-score	-0.0132***	0.0311***	0.0366***	0.0294***	0.0322***	0.0131***	-0.00655*	-0.000810
	(0.00324)	(0.00459)	(0.00396)	(0.00390)	(0.00365)	(0.00376)	(0.00355)	(0.00355)
Weight-for-length z-score lag 1	0.629***	0.861***	0.861***	0.869***	0.871***	0.889***	0.892***	0.887***
	(0.00249)	(0.00464)	(0.00400)	(0.00404)	(0.00389)	(0.00407)	(0.00386)	(0.00381)
Time (days)	0.000156***	-8.13e-05	-0.000523***	-8.58e-05	0.000461***	-8.75e-06	-0.000329***	-0.000429**
	(7.83e-06)	(0.000220)	(0.000130)	(0.000127)	(0.000116)	(0.000118)	(0.000114)	(0.000210)
Sin(2π(day/365.25))	-0.0295***	-0.0394**	-0.0695***	-0.0336***	-0.0731***	-0.0333***	-0.0681***	-0.0765***
	(0.00183)	(0.0165)	(0.0109)	(0.0120)	(0.00970)	(0.0109)	(0.00949)	(0.0209)
Cos(2π(day/365.25))	0.0538***	-0.00248	-0.0355***	0.0470***	0.00892	0.0439***	0.00582	0.0110
	(0.00185)	(0.0197)	(0.0124)	(0.0106)	(0.0109)	(0.00998)	(0.0107)	(0.0111)
Sin(4π(day/365.25))	0.0799***	0.0923***	0.0787***	0.0637***	0.0503***	0.0402***	0.0443***	0.0496***
	(0.00178)	(0.00797)	(0.00602)	(0.00587)	(0.00538)	(0.00549)	(0.00520)	(0.00770)
Cos(4π(day/365.25))	0.0839***	0.139***	0.0903***	0.118***	0.130***	0.123***	0.0797***	0.0837***
	(0.00186)	(0.0111)	(0.00784)	(0.00750)	(0.00694)	(0.00694)	(0.00676)	(0.00787)
CSWB arm	-0.0303**	-0.0276**	-0.0297***	-0.0214**	0.00690	-0.0158	-0.0305***	0.000495
	(0.0126)	(0.0134)	(0.0110)	(0.0106)	(0.00986)	(0.00996)	(0.00948)	(0.00952)
SC+ arm	0.0143	0.0191	-0.0102	-0.00165	0.0110	0.00468	-0.0185**	-0.00940
	(0.0124)	(0.0128)	(0.0108)	(0.0104)	(0.00965)	(0.00979)	(0.00929)	(0.00945)
RUSF arm	0.00520	-0.0113	-0.00280	0.00732	0.0273***	0.0114	-0.0244**	0.00153
	(0.0128)	(0.0129)	(0.0111)	(0.0107)	(0.00987)	(0.0100)	(0.00950)	(0.0100)
Illness in previous 2 weeks	-0.240***	-0.214***	-0.237***	-0.242***	-0.202***	-0.210***	-0.192***	-0.238***
	(0.00293)	(0.00958)	(0.00807)	(0.00788)	(0.00736)	(0.00760)	(0.00756)	(0.00765)
Constant	-0.336***	-0.0865*	0.103***	0.0242	-0.225***	0.00826	0.205***	0.289*
	(0.0100)	(0.0443)	(0.0370)	(0.0477)	(0.0540)	(0.0657)	(0.0740)	(0.150)
Observations	97,168	10,935	14,095	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,908	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 32. Weight-for-length z-score as outcome, concurrent length-for-age z-score as predictor, females

VARIABLES	Concurrent Girls	Concurrent Girls 6-8	Concurrent Girls 9-11	Concurrent Girls 12-14	Concurrent Girls 15-17	Concurrent Girls 18-20	Concurrent Girls 21-23	Concurrent Girls 24-28
Length-for-age z-score	-0.0305***	0.0367***	0.0282***	0.0279***	0.0250***	0.00628	-0.0120**	-0.00744
	(0.00466)	(0.00660)	(0.00568)	(0.00565)	(0.00539)	(0.00549)	(0.00510)	(0.00509)
Weight-for-length z-score lag 1	0.623***	0.855***	0.875***	0.870***	0.875***	0.890***	0.892***	0.888***
	(0.00359)	(0.00662)	(0.00569)	(0.00569)	(0.00563)	(0.00578)	(0.00544)	(0.00535)
Time (days)	9.20e-05***	-0.000257	-0.000382**	-0.000146	0.000347**	9.12e-05	-0.000404***	-0.000490*
	(1.09e-05)	(0.000290)	(0.000170)	(0.000170)	(0.000160)	(0.000161)	(0.000156)	(0.000295)
Sin(2π(day/365.25))	-0.0208***	-0.0203	-0.0588***	-0.0352**	-0.0532***	-0.0281*	-0.0665***	-0.0727**
	(0.00251)	(0.0216)	(0.0145)	(0.0159)	(0.0136)	(0.0148)	(0.0131)	(0.0293)
Cos(2π(day/365.25))	0.0523***	-0.0222	-0.0182	0.0509***	0.0176	0.0527***	0.00239	0.0252
	(0.00252)	(0.0263)	(0.0162)	(0.0144)	(0.0149)	(0.0139)	(0.0145)	(0.0157)
Sin(4π(day/365.25))	0.0767***	0.0852***	0.0646***	0.0641***	0.0450***	0.0364***	0.0484***	0.0485***
	(0.00244)	(0.0108)	(0.00802)	(0.00792)	(0.00744)	(0.00757)	(0.00711)	(0.0107)
Cos(4π(day/365.25))	0.0806***	0.145***	0.0992***	0.118***	0.125***	0.105***	0.0736***	0.0813***
	(0.00253)	(0.0148)	(0.0105)	(0.0101)	(0.00965)	(0.00961)	(0.00927)	(0.0110)
CSWB arm	-0.0320*	-0.0354*	-0.00785	-0.0306**	-0.00634	-0.00729	-0.0351***	-0.0106
	(0.0177)	(0.0181)	(0.0148)	(0.0144)	(0.0137)	(0.0138)	(0.0130)	(0.0131)
SC+ arm	0.00934	0.00659	-0.00410	-0.0115	0.0126	0.00646	-0.0218*	-0.0164
	(0.0174)	(0.0174)	(0.0146)	(0.0142)	(0.0135)	(0.0137)	(0.0128)	(0.0130)
RUSF arm	0.0101	-0.00643	0.0128	-0.00185	0.0309**	0.0171	-0.0145	0.00377
	(0.0179)	(0.0174)	(0.0148)	(0.0144)	(0.0136)	(0.0138)	(0.0130)	(0.0137)
Illness in previous 2 weeks	-0.226***	-0.173***	-0.220***	-0.218***	-0.190***	-0.204***	-0.174***	-0.240***
	(0.00403)	(0.0130)	(0.0109)	(0.0108)	(0.0103)	(0.0107)	(0.0105)	(0.0107)
Constant	-0.299***	-0.0447	0.0674	0.0607	-0.173**	-0.0552	0.238**	0.328
	(0.0139)	(0.0585)	(0.0487)	(0.0637)	(0.0743)	(0.0899)	(0.101)	(0.210)
Observations	47,742	5,349	6,913	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,409	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 33. Weight-for-length z-score as outcome, concurrent length-for-age z-score as predictor, males

VARIABLES	Concurrent Boys	Concurrent Boys 6-8	Concurrent Boys 9-11	Concurrent Boys 12-14	Concurrent Boys 15-17	Concurrent Boys 18-20	Concurrent Boys 21-23	Concurrent Boys 24-28
Length-for-age z-score	-0.00180	0.0229***	0.0413***	0.0284***	0.0375***	0.0170***	-0.00130	0.00616
	(0.00450)	(0.00643)	(0.00556)	(0.00544)	(0.00501)	(0.00520)	(0.00499)	(0.00499)
Weight-for-length z-score lag 1	0.632***	0.866***	0.850***	0.866***	0.867***	0.887***	0.892***	0.886***
	(0.00345)	(0.00648)	(0.00562)	(0.00575)	(0.00542)	(0.00577)	(0.00550)	(0.00541)
Time (days)	0.000212***	0.000120	-0.000700***	-2.11e-05	0.000568***	-0.000103	-0.000244	-0.000371
	(1.13e-05)	(0.000332)	(0.000196)	(0.000190)	(0.000168)	(0.000172)	(0.000168)	(0.000298)
Sin(2π(day/365.25))	-0.0378***	-0.0613**	-0.0806***	-0.0307*	-0.0923***	-0.0379**	-0.0687***	-0.0803***
	(0.00267)	(0.0251)	(0.0161)	(0.0180)	(0.0138)	(0.0159)	(0.0137)	(0.0298)
Cos(2π(day/365.25))	0.0552***	0.0197	-0.0562***	0.0427***	0.00105	0.0360**	0.00972	-0.00235
	(0.00270)	(0.0292)	(0.0188)	(0.0155)	(0.0159)	(0.0144)	(0.0158)	(0.0158)
Sin(4π(day/365.25))	0.0831***	0.0988***	0.0932***	0.0638***	0.0559***	0.0438***	0.0406***	0.0509***
	(0.00260)	(0.0117)	(0.00896)	(0.00867)	(0.00778)	(0.00795)	(0.00758)	(0.0111)
Cos(4π(day/365.25))	0.0869***	0.130***	0.0807***	0.117***	0.135***	0.141***	0.0860***	0.0861***
	(0.00270)	(0.0165)	(0.0116)	(0.0111)	(0.00995)	(0.0100)	(0.00981)	(0.0112)
CSWB arm	-0.0286	-0.0187	-0.0509***	-0.0122	0.0203	-0.0235	-0.0263*	0.0109
	(0.0179)	(0.0196)	(0.0163)	(0.0155)	(0.0142)	(0.0143)	(0.0137)	(0.0138)
SC+ arm	0.0196	0.0342*	-0.0161	0.00836	0.00973	0.00408	-0.0159	-0.00322
	(0.0175)	(0.0187)	(0.0159)	(0.0152)	(0.0138)	(0.0140)	(0.0134)	(0.0136)
RUSF arm	-0.00176	-0.0148	-0.0200	0.0153	0.0232	0.00663	-0.0346**	-0.000501
	(0.0183)	(0.0190)	(0.0165)	(0.0157)	(0.0142)	(0.0145)	(0.0138)	(0.0146)
Illness in previous 2 weeks	-0.254***	-0.250***	-0.251***	-0.263***	-0.213***	-0.217***	-0.210***	-0.236***
	(0.00423)	(0.0140)	(0.0118)	(0.0115)	(0.0105)	(0.0108)	(0.0109)	(0.0109)
Constant	-0.371***	-0.138**	0.146***	-0.0188	-0.276***	0.0642	0.167	0.255
	(0.0144)	(0.0665)	(0.0559)	(0.0710)	(0.0784)	(0.0958)	(0.109)	(0.212)
Observations	49,426	5,586	7,182	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,499	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 34. Weight-for-length z-score as outcome, lagged length-for-age z-score as predictor

VARIABLES	Lag 1	Lag 1 6-8	Lag 1 9-11	Lag 1 12-14	Lag 1 15-17	Lag 1 18-20	Lag 1 21-23	Lag 1 24-28
Length-for-age z-score lag 1	0.0549***	0.0700***	0.0556***	0.0440***	0.0438***	0.0255***	0.00611*	0.0117***
	(0.00302)	(0.00448)	(0.00389)	(0.00386)	(0.00361)	(0.00373)	(0.00351)	(0.00351)
Weight-for-length z-score lag 1	0.629***	0.856***	0.857***	0.864***	0.867***	0.884***	0.887***	0.884***
	(0.00240)	(0.00455)	(0.00394)	(0.00399)	(0.00385)	(0.00404)	(0.00384)	(0.00379)
Time (days)	0.000234***	-5.46e-05	-0.000497***	-8.69e-05	0.000471***	-2.94e-06	-0.000328***	-0.000426**
	(7.90e-06)	(0.000218)	(0.000129)	(0.000127)	(0.000116)	(0.000118)	(0.000114)	(0.000210)
Sin(2π(day/365.25))	-0.0302***	-0.0422***	-0.0710***	-0.0348***	-0.0725***	-0.0329***	-0.0684***	-0.0762***
	(0.00184)	(0.0164)	(0.0108)	(0.0120)	(0.00967)	(0.0108)	(0.00949)	(0.0209)
Cos(2π(day/365.25))	0.0534***	-0.00723	-0.0343***	0.0503***	0.00940	0.0439***	0.00585	0.0114
	(0.00185)	(0.0195)	(0.0123)	(0.0106)	(0.0109)	(0.00997)	(0.0107)	(0.0111)
Sin(4π(day/365.25))	0.0805***	0.0960***	0.0810***	0.0644***	0.0509***	0.0404***	0.0447***	0.0497***
	(0.00179)	(0.00791)	(0.00600)	(0.00586)	(0.00537)	(0.00548)	(0.00520)	(0.00770)
Cos(4π(day/365.25))	0.0849***	0.137***	0.0902***	0.119***	0.130***	0.123***	0.0794***	0.0835***
	(0.00186)	(0.0110)	(0.00780)	(0.00748)	(0.00692)	(0.00693)	(0.00676)	(0.00786)
CSWB arm	-0.0319***	-0.0328**	-0.0320***	-0.0232**	0.00594	-0.0167*	-0.0309***	0.000488
	(0.0118)	(0.0133)	(0.0110)	(0.0106)	(0.00984)	(0.00995)	(0.00949)	(0.00952)
SC+ arm	0.00301	0.0127	-0.0129	-0.00495	0.00916	0.00264	-0.0207**	-0.0119
	(0.0115)	(0.0127)	(0.0108)	(0.0104)	(0.00962)	(0.00978)	(0.00929)	(0.00945)
RUSF arm	-0.00204	-0.0160	-0.00480	0.00526	0.0262***	0.0101	-0.0258***	0.000487
	(0.0120)	(0.0128)	(0.0110)	(0.0107)	(0.00984)	(0.0100)	(0.00950)	(0.0100)
Illness in previous 2 weeks	-0.242***	-0.216***	-0.239***	-0.243***	-0.203***	-0.211***	-0.192***	-0.238***
	(0.00293)	(0.00950)	(0.00804)	(0.00786)	(0.00735)	(0.00759)	(0.00756)	(0.00765)
Constant	-0.290***	-0.0658	0.108***	0.0365	-0.219***	0.0178	0.218***	0.302**
	(0.00945)	(0.0439)	(0.0369)	(0.0476)	(0.0539)	(0.0656)	(0.0740)	(0.150)
Observations	97,168	10,935	14,095	14,092	14,003	13,888	14,224	15,915
Number of groups	5,039	4,908	5,020	5,017	4,984	4,993	5,002	5,033

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 35. Weight-for-length z-score as outcome, lagged length-for-age z-score as predictor, female

VARIABLES	Lag 1 Girls	Lag 1 Girls 6-8	Lag 1 Girls 9-11	Lag 1 Girls 12-14	Lag 1 Girls 15-17	Lag 1 Girls 18-20	Lag 1 Girls 21-23	Lag 1 Girls 24-28
Length-for-age z-score lag 1	0.0425***	0.0778***	0.0491***	0.0437***	0.0366***	0.0203***	0.00107	0.00595
	(0.00436)	(0.00642)	(0.00557)	(0.00557)	(0.00536)	(0.00547)	(0.00506)	(0.00505)
Weight-for-length z-score lag 1	0.624***	0.851***	0.870***	0.865***	0.871***	0.885***	0.887***	0.885***
	(0.00347)	(0.00649)	(0.00562)	(0.00562)	(0.00557)	(0.00574)	(0.00542)	(0.00533)
Time (days)	0.000174***	-0.000208	-0.000358**	-0.000137	0.000358**	9.58e-05	-0.000402***	-0.000493*
	(1.09e-05)	(0.000287)	(0.000169)	(0.000169)	(0.000159)	(0.000161)	(0.000156)	(0.000295)
Sin(2π(day/365.25))	-0.0214***	-0.0263	-0.0607***	-0.0353**	-0.0527***	-0.0281*	-0.0669***	-0.0725**
	(0.00252)	(0.0213)	(0.0145)	(0.0159)	(0.0135)	(0.0148)	(0.0131)	(0.0293)
Cos(2π(day/365.25))	0.0517***	-0.0257	-0.0164	0.0537***	0.0174	0.0521***	0.00285	0.0257
	(0.00253)	(0.0260)	(0.0161)	(0.0143)	(0.0149)	(0.0138)	(0.0145)	(0.0157)
Sin(4π(day/365.25))	0.0771***	0.0891***	0.0666***	0.0650***	0.0455***	0.0368***	0.0488***	0.0484***
	(0.00244)	(0.0107)	(0.00799)	(0.00790)	(0.00742)	(0.00756)	(0.00711)	(0.0107)
Cos(4π(day/365.25))	0.0816***	0.143***	0.0990***	0.118***	0.125***	0.104***	0.0732***	0.0812***
	(0.00254)	(0.0146)	(0.0104)	(0.0101)	(0.00963)	(0.00960)	(0.00928)	(0.0110)
CSWB arm	-0.0334**	-0.0402**	-0.0103	-0.0322**	-0.00736	-0.00821	-0.0355***	-0.0106
	(0.0165)	(0.0179)	(0.0148)	(0.0144)	(0.0137)	(0.0138)	(0.0130)	(0.0131)
SC+ arm	-0.000130	0.00271	-0.00644	-0.0144	0.0112	0.00429	-0.0240*	-0.0189
	(0.0162)	(0.0172)	(0.0145)	(0.0142)	(0.0134)	(0.0137)	(0.0128)	(0.0130)
RUSF arm	0.00441	-0.0109	0.0112	-0.00340	0.0298**	0.0158	-0.0158	0.00286
	(0.0167)	(0.0172)	(0.0147)	(0.0144)	(0.0136)	(0.0138)	(0.0130)	(0.0137)
Illness in previous 2 weeks	-0.226***	-0.175***	-0.222***	-0.219***	-0.191***	-0.204***	-0.173***	-0.240***
	(0.00404)	(0.0129)	(0.0109)	(0.0107)	(0.0103)	(0.0106)	(0.0105)	(0.0107)
Constant	-0.260***	-0.0317	0.0727	0.0695	-0.167**	-0.0439	0.250**	0.346
	(0.0131)	(0.0579)	(0.0485)	(0.0636)	(0.0742)	(0.0898)	(0.101)	(0.210)
Observations	47,742	5,349	6,913	6,952	6,864	6,850	7,011	7,797
Number of groups	2,484	2,409	2,475	2,472	2,457	2,466	2,460	2,480

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Supplemental Table 36. Weight-for-length z-score as outcome, lagged length-for-age z-score as predictor, male

VARIABLES	Lag 1 Boys	Lag 1 Boys 6-8	Lag 1 Boys 9-11	Lag 1 Boys 12-14	Lag 1 Boys 15-17	Lag 1 Boys 18-20	Lag 1 Boys 21-23	Lag 1 Boys 24-28
Length-for-age z-score lag 1	0.0627***	0.0605***	0.0591***	0.0423***	0.0491***	0.0283***	0.0112**	0.0181***
	(0.00421)	(0.00631)	(0.00547)	(0.00538)	(0.00494)	(0.00514)	(0.00493)	(0.00492)
Weight-for-length z-score lag 1	0.632***	0.860***	0.846***	0.862***	0.863***	0.882***	0.887***	0.883***
	(0.00333)	(0.00635)	(0.00554)	(0.00569)	(0.00536)	(0.00572)	(0.00547)	(0.00539)
Time (days)	0.000286***	0.000124	-0.000669***	-3.03e-05	0.000576***	-9.57e-05	-0.000243	-0.000363
	(1.14e-05)	(0.000329)	(0.000195)	(0.000189)	(0.000168)	(0.000172)	(0.000168)	(0.000297)
Sin(2π(day/365.25))	-0.0385***	-0.0613**	-0.0818***	-0.0328*	-0.0915***	-0.0374**	-0.0689***	-0.0800***
	(0.00267)	(0.0249)	(0.0160)	(0.0180)	(0.0138)	(0.0159)	(0.0137)	(0.0298)
Cos(2π(day/365.25))	0.0551***	0.0133	-0.0553***	0.0463***	0.00210	0.0366**	0.00944	-0.00203
	(0.00270)	(0.0290)	(0.0187)	(0.0155)	(0.0158)	(0.0143)	(0.0158)	(0.0158)
Sin(4π(day/365.25))	0.0839***	0.102***	0.0956***	0.0643***	0.0565***	0.0438***	0.0410***	0.0512***
	(0.00260)	(0.0116)	(0.00893)	(0.00865)	(0.00775)	(0.00794)	(0.00757)	(0.0111)
Cos(4π(day/365.25))	0.0878***	0.130***	0.0809***	0.118***	0.135***	0.141***	0.0857***	0.0858***
	(0.00270)	(0.0163)	(0.0116)	(0.0110)	(0.00992)	(0.00999)	(0.00980)	(0.0112)
CSWB arm	-0.0305*	-0.0242	-0.0530***	-0.0141	0.0194	-0.0242*	-0.0268*	0.0108
	(0.0168)	(0.0194)	(0.0162)	(0.0155)	(0.0141)	(0.0143)	(0.0137)	(0.0138)
SC+ arm	0.00633	0.0253	-0.0193	0.00467	0.00743	0.00208	-0.0184	-0.00572
	(0.0164)	(0.0186)	(0.0158)	(0.0152)	(0.0138)	(0.0140)	(0.0134)	(0.0136)
RUSF arm	-0.0100	-0.0198	-0.0223	0.0128	0.0221	0.00535	-0.0362***	-0.00178
	(0.0172)	(0.0189)	(0.0164)	(0.0157)	(0.0142)	(0.0144)	(0.0138)	(0.0146)
Illness in previous 2 weeks	-0.255***	-0.253***	-0.253***	-0.265***	-0.214***	-0.218***	-0.211***	-0.237***
	(0.00423)	(0.0139)	(0.0118)	(0.0114)	(0.0105)	(0.0108)	(0.0109)	(0.0109)
Constant	-0.320***	-0.109*	0.150***	-0.00308	-0.269***	0.0720	0.181*	0.263
	(0.0136)	(0.0659)	(0.0556)	(0.0709)	(0.0781)	(0.0956)	(0.108)	(0.212)
Observations	49,426	5,586	7,182	7,140	7,139	7,038	7,213	8,118
Number of groups	2,555	2,499	2,545	2,545	2,527	2,527	2,542	2,553

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Chapter 6: Peak timing of growth faltering among young children coincides with highest ambient temperatures in Burkina Faso

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This file includes: Main text, Figures 1-6, Tables 1-3, Supplementary Tables 1-2, Supplementary Figures 1-3

Abstract

Seasonal cycles in climatic factors such as temperature and precipitation affect the drivers of child growth and contribute to seasonal fluctuations in undernutrition. Current knowledge linking climatic seasonality to child growth measures is limited by categorical definitions of seasons that rely on assumptions about their timing and fail to consider their magnitude. In this study, we disentangle the relationship between several climatic factors and growth indicators, using harmonic regression models to determine how peak timing in indicators for growth faltering are related to peaks in temperature, precipitation, and vegetation. Longitudinal anthropometric data collected between August 2014-December 2016 from 5,039 Burkinabè children measured monthly from age 6-28 months were linked with remotely sensed data on daily maximum air temperature, precipitation, and vegetation. We find that length and weight velocity (cm/month, kg/month) are slowest twice a year, coinciding both times with the highest temperatures, as rains are beginning, and as they taper off, and with peak fever and diarrhea incidence. Our results challenge the popular notion that children are most vulnerable to growth faltering during the rainy season. Pathogens causing diarrheal disease and fever thrive and have more opportunities to infect children while temperatures are high, and precipitation is low. This highlights the importance of programmatic and policy-level changes that optimize the timing of nutrition interventions and address specific environmental growth-limiting conditions.

Introduction

Reducing growth faltering and undernutrition in young children, often defined as failure to achieve expected height-for-age and weight-for-height ratios, is a global health priority, important for economic productivity and human capital development in low- and middle- income countries (1). While progress is being made towards the goal of reducing all forms of undernutrition by 2030 (2, 3), the complex interactions among child growth, food systems, climate change, and the environment make identifying holistic interventions to reduce undernutrition challenging (4, 5).

The immediate (diets and infectious disease) and underlying (food security, feeding and caregiving resources, and access to safe and hygienic environment) drivers of undernutrition follow seasonal patterns (5–10) – they vary throughout the year in a cyclic nature, fluctuating with regard to their magnitude, timing and duration (11). These fluctuations translate to fluctuations in the incidence and prevalence of undernutrition, often referred to as the seasonality of undernutrition, which has been the subject of many studies in nutrition and food security (12).

Current knowledge on seasonality of growth is based on numerous studies that consider seasonal periods, or large periods of time, usually as binary indicators such as rainy versus dry seasons, or pre-harvest versus harvest periods. Most of these studies have found reductions in weight gain (13–15), lower weight-for-length z-scores (WLZ) (9, 16–21), and higher incidence of wasting (WLZ < 2 SD below the growth reference (22)) (23) during the rainy, pre-harvest seasons compared to the dry, harvest seasons, likely due to more infections (9, 13, 24, 25), less time for caretaking (9, 18), and poor food availability (8, 10). Seasonal variation in length or height measurements is less common; some studies report little or no seasonal differences in stunting (length/height-for-age < 2 SD below the growth reference (22)) (6, 8, 19), while others

find that similar to weight metrics, children have slower height gain (15) and more stunting (9, 18, 23) during the rainy, pre-harvest season. Fewer studies have presented results showing that children gain length and weight faster during the rainy, pre-harvest season, with the hypothesis that illness was more common in the dry, post-harvest season in these samples, and was a bigger driver to undernutrition than inadequate food access during the rainy season (26, 27).

While these studies form the basis of our knowledge of growth seasonality, they are almost all limited by categorization of the main explanatory variable for season. In fact, a recent review of methods used to study seasonality of malnutrition in the African drylands found that over half of the 24 studies included in the review defined distinct "seasons" as 2-4 time periods throughout the year, and an additional six studies formulated conclusions based on visualizations of nutrition outcomes by month (12). Such characterization of seasons as a few time periods improperly assumes that seasons correspond precisely to calendar months, leaves no room for inter-annual variation in climatic seasons (28, 29), does not allow for precise estimates of peak timing of growth faltering during the seasons, does not account for climate variability across regions, and eludes disentanglement of the effects of specific climatic conditions on growth (12). The relationship between mean annual precipitation and temperature and growth has been examined in several studies (30–33), but results from these studies are limited by the use of aggregate yearly means. Knowledge from the current available literature on climatic seasonality and growth is thus severely limited by broad, categorical definitions of climatic seasonality, and lack of disaggregated data on specific climatic conditions.

In this study, we investigate the relationship between peak temperature, precipitation, and vegetation with peak timing of growth faltering among infants and young children using harmonic regression models to address the aforementioned limitations of the current growth

seasonality literature. Peak timing of growth faltering is considered the period in which anthropometric metrics are at their worst, which is represented by the nadir in growth indices. Therefore, we compare peaks in temperature, precipitation, vegetation and morbidity with nadirs in growth indices. We check for multiple yearly peaks in growth indices using higher order sine and cosine terms and disaggregate our models by child sex, as suggested by Marshak et al. (12). In addition, we examine the direct and indirect effects of the same climatic variables on undernutrition. Understanding the seasonal cycles in the climatic factors that affect the drivers of undernutrition has the potential to vastly improve planning, timing, and targeting of interventions aimed at improving nutrition in growing children.

Methods

Study design and data sources

Anthropometric and morbidity data used in this study were collected in Sanmatenga Province, Burkina Faso between August 13, 2014 and December 28, 2016 during a longitudinal study comparing the cost-effectiveness of four supplementary foods in preventing malnutrition. Healthy children (mid-upper-arm circumference > 11.5 cm) enrolled in the blanket supplementary feeding program at 6 months were measured monthly until they reached 28 months, for an average of 22 measurements per child. Measurements were taken in duplicate and included recumbent length, weight, and mid-upper-arm circumference. Enumerators completed a rigorous training program and participated in standardization exercises every three months. At each monthly measurement visit, caregivers were asked if their child had experienced any illness in the previous two weeks, including fever, diarrhea, cough, rapid breathing, difficulty breathing, or confirmed malaria. In addition, caregivers gave self-reports of any fever or diarrhea on the day of measurement itself. Food security was assessed using the Household Food Insecurity Access

Scale (34) only twice per child, at study entry and exit, and thus is only assessed cross-sectionally in this analysis. After imputation using simple linear predictions of missing and implausible values identified using the jackknifed residual method (35), and restriction of the dataset to children who had a minimum of 20 measurements, the final dataset used for analyses consisted of 108,580 measurements from 5,039 children, comprising 82% of the original data. Further details on methods and results from the original trial are available elsewhere (36).

Daily time series of three remotely sensed climatic variables, including the Normalized Difference Vegetation Index (NDVI), maximum temperature, and precipitation, were merged with the anthropometric data using GPS coordinates from each of the 199 villages in the study area. The NDVI was downloaded from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record of Advanced Very High Resolution Radiometer Surface Reflectance (37). For temperature and precipitation, we used the Climate Hazards center Infrared Temperature with Stations (CHIRTS) high-resolution daily maximum air temperature data (38), and the Climate Hazards Infrared Precipitation with Stations (CHIRPS) high-resolution daily precipitation data (39). All climatic data were downloaded at a $5km^2$ spatial resolution. Data were downloaded, extracted and merged using R-studio (40).

Study setting

Burkina Faso is a landlocked country in West Africa that relies on rainfed agriculture as its primary economic activity, with 90% of the workforce employed in agriculture. Sanmatenga Province is located in the center-North region of Burkina Faso, where growing seasons are shorter than average for the country, agriculture is less diversified, and rainfall variability is higher (41). The rainy season in Burkina Faso is unimodal, with most rains occurring between

June and September. Since the period between 1920-1969, rainfall has substantially declined and temperature has increased significantly (41, 42).

Growth Outcomes

We modeled continuous outcomes for both attained size at each follow-up visit using age- and sex-standardized indices of weight and length (i.e., WLZ, weight-for-age z-scores (WAZ), and length-for-age z-scores (LAZ)) and growth velocity (weight and length velocity, weight-velocity z-scores (WVZ), and length-velocity z-scores (LVZ)). While attained size measures incorporate growth history and intrinsically include information on past growth up to the point of measurement, velocity measurements are indicative of present growth, and thus provide information on current growth-limiting conditions (15, 43). We therefore considered length velocity (cm/month) and weight velocity (kg/month) as the primary metrics of growth in this study. Length and weight velocities were calculated by taking the difference between previous and current measurements, dividing by the time gap between them, and multiplying by 30.44 to get velocities in cm/month and kg/month for length and weight, respectively.

Anthropometric indices and indicators of child growth were calculated using the Stata macro developed based on the 2006 WHO Child Growth Standards (22, 44). Z-scores identified as biologically implausible (+/- 6 SD for LAZ, +/- 5 SD for WLZ, WAZ) were flagged automatically by the macro and removed. Growth velocity z-scores were calculated manually in Stata using the tabulated Lambda-Mu-Sigma (LMS) parameters from the 2009 WHO Child Growth Standards (45). Because the WHO-2009 growth standards are restricted to children under 2, and the lowest granularity references available are in 2-month windows, we calculated velocity z-scores for each 2-month interval for children between 6-24 months. Velocity z-scores

are thus constant between each two-month interval (e.g., 6-8 months, 8-10 months, 10-12 months, etc.).

Climatic exposures

Since all three climatic variables were merged into the anthropometric dataset at the village level, each village has unique values for daily maximum temperature (°C), daily precipitation (mm), and daily NDVI. The NDVI takes remotely sensed images and divides the normalized difference between red and near infrared light bands by their sum to indicate the density of green vegetation. Values for NDVI range from -1 (water) to 1 (rainforest), with numbers close to zero corresponding to barren areas made up of rock or sand (37).

Morbidity exposures

Variables for current fever or diarrhea at the time of measurement, as well as reported upper-respiratory symptoms (cough, difficulty breathing, rapid breathing), and confirmed malaria in the two weeks prior to the interview were each modeled as continuous variables for prevalence (percent of the population reporting each illness at a given time period). In addition, a dichotomous indicator for any illness in the previous two weeks, combining all upper-respiratory symptoms, fever, diarrhea, confirmed malaria, accidents, or burns, was also modeled as a continuous variable for prevalence of any illness.

Food and nutrition security exposures

We descriptively analyzed cross-sectional food and nutrition security data collected at different times throughout the study period. The Household Food Insecurity Access Scale (HFIAS) (34) was recorded for each study participant at two time-points – study entry and exit. In addition, for a subset of 1,615 participants who were subject to an in-depth interview, we collected data on household drinking water E.coli concentration based on the AquagenX

Compartment Bag Test (46), and dietary diversity scores from 24-hour recalls of the child's diet on the day prior to the interview, calculated using the food groups from the Infant and Young Child Minimum Diet Diversity scale, ranging from 0-8 (47). On a further subset of 176 participants, we timed the number of hours the child was breastfed per day during four-day in-home observations.

Modeling seasonality

Harmonic regression models, also commonly referred to as Fourier or Trigonometric regressions, were used to estimate the magnitude and timing of seasonal peaks in temperature, precipitation, NDVI and measures of morbidity, as well as nadirs in child growth metrics. This method allows for the use of only two parameters, maximizing degrees of freedom and imposing symmetry and repetition in the rise and fall of the curves over the period of a year (48). In the simplest form of the models, referred to herein as base models, amplitude of the peaks was estimated using sine and cosine functions, and peak timing was estimated using a continuous daily calendar time indicator, centered with the origin at zero to represent the first day of the study (August 13, 2014). Base models were fit with multi-level mixed effects linear regressions (equation 1) for all outcomes except precipitation, which was fit using a negative binomial model (equation 2). Note that binary outcomes for morbidities were fit using both logistic and linear regressions, with almost identical results, so we use linear models for ease of interpretation:

1. $Y_{ijd} = \beta_{0ij} + \beta_{1ij}d + \beta_{2ij}\sin(2\pi\omega d) + \beta_{3ij}\cos(2\pi\omega d) + \beta_{4ij}\sin(4\pi\omega d) + \beta_{5ij}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{ijd}$;
2. $\log(E|Y_{ijd}) = \beta_{0ij} + \beta_{1ij}d + \beta_{2ij}\sin(2\pi\omega d) + \beta_{3ij}\cos(2\pi\omega d) + \beta_{4ij}\sin(4\pi\omega d) + \beta_{5ij}\cos(4\pi\omega d) + \alpha_i + \varepsilon_{ijd}$;

where Y_{ijd} (or $\log(E|Y_{ijd})$ from equation 2) is the growth outcome, or climatic or morbidity exposure for child *i* in village *j* on study day *d* for linear models. The coefficient β_1 represents a control for the overall time trend of the model. Peak timing and magnitude are

estimated by the coefficients of the sine and cosine terms where ω represents the frequency of the annual cycle in days accounting for the 2016 leap year and is a constant equal to 1/365.25. Individual child level random effects are accounted for by α_i, and ε_{ijd} is the time-varying error term. For each growth outcome and climatic variable, to determine the number of peaks per year, we examined graphs of the mean of the variable over time, as well as testing the statistical significance of 2π and 4π terms. Pairs of sine and cosine terms were removed if they were not statistically significant at the 5% significance level ($p<0.05$). If both 2π and 4π terms were significant and graphical representations of the variables indicated two peaks, both pairs of terms were kept in the model. While we recognize the importance of age as a predictor of growth outcomes, and that seasonality patterns may be age-dependent (6), including age terms in these models would have over-complicated interpretation, and the time trend closely approximates the aging of the cohort; thus we did not include age as a covariate in these models. However, to visualize changes in anthropometry by age, we constructed heat plots to examine how anthropometric indicators change over time in relation to age.

Peaks and nadirs in timing for each curve were determined by ordering the predicted values for each outcome chronologically, taking their first derivatives, and identifying each point at which the value of the first derivative changed signs. To determine peak timing, the corresponding dates at each change point were noted as peaks when values changed from positive to negative, and nadirs when values changed from negative to positive. The worst periods for growth faltering, or "peak growth faltering" is considered the nadir for each anthropometric metric. The lag period between each climatic variable and each growth outcome was thus calculated as the difference between the dates of climatic variable peaks and growth outcome nadirs. Magnitude of seasonal peaks was determined by taking the average difference in

predicted yearly peak and nadir values to get the amplitude of the peak, representing its absolute intensity.

The statistical relationship between each of the climatic exposures and metrics of child growth was assessed separately for each climatic factor using multi-level mixed effects linear regressions by adapting the above equation as follows:

$$Y_{ijd} = \beta_{0ij} + \beta_{1ij} d + \beta_{2ij} \sin(2\pi\omega d) + \beta_{3ij} \cos(2\pi\omega d) + \beta_{4ij} \sin(4\pi\omega d) + \beta_{5ij} \cos(4\pi\omega d) + \beta_{6jd} C + \beta_{7ij} I + \alpha_i + \varepsilon_{ijd};$$

where the effects of the climatic exposure, *C*, is estimated by the β_6 coefficient, and any reported illness, *I*, in the past two weeks is controlled for by β_7. Unadjusted relationships between the climatic exposures and growth, as well as any illness and growth were also modeled. Models were stratified by child sex to test for differential effects by sex.

Ethics

The original study in which anthropometric data were collected was approved by the Tufts University Health Sciences Institutional Review Board (IRB #: 10899) as well as the ethics board of the Ministry of Health in Burkina Faso (#: 2013-10-090). Secondary analysis of anthropometric and remote sensing data for the present study was exempt by the Tufts University Health Sciences Institutional Review Board (IRB ID: STUDY00000255).

Results

Anthropometry by age

Heat-plots of each anthropometric indicator over time by child age show how the cohort ages together over time (**Figure 1**). Since enrollment was done on a rolling basis, there are about 5 overlapping age categories at the beginning and end of the study as enrollments and exits began, and a larger range of ages at each calendar date in the middle months of the study. Cells

in which the sample size was less than 4 children were removed. The plots reveal seasonality among all anthropometric indicators except length-for-age, which declines as children age without an apparent seasonal pattern, starting at a mean ranging from about -0.5 to -0.8 SD when the cohort is 6-13 months old, and ending at a mean ranging from -1.4 to -1.5 SD once the cohort has reached to 20-29 months. While length velocity also declines as children age, showing an overall downward trend over time, vertical striations in the heat plot show that it varies by study month as well. Despite overall declines in absolute length velocity over time, age- and sex-standardized LVZ displays an opposing pattern, increasing slightly as children age, with seasonal patterns. Weight-for-length z-scores and weight-for-age z-scores show strong seasonality, with the absolute worst periods occurring intermittently when the children are between 8-18 months, and less drastic seasonal effects thereafter when fewer children are in the most vulnerable age range. Weight velocity (both absolute and z-scores) reveals very strong seasonal variation; WVZ shows similar patterns to WLZ and WAZ, with decreasing magnitude of seasonal changes as children age, while no general time trends are apparent in absolute weight velocity as children age.

Seasonality of climatic factors

Figure 2 displays scatterplots of vegetation, precipitation, and maximum temperature over time for each of the 199 villages in the study. Precipitation and vegetation appear to be unimodal, with singular yearly peaks in vegetation around September, following closely after yearly peaks in precipitation in August. Temperature, however, is bimodal, with a primary, larger peak in April and a secondary, smaller peak in October. There is some variation at the village level, especially for precipitation. Across all time points and villages, maximum daily temperature ranges from 26.2 to 44.8 °C, precipitation in mm/5km^2/day ranges from 0-55.8, and

NDVI ranges from 0.12-0.55. Anthropometric data were collected starting in August 2014, when precipitation was near its peak, and ending in December 2016 during the coldest and driest part of the year.

Harmonic models revealed two significant peaks for all three climatic variables, as sine and cosine pairs for both 2π and 4π terms were significant (**Supplementary Table 1**). However, for precipitation models, the significance of the 4π terms is an amplification of the 2π terms, and only one true peak per year was identified using the harmonic model's predicted values. Model predictions, graphed in **Figure 3**, show that temperature peaks at 42°C on April 26, and again at 36°C on October 24. Precipitation peaks three months (110 days) after the higher temperature peak in April, at an average of 8.5 mm/5 km^2 on August 14, which is followed by peak NDVI (0.39) 42 days later on September 25. The magnitude of climatic factor seasonality is displayed in **Table 1**, which shows that the highest temperature peaks in April, with an amplitude of 10°C, are twice the size of the second temperature peaks in October which have an amplitude of 4.5°C. The amplitude of the precipitation peak is equal to its highest value (8.5 mm/5km^2) since precipitation for several months of the year bottoms out at zero. The large NDVI peak has an amplitude of 0.21, doubling in height from the nadir to the peak.

Seasonality of growth, morbidity, and food and nutrition security

Fluctuations in velocity measures and attained size indicators reveal two yearly peaks in the seasonal timing of growth faltering. The worst periods (nadirs) for both weight and length velocities coincide with peak temperature (**Figures 4 & 5**). The biggest nadirs for length and weight velocity occur in April (weight) and May (length), coinciding with the highest peaks in temperature. The secondary nadirs in October (weight) and November (length), which are smaller in magnitude, coincide with the second, smaller peaks in temperature in October (**Table**

1). Length velocity is slowest 31 days after the first temperature peak in April, and 28 days after the second. Similarly, weight velocity is slowest 13 days before the first temperature peak, and 11 days before the second (**Table 2**). While nadirs in growth velocity do not appear to coincide with peak precipitation, the slowest points for growth velocity do happen as the rains begin and end, hitting their first nadir as precipitation starts to rise, and again as it comes back down towards zero. Synchronization of growth with vegetation depends on the anthropometric indicator. Weight velocity hits its nadir 18 days after the primary NDVI peak, but the nadir for length velocity follows the same peak by 57 days.

Other anthropometric indicators for both attained size, and velocity z-scores show comparable timing and levels of synchronization with temperature and precipitation and are similarly varied in relation to NDVI (**Supplementary Figures 1-3**). Length and weight velocity z-scores are the lowest around the major NDVI peak, happening only 4 days after the peak (LVZ) or 14 days prior (WVZ). Attained WAZ and WLZ hit their lowest points between 39-46 days after peak NDVI.

The major peak in vegetation happens in September, only 5 days apart from the peak in confirmed malaria cases, while precipitation is still high, but beginning to recede. The secondary, small vegetation peak happens in March, as the rains commence, and is again followed by a peak in malaria, shortly thereafter. In both cycles, about a month later, temperature peaks (in October, and in April), coinciding each time with anthropometric indicator nadirs, a peak in fever prevalence, and once with the only yearly peak for diarrhea, in October (**Table 2**).

Length-for-age z-scores are the only indicators examined that show no seasonal patterns, declining stably as children age, as shown in the heat-plots of **Figure 1**, and further confirmed by the consistently negative slope of LAZ predictions from harmonic regressions. While 2π sine and

cosine terms for LAZ models were statistically significant, there were no apparent peaks or nadirs, only slight undulations in the overall downward slope of LAZ over time. Both weight and length velocity z-scores show substantial upward trends over time, increasing as time progresses and the cohort of children ages, while raw length velocity decreases over time.

There were no meaningful differences in the timing or magnitude of seasonality by child sex; however, boys started with lower values for anthropometric indicators than girls (**Supplementary Table 2**).

Analyses of food and nutrition security variables are limited to mean values by calendar month (**Figure 6**) and give a broad idea of the seasonality of food and nutrition security in our sample. Household food insecurity is at its highest in the months of August and September and is relatively stable throughout the rest of the year. *E. coli* concentration is generally high throughout the entire year, at average levels deemed high risk and unsafe, but the highest levels appear to occur in April-May, July, and September. Diet diversity scores are low throughout the year, with an overall mean score below 3, and are lowest in November and December. Children are breastfed for the least amount of time in April and May, and again in August and September, with highest breastfeeding times in January and February and June and July; however, these data are based on a sample subset of the study population.

Statistical associations among climatic variables and growth outcomes

Examination of the statistical relationships among climatic factors, morbidity, and growth, displayed in **Table 3**, shows a strong and significant negative correlation between morbidity and anthropometric indicators, and varied relationships between climatic factors and the same indicators. Conditional on time and seasonality trends (time trends closely approximate aging of the cohort), morbidity is strongly associated with decreases in all anthropometric

indicators, except WVZ. On average, those who reported any illness in the 2 weeks prior to their measurement had weight velocities 0.17 kg/month slower and length velocities 0.08 cm/month slower than those who did not report illness. These constitute changes of substantial magnitude for weight velocity, given that average weight velocity ranges from 0.15-0.20 kg/month depending on child age. Changes in length velocities are of smaller magnitude, constituting an 11.5% reduction in length velocity of the oldest children who have average length velocities around 0.69 cm/month, and a 6.2% reduction among the youngest who have higher average length velocities of 1.29 cm/month.

Relationships with temperature differ for weight versus length growth metrics. For example, when current temperature is higher, weight related anthropometric indices (weight velocity, WAZ, WLZ) are lower, and length related anthropometric indices (length velocity, LAZ, LVZ) increase. The only weight-related metric that increases when temperature is higher is WVZ. However, when temperature from the previous month increases, LVZ decreases, there are no significant changes in WLZ, and all other indicators increase. Precipitation was not a significant predictor of anthropometric indicators, with the exception of WLZ and WAZ, which decrease slightly as precipitation increases, when controlling for morbidity. Lastly, higher NDVI is strongly associated with higher weight velocity, LAZ, WAZ, and WLZ, and with lower length velocity (**Table 3**).

Discussion

In the face of climate change, any progress that has been made in reducing the prevalence of malnutrition in all its forms risks stalling, or worse, reversal (49). Growth seasonality work has been instrumental in planning interventions that mitigate risks at times of the year when children are most vulnerable to nutritional crises; however, as the climate changes, and climatic

seasonality shifts (50, 51), widely accepted paradigms for growth seasonality may no longer apply. We build on and update prior seasonality work by fitting harmonic models to longitudinal data, identifying with precision the temporal relationship among growth outcomes, climatic factors, and morbidity. Our findings contradict the widely held notion based on multiple studies, that growth faltering peaks during the rainy, pre-harvest season (9, 13–21). Instead, we find that among our sample of children from central-northern Burkina Faso, growth indicators are highly synchronized with temperature and the prevalence of fever. Anthropometric indices for growth faltering based on both attained size and growth velocity all have two clear peaks, as do temperature and fever. Not only does the slowest growth for both length and weight consistently happen within a month of peak temperature and fever each time they occur during the yearly cycle, but the magnitude of peaks in temperature are related to the magnitude of nadirs in growth. The highest peaks in temperature correspond with the lowest growth nadirs. In relation to precipitation and vegetation, growth is slowest as the rains begin and there is an initial slight peak in vegetation, and again as they taper off while vegetation hits its large peak.

The commonly accepted theory that growth faltering is accelerated during the rainy season, when food is in short supply, caregivers have less time to look after their children, and disease incidence is highest, has largely been informed by studies that have considered seasonality as a categorical (usually binary) predictor of growth (8, 13, 52, 53, 15, 17–19, 21, 23, 24, 26). A few studies have looked at calendar month as a predictor of growth among young children using more than simple visual inspection (9, 16, 20). These analyses included data from Bangladesh (20), the Gambia (9), and a multi-country dataset from 31 countries (16), and all found that the periods of lowest growth happened during the rainy season or monsoon months. However, each of these analyses are limited either by assumptions about when the rainy season

occurs in relation to the dry season, imprecise definitions of seasonal rainfall peaks, lack of data on other climatic factors that vary by season, or the averaging of seasonal patterns across all age groups. The frequency of our anthropometric and climate measurements combined with our large sample size allowed us to build a daily time series of growth measures and climatic indicators and obtain precise estimates for the seasonal timing of growth faltering and its relation to climatic factors. Our analysis is not limited by assumptions about categorical seasons or by aggregated monthly mean precipitation. In addition to controlling for time trends and seasonality, our models allow for two seasonal peaks per year, increasing the accuracy of our predictions. It is therefore not surprising that our results diverge from commonly accepted knowledge, given our models' ability to disaggregate the effects of multiple climatic factors at such a granular temporal and spatial level.

There are several plausible explanations for our findings. The assertion that food and nutrition security is compromised during the rainy, pre-harvest season may not hold true across all contexts. While we were unable to measure food and nutrition security longitudinally and therefore unable to build harmonic models of household food security scores over time, examination of monthly means for a variety of food and nutrition security variables collected during interviews (diet diversity, breastfeeding time) throughout the study period, or at study entry and exit (food security) shows no clear monthly patterns across all measures of food and nutrition security. When food insecurity scores are higher, for example, diet diversity scores are lower. Our findings are similar to a study conducted in Ethiopia comparing pre- and post-harvest food security and growth, in which authors also observed faster weight and length velocities during the pre-harvest season, and that seasonality among food security measures was inconsistent (26). We note another limitation of our food security data is that all study

participants were receiving an extra household ration of 10 kg of split green peas and 4 liters of fortified vegetable oil per month, between June and September. It is possible that the presence of this ration influenced household food security during this time period; however, the greatest levels of household food insecurity overlap with the distribution of this household ration, and growth measurements did not appear to correspond to measures of household food insecurity, regardless.

In addition, as previous studies have shown, infection may be the dominant driver of nutritional status, rather than food insecurity (10). Results from our regression models revealed morbidity to be the overwhelming driver of anthropometric indices. There is no question in our study that the seasonality of fever and diarrhea prevalence overlap with the periods of slowest growth. Given the additional overlap with the highest temperatures, which happen as the rains are beginning and then tapering off, the combination of climatic conditions during these times must be prime for infection. Indeed, bacterial pathogens replicate faster and survive longer in higher temperatures (54–57) and the shortage of water during the hot, dry season may necessitate consumption of unsafe water and reduce hygiene practices (58). A study examining the impact of rainfall and temperature on the prevalence of diarrhea in 14 Sub-Saharan African countries showed that higher temperatures increased the prevalence of diarrhea, as did rainfall scarcity (59). Additional studies in Ethiopia and Tanzania have determined that the dry, pre-rainy season in which temperatures are highest as the rains are just starting and still sparse is the highest risk period for diarrheagenic *E. coli* (57, 60). Diarrheal *E. coli* are among the most common diarrhea-causing pathogens in Burkinabè children (61), so the period of highest ambient temperatures is likely related to an increase in these pathogens in the context of Burkina Faso as well. It is possible that the combination of high temperatures that breed diarrheagenic pathogens, and small

amounts of rain that allow for consumption and use of unsafe surface water contribute to the high incidence of diarrhea and fever during the hottest parts of the year, while precipitation is present, it is limited and inconsistent. Our analyses of *E. coli* concentration in drinking water are limited to monthly averages, but some of the highest concentrations are found in the hottest months of April and May. Dehydration, likely related to both diarrhea and fever, has also been found to occur more often during the dry season (60), adding to the probable links among high temperatures, low precipitation, infection, and undernutrition.

The main limitations of this study are the lack of longitudinal food and nutrition security data, and the potential confounding due to universal rainy season household rations. In addition, morbidity data are self-reported by caregivers, and may over- or under-estimate true incidence; however, we have no reason to believe that reporting practices would differ by season. Last, 2.5 years of data may be considered insufficient by some standards to draw definitive conclusions about seasonality, and the imposition of symmetry in the rise and fall of seasonal curves by harmonic models may over-simplify true seasonal variations. The strengths of our design, in which we use a fine spatial and temporal resolution to precisely match climatic data to anthropometry allowed us to disaggregate and disentangle the differential effects of the multiple climatic and environmental drivers of growth.

Our study results challenge the prevalent assumption that children are most vulnerable to growth faltering during the rainy season. Instead, we assert that the combination of high temperatures and low, but not zero, precipitation are prime conditions for diarrheal disease and fever, which are more important drivers of undernutrition than food scarcity during the rainy season. In the short term, programs aimed at reducing malnutrition should focus on preventing infection during this period, accessibility to safe drinking water, and addressing the community-

level environmental conditions that stimulate the growth of *E. coli* or other diarrheagenic bacteria. In the long term, as global temperatures increase and rainfall becomes less predictable and consistent, policies aimed at addressing climate change will be imperative to protect the nutrition and health of children most vulnerable to its effects.

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Tables and figures

Table 1. Timing and magnitude of peaks and nadirs in anthropometric indicators, climatic variables and morbidity

	Peak timing	Nadir timing	Mean Amplitude
Length velocity (cm/month)	6-Jan	27-May	0.3231
	25-Jul	21-Nov	0.1958
Weight velocity (kg/month)	7-Jan	13-Apr	0.0876
	17-Jul	13-Oct	0.1846
Length velocity z-score	15-Jan	12-Apr	0.1358
	12-Aug	29-Sep	0.0223
Weight velocity z-score	9-Dec	15-Mar	0.3112
	22-Jun	11-Sep	0.1994
Weight-for-age z-score	1-Feb	23-May	0.3343
	23-Aug	10-Nov	0.1143
Weight-for-length z-score	3-Feb	18-May	0.3767
	24-Aug	3-Nov	0.1167
Precipitation (mm)	14-Aug	16-Jan	8.5100
NDVI	25-Sep	11-Jan	0.2093
	4-Mar	18-May	0.0478
Temperature (°C)	26-Apr	7-Aug	9.9113
	24-Oct	12-Jan	4.5538
Fever[a]	25-Mar	3-Jul	0.0383
	15-Oct	30-Jan	0.0477
Diarrhea[a]	23-Oct	19-Jul	0.0301
Upper-respiratory symptoms[b,c]	3-Jan	4-Aug	0.0841
Confirmed malaria[c]	30-Sep	22-Jan	0.0576
	28-Mar	6-Jun	0.0124
Any illness[c]	2-Mar	9-Jul	0.1802
	25-Oct	29-Jan	0.0672

Notes: Length-for-age z-scores not reported due to lack of seasonality
[a]Current illness self-reported by caregivers on the day of measurement
[b]Upper respiratory symptoms include cough, difficulty breathing, and/or rapid breathing
[c]Self-reported morbidities in the two weeks prior to measurement

Table 2. Lag between peak timing of climatic factors and nadir in anthropometric indices

	Precipitation		Temperature		NDVI	
	Lag 1	Lag 2[a]	Primary Lag	Secondary Lag	Primary Lag	Secondary Lag[a]
Length velocity (cm/month)	-79	99	31	28	57	84
Weight velocity (kg/month)	-123	60	-13	-11	18	40
Length velocity z-score	-124	46	-14	-25	4	39
Weight velocity z-score	-152	28	-42	-43	-14	11
Weight-for-age z-score	-83	88	27	17	46	80
Weight-for-length z-score	-88	81	22	10	39	75
Fever[b]	-142	62	-32	-9	20	21
Diarrhea[b]	70		180	-1	28	233
Upper-respiratory symptoms[c,d]	-223		-113	-294	-265	-60
Confirmed malaria[d]	-139	47	-29	-24	5	24
Any illness[d]	-165	72	-55	1	30	-2

Notes: Lag periods, presented in number of days, are calculated by subtracting peak climatic factor dates from nadir anthropometric indicator dates, which indicates the lowest attained size and slowest growth, or subtracting peak climatic factor dates from peak morbidity dates. Primary lags refer to the lag times from the larger peaks, and secondary lags refer to lag times from the smaller peaks. Precipitation has only one peak, so there is no distinction between primary or secondary lags.

[a]Since precipitation has only one peak, second lags for precipitation indicate the time between the single peak of precipitation and NDVI and the second nadir for anthropometric indicators, or between the single precipitation and NDVI peak and the second morbidity peak for morbidities with two peaks.

[b]Current illness self-reported by caregivers on the day of measurement

[c]Upper respiratory symptoms include cough, difficulty breathing, and/or rapid breathing

[d]Self-reported morbidities in the two weeks prior to measurement

Table 3. Relationship between climatic variables and anthropometric outcomes. Results from harmonic regressions controlling for time trends and seasonality

Outcome:	Length Velocity	Weight Velocity	LVZ	WVZ	LAZ	WAZ	WLZ
Temperature Models							
Temperature	0.0088***	-0.0048***	0.0061***	0.0037***	0.0031***	-0.0033***	-0.0055***
	(0.0070, 0.0105)	*(-0.0059, -0.0038)*	*(0.0030, 0.0092)*	*(0.0024, 0.0051)*	*(0.0025, 0.0038)*	*(-0.0045, -0.0021)*	*(-0.0070, -0.0040)*
Adjusted temperature							
Adjusted temperature	0.0080***	-0.0050***	0.0058***	0.0034***	0.0032***	-0.0034***	-0.0056***
	(0.0062, 0.0098)	*(-0.0060, -0.0039)*	*(0.0026, 0.0091)*	*(0.0020, 0.0048)*	*(0.0026, 0.0038)*	*(-0.0047, -0.0022)*	*(-0.0072, -0.0041)*
Morbidity	-0.0845***	-0.1722***	-0.1060***	0.0121***	-0.0098***	-0.1757***	-0.2351***
	(-0.0922, -0.0769)	*(-0.1766, -0.1678)*	*(-0.1201, -0.0918)*	*(0.0059, 0.0182)*	*(-0.0144, -0.0053)*	*(-0.1812, -0.1701)*	*(-0.2420, -0.2282)*
Lagged temperature							
Lagged temperature	0.0036***	0.0046***	-0.0066***	0.0020**	0.0006**	0.0018***	0.0008
	(0.0018, 0.0054)	*(0.0036, 0.0057)*	*(-0.0098, -0.0034)*	*(0.0005, 0.0034)*	*(0.0000, 0.0013)*	*(0.0006, 0.0030)*	*(-0.0007, 0.0023)*
Morbidity	-0.0842***	-0.1719***	-0.1054***	0.0078**	-0.0044**	-0.1749***	-0.2370***
	(-0.0919, -0.0765)	*(-0.1764, -0.1675)*	*(-0.1197, -0.0910)*	*(0.0015, 0.0140)*	*(-0.0089, 0.0001)*	*(-0.1804, -0.1694)*	*(-0.2439, -0.2302)*
Precipitation Models							
Precipitation	0.0002	0.0006*	-0.0009	0.0000	-0.0001	-0.0006*	-0.0013**
	(-0.0007, 0.0010)	*(0.0001, 0.0011)*	*(-0.0025, 0.0007)*	*(-0.0007, 0.0007)*	*(-0.0005, 0.0004)*	*(-0.0011, 0.000)*	*(-0.0020, -0.0006)*
Adjusted precipitation							
Adjusted precipitation	0.0002	0.0004	-0.0010	0.0001	0.0000	-0.0008**	-0.0017***
	(-0.0006, 0.0011)	*(-0.0001, 0.0009)*	*(-0.0026, 0.0006)*	*(-0.0006, 0.0008)*	*(-0.0005, 0.0005)*	*(-0.0014, -0.0003)*	*(-0.0024, -0.0010)*
Morbidity	-0.0844***	-0.1723***	-0.1060***	0.0121***	-0.0088***	-0.1761***	-0.2354***
	(-0.0921, -0.0767)	*(-0.1767, -0.1678)*	*(-0.1201, -0.0918)*	*(0.0060, 0.0183)*	*(-0.0133, -0.0042)*	*(-0.1816, -0.1706)*	*(-0.2423, -0.2285)*
Lagged precipitation							
Lagged precipitation	-0.0007	-0.0001	-0.0006	0.0003	0.0001	-0.0009**	-0.0015***
	(-0.0016, 0.0002)	*(-0.0006, 0.0004)*	*(-0.0023, 0.0011)*	*(-0.0004, 0.0011)*	*(-0.0003, 0.0006)*	*(-0.0015, -0.0003)*	*(-0.0022, -0.0008)*
Morbidity coefficient	-0.0844***	-0.1722***	-0.1050***	0.0077**	-0.0045**	-0.1753***	-0.2371***

	(-0.0921, -0.0767)	*(-0.1766, -0.1677)*	*(-0.1194, -0.0907)*	*(0.0015, 0.0140)*	*(-0.0089, 0.0000)*	*(-0.1807, -0.1698)*	*(-0.2440, -0.2302)*
NDVI Models							
NDVI	-0.0647	0.0961**	0.1163	-0.4860***	0.2388***	0.5187***	0.6909***
	(-0.1789, 0.0495)	*(0.0391, 0.1498)*	*(-0.1023, 0.3349)*	*(-0.5770, -0.3951)*	*(0.1976, 0.2800)*	*(0.4326, 0.6047)*	*(0.5839, 0.7980)*
Adjusted NDVI							
Adjusted NDVI	-0.1168	0.1053**	0.1149	-0.4951***	0.2346***	0.5129***	0.6922***
	(-0.2334, -0.0002)	*(0.0442, 0.1641)*	*(-0.1100, 0.3398)*	*(-0.5885, -0.4018)*	*(0.1921, 0.2770)*	*(0.4245, 0.6012)*	*(0.5823, 0.8021)*
Morbidity	-0.0845***	-0.1722***	-0.1058***	0.0120***	-0.0094***	-0.1756***	-0.2348***
	(-0.0922, -0.0768)	*(-0.1766, -0.1677)*	*(-0.1200, -0.0917)*	*(0.0058, 0.0182)*	*(-0.0140, -0.0050)*	*(-0.1812, -0.1701)*	*(-0.2416, -0.2279)*
Lagged NDVI							
Lagged NDVI	-0.0240	-0.0404	0.3969***	-0.2672***	0.1906***	0.3367***	0.4703***
	(-0.1359, 0.0880)	*(-0.0979, 0.0203)*	*(0.1778, 0.6161)*	*(-0.3556, -0.1789)*	*(0.1484, 0.2328)*	*(0.2529, 0.4205)*	*(0.3657, 0.5748)*
Morbidity	-0.0844***	-0.1722***	-0.1054***	0.0080**	-0.0059***	-0.1757***	-0.2377***
	(-0.0921, -0.0767)	*(-0.1766, -0.1677)*	*(-0.1198, -0.0910)*	*(0.0018, 0.0143)*	*(-0.0104, -0.0014)*	*(-0.1812, -0.1702)*	*(-0.2446, -0.2309)*
Morbidity Model							
Morbidity	-0.0840***	-0.1721***	-0.1056***	0.0122***	-0.0087***	-0.1760***	-0.2354***
	(-0.0917, -0.0763)	*(-0.1765, -0.1677)*	*(-0.1198, -0.0915)*	*(0.0060, 0.0183)*	*(-0.0132, -0.0042)*	*(-0.1815, -0.1704)*	*(-0.2422, -0.2285)*

Note: Data are coefficients from harmonic regression models. Time trends are controlled for using a daily time indicator, and the magnitude and timing of seasonal peaks is controlled for using sine and cosine functions. Separate models were run for each climatic factor. Morbidity includes any reported illness in the two weeks prior to the measurement date. 95% confidence intervals in parentheses. *p<0.05; **p<0.01; ***p<0.001

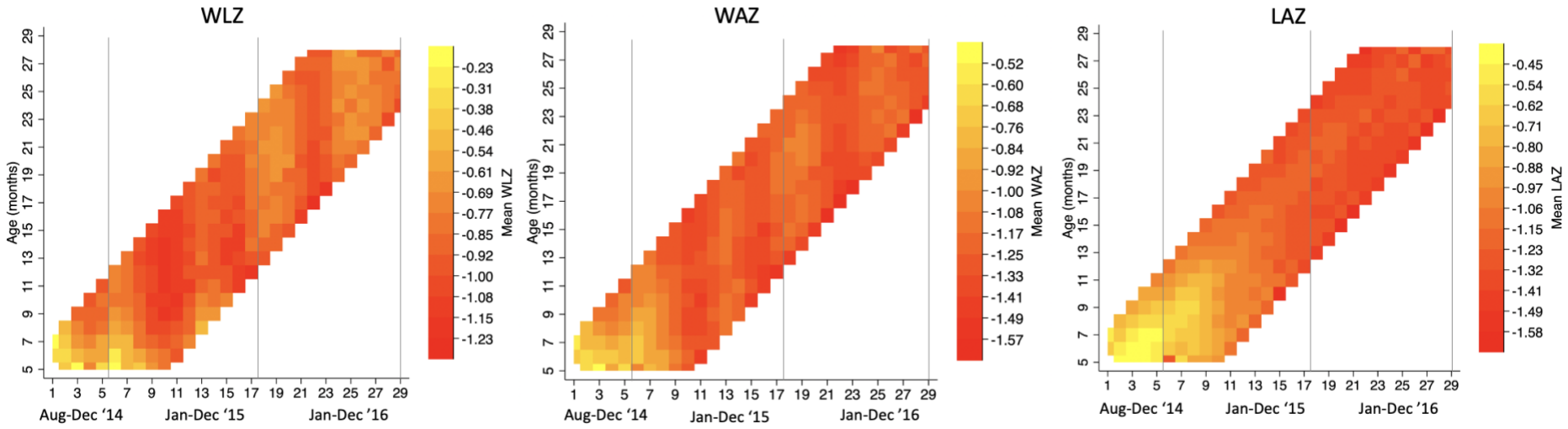


Figure 1A. Heat-plots showing mean anthropometric indices by age and calendar time. Study month 1= August 2014, study month 29 = December 2016. WLZ = weight-for-length z-score; LAZ = length-for-age z-score; WAZ=weight-for-age z-score

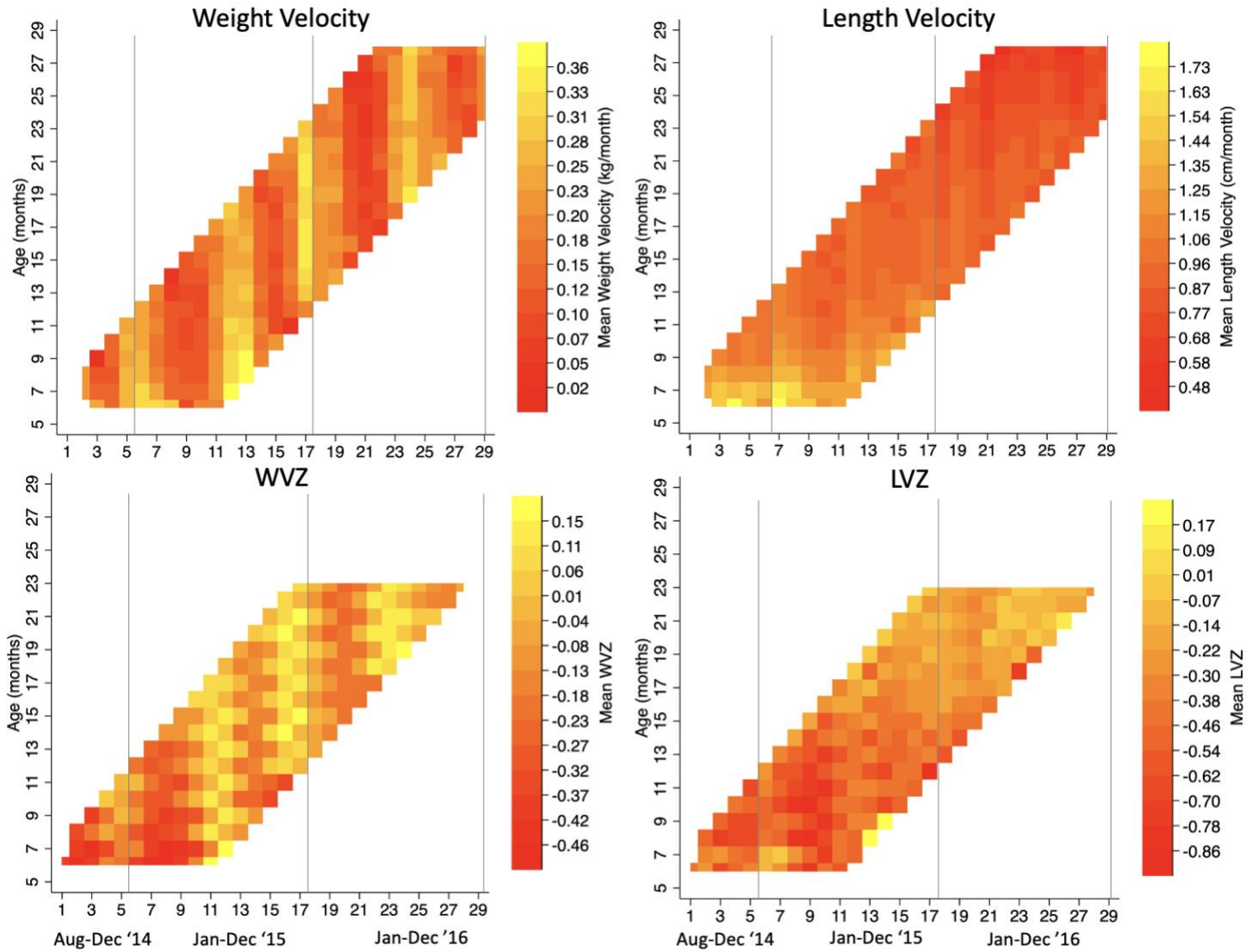


Figure 1B. Heat-plots showing mean anthropometric velocity by age and calendar time. Study month 1= August 2014, study month 29 = December 2016. WVZ = weight velocity z-score; LVZ = length velocity z-score.

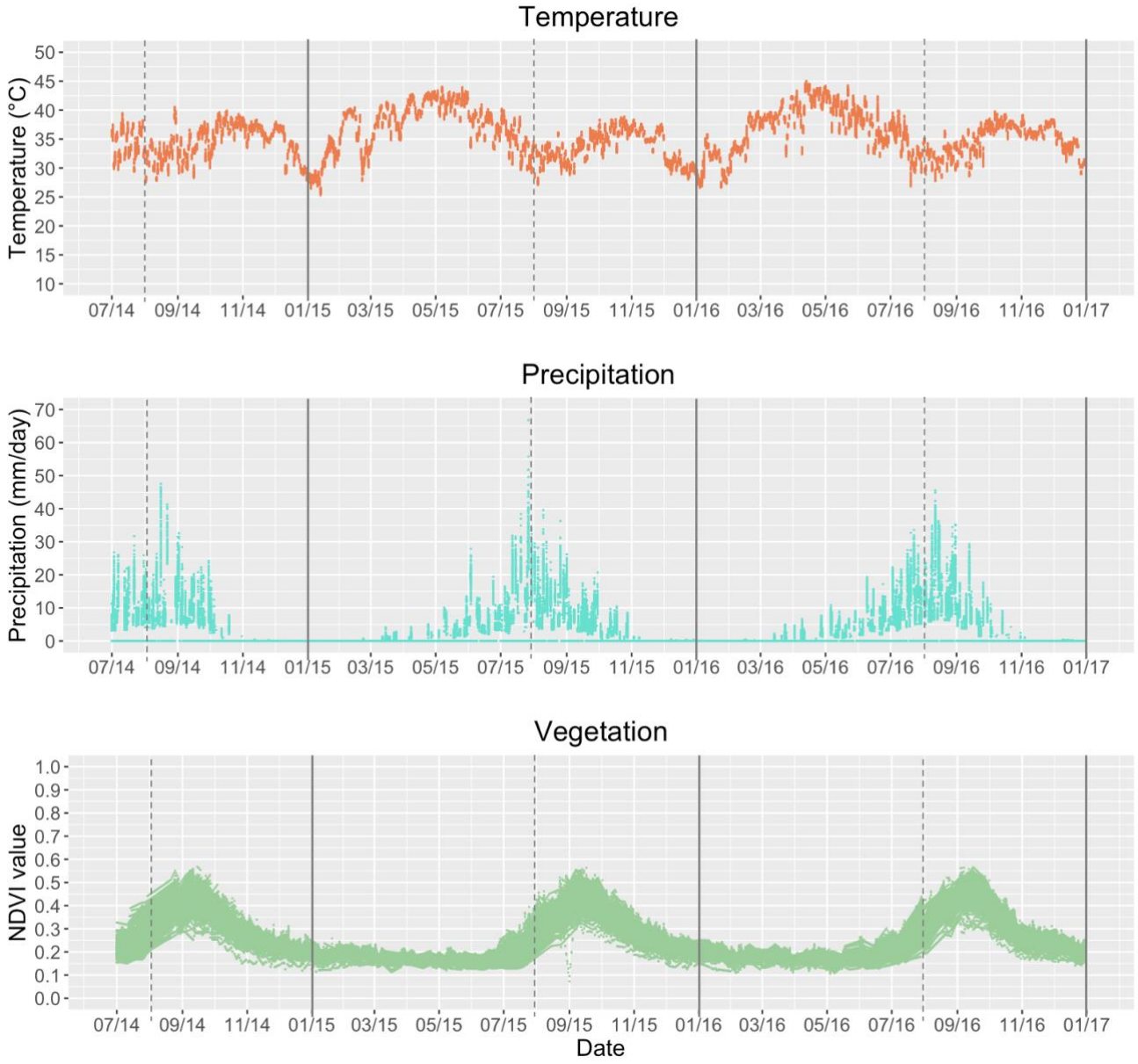


Figure 2. Seasonality of climatic variables in 199 villages in Sanmatenga Province, Burkina Faso, 2014-2016. Temperature is maximum daily temperature. Vegetation is expressed as the Normalized Difference Vegetation Index (NDVI). Solid reference lines indicate calendar years; dotted reference lines indicate study years.

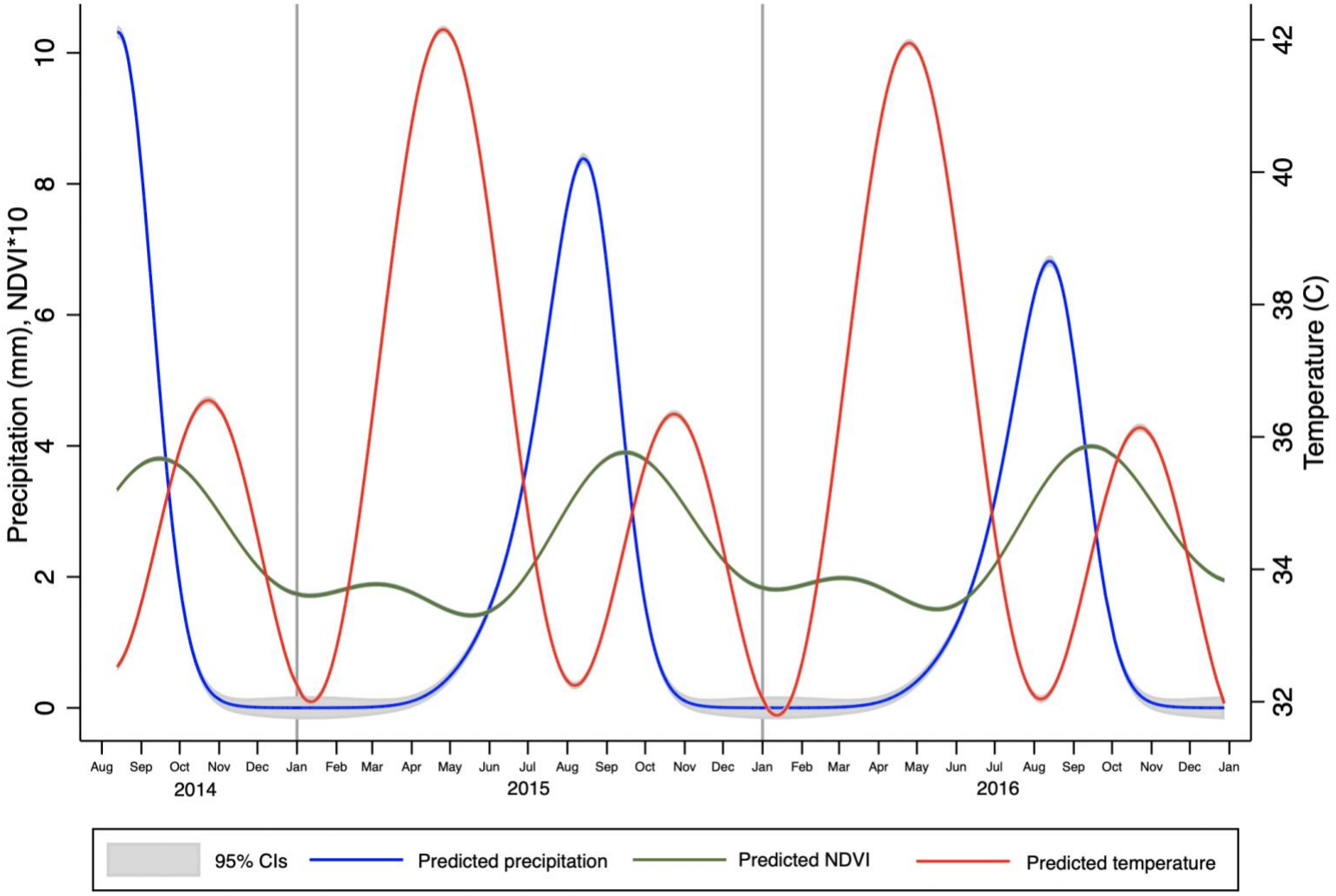


Figure 3. Harmonic model predictions of daily precipitation (mm), Normalized Difference Vegetation Index (NDVI), and maximum temperature (°C).

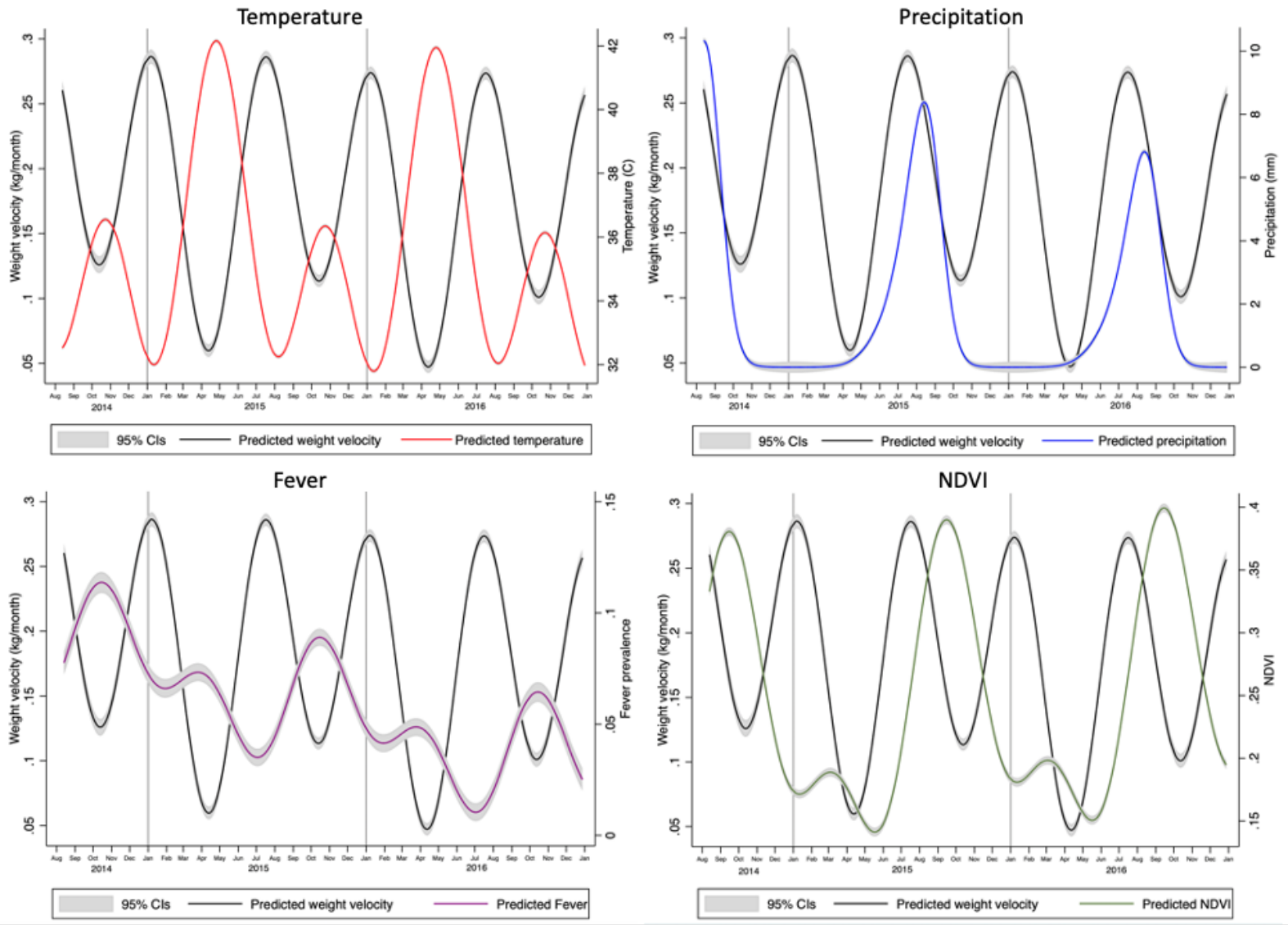


Figure 4. Weight velocity seasonality using harmonic model predictions, overlaid on selected climatic and morbidity predictions. Light gray reference lines indicate calendar years

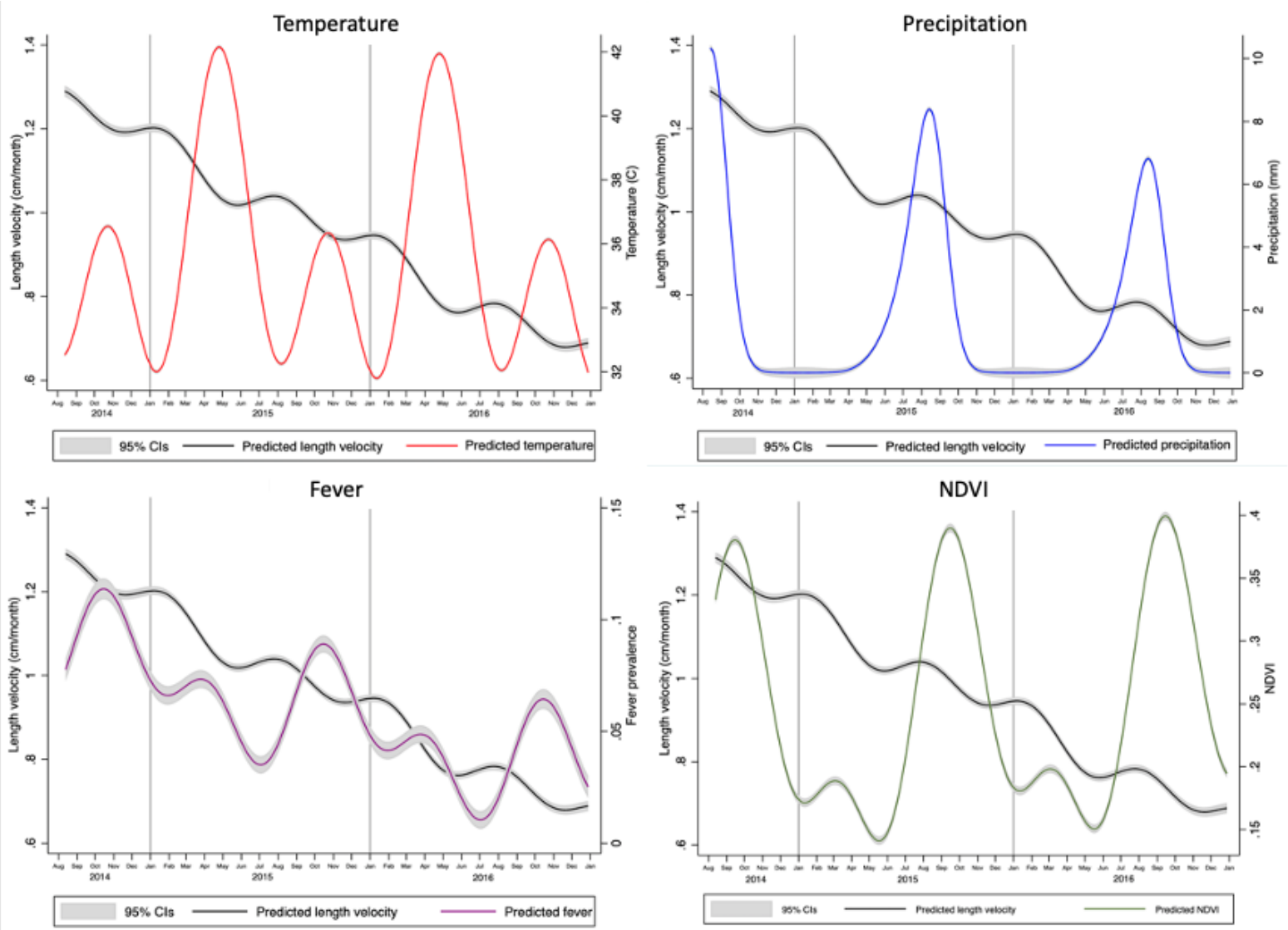


Figure 5. Length velocity seasonality using harmonic model predictions, overlaid on selected climatic and morbidity predictions. Light gray reference lines indicate calendar years

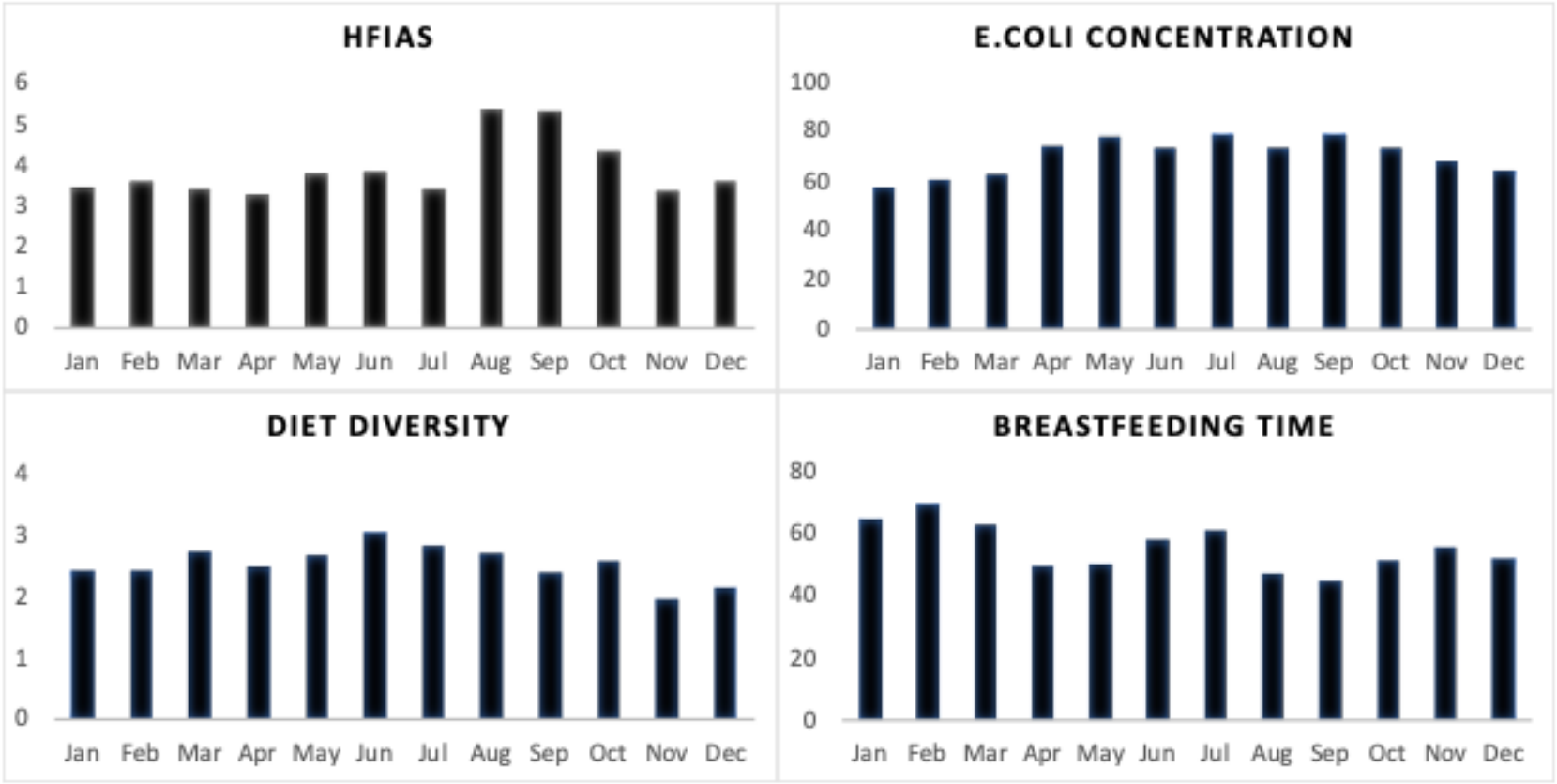


Figure 6. Mean food and nutrition security variables by calendar month. HFIAS = Household Food Insecurity Access Score. E.coli concentration is from household drinking water source, and was tested using the AquagenX Compartment Bag Test. Diet diversity was calculated using the Infant and Young Child Minimum Diet Diversity scale, with values ranging from 0-8. Breastfeeding time is average time in minutes per day and was clocked during 4-day in-home observations.

Supplementary Material

Supplementary Table 1. Summary of harmonic model results

Outcome	$\beta 0$	$\beta 1$	p-value	$\beta 2$	p-value	$\beta 3$	p-value	$\beta 4$	p-value	$\beta 5$	p-value
Growth Outcomes											
LV	1.2667	-0.0007	0.000	-0.0108	0.000	0.0205	0.000	0.0300	0.000	0.0132	0.000
LV boys	1.2515	-0.0007	0.000	-0.0115	0.001	0.0242	0.000	0.0239	0.000	0.0135	0.000
LV girls	1.2827	-0.0007	0.000	-0.0101	0.006	0.0166	0.000	0.0363	0.000	0.0126	0.001
WV	0.1957	0.0000	0.000	-0.0301	0.000	0.0027	0.068	0.0367	0.000	0.0905	0.000
WV boys	0.1869	0.0000	0.021	-0.0349	0.000	0.0001	0.946	0.0373	0.000	0.0927	0.000
WV girls	0.2049	-0.0001	0.000	-0.0251	0.000	0.0053	0.010	0.0362	0.000	0.0883	0.000
LVZ	-0.6933	0.0008	0.000	-0.0481	0.000	0.0308	0.000	0.0360	0.000	0.0593	0.000
LVZ boys	-0.6832	0.0008	0.000	-0.0530	0.000	0.0383	0.000	0.0291	0.000	0.0521	0.000
LVZ girls	-0.7058	0.0008	0.000	-0.0430	0.000	0.0230	0.000	0.0432	0.000	0.0668	0.000
WVZ	-0.2604	0.0004	0.000	-0.0604	0.000	-0.0280	0.000	-0.0858	0.000	0.1163	0.000
WVZ boys	-0.2940	0.0005	0.000	-0.0694	0.000	-0.0341	0.000	-0.0910	0.000	0.1179	0.000
WVZ girls	-0.2250	0.0004	0.000	-0.0511	0.000	-0.0215	0.000	-0.0803	0.000	0.1144	0.000
LAZ	-0.6022	-0.0011	0.000	0.0032	0.021	0.0116	0.000				
WAZ	-1.0470	-0.0003	0.000	-0.0204	0.000	0.0740	0.000	0.0922	0.000	0.0051	0.003
WAZ boys	-1.1766	-0.0003	0.000	-0.0282	0.000	0.0817	0.000	0.0934	0.000	0.0034	0.166
WAZ girls	-0.9065	-0.0004	0.000	-0.0123	0.000	0.066	0.000	0.0911	0.000	0.0068	0.000
WLZ	-0.9095	0.0001	0.000	-0.0227	0.000	0.0926	0.000	0.1221	0.000	0.0178	0.000
WLZ boys	-0.9976	0.0001	0.000	-0.0350	0.000	0.1029	0.000	0.1262	0.000	0.0152	0.000
WLZ girls	-0.8092	0.0001	0.000	-0.0100	0.000	0.0821	0.000	0.1179	0.000	0.0204	0.000
Climate Outcomes											
NDVI	0.2271	0.0000	0.000	-0.0992	0.000	-0.0149	0.000	0.0335	0.000	-0.0418	0.000
Precipitation	-1.5073	-0.001	0.000	-1.3985	0.000	-3.8354	0.000	0.1380	0.000	-0.7829	0.000
Temperature	36.0037	-0.001	0.000	2.5491	0.000	-1.2967	0.000	-2.496	0.000	-2.370	0.000

Morbidity Outcomes											
Fever	0.0857	-0.0001	0.000	-0.0130	0.000	0.0128	0.000	-0.005	0.000	-0.0160	0.000
Diarrhea	0.0770	-0.0001	0.000	-0.0029	0.001	0.0059	0.000				
URS	0.1072	-0.0001	0.000	0.0146	0.000	0.0275	0.000	-0.0037	0.000	-0.0039	0.000
Malaria	0.0145	0.0000	0.000	-0.0249	0.000	0.0010	0.096	0.0014	0.013	-0.0155	0.000
Any illness	0.4471	-0.0003	0.000	-0.0082	0.000	0.0692	0.000	-0.0100	0.000	-0.0398	0.000

Notes: Notes: LAZ = length-for-age z-scores; WLZ=weight-for-length z-scores; LVZ = length velocity z-scores; WVZ = weight velocity z-scores; LV = length velocity (cm/month); WV = weight velocity (kg/month); URS = upper respiratory symptoms; NDVI = Normalized Difference Vegetation Index

$\beta 0$ =Intercept;
$\beta 1$=time trend;

$\beta 2= \sin(2\pi(\frac{day}{365.25}))$
$\beta 3= \cos(2\pi(\frac{day}{365.25}))$
$\beta 4= \sin(4\pi(\frac{day}{365.25}))$
$\beta 5= \cos(4\pi(\frac{day}{365.25}))$

Supplementary Table 2. Specific timing and magnitude of peaks and nadirs in anthropometric indices, climatic variables and morbidity, including models stratified by child sex

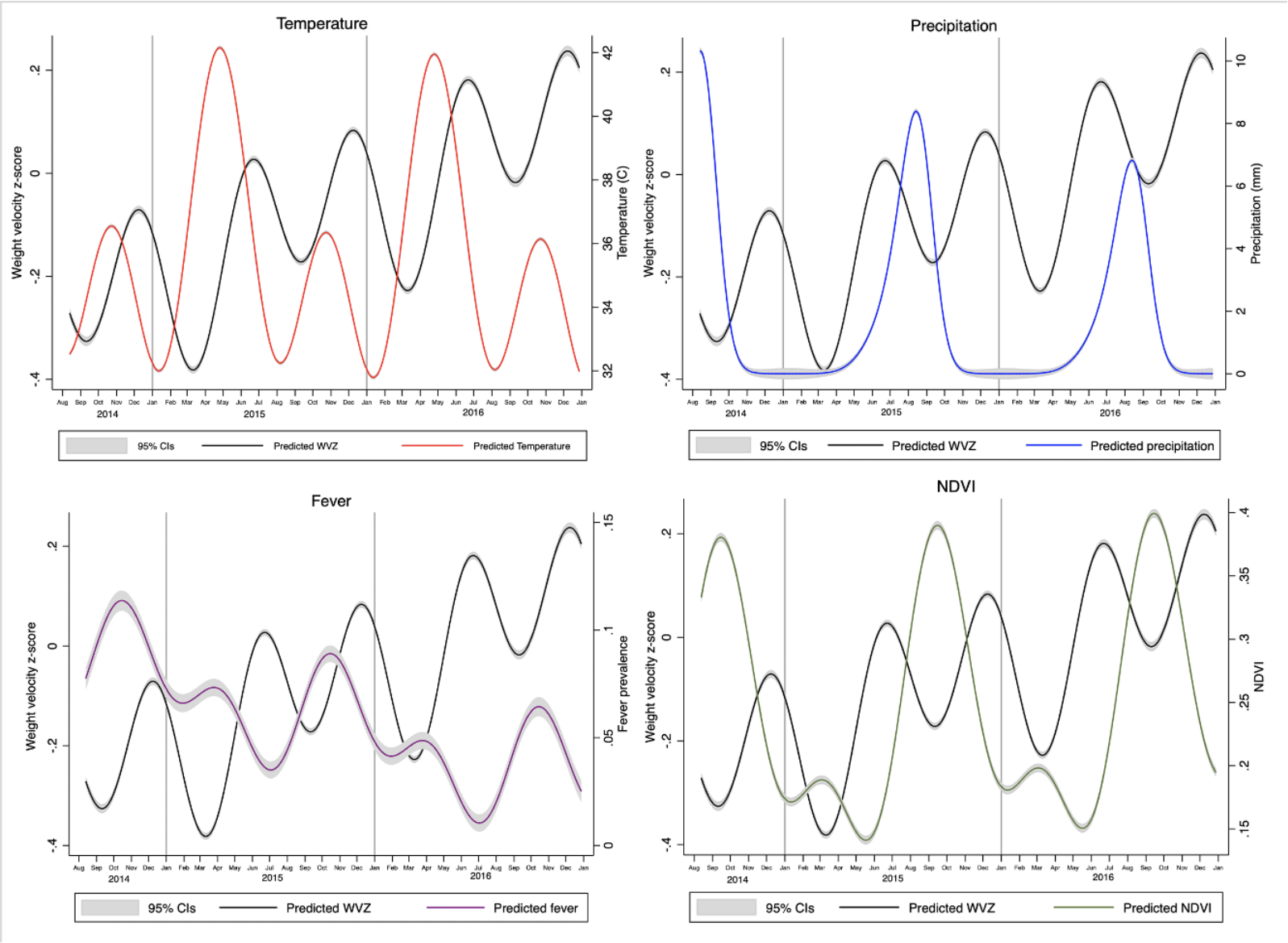
	Peak timing	Peak value	Nadir timing	Nadir value	Amplitude
LV			20-Nov-14	1.19214623	NA
	6-Jan-15	1.20227843	27-May-15	1.01829687	0.18398156
	25-Jul-15	1.03973408	21-Nov-15	0.93570306	0.10403102
	6-Jan-16	0.94583564	26-May-16	0.76185244	0.1839832
	24-Jul-16	0.78328991	20-Nov-16	0.67925981	0.1040301
LV boys			20-Nov-14	1.18635625	-1.1863562
	28-Dec-14	1.19090409	30-May-15	1.00556801	0.18533608
	20-Jul-15	1.01763736	20-Nov-15	0.92998747	0.0876499
	28-Dec-15	0.93453684	29-May-16	0.74919663	0.18534022
	20-Jul-16	0.7612689	19-Nov-16	0.67361981	0.08764909
	27-Dec-16	0.67816836			NA
LV girls			21-Nov-14	1.19831827	NA
	13-Jan-15	1.21615695	25-May-15	1.03152231	0.18463465
	28-Jul-15	1.06331578	21-Nov-15	0.94180301	0.12151277
	14-Jan-16	0.9596422	24-May-16	0.77500566	0.18463654
	28-Jul-16	0.8068018	20-Nov-16	0.68528987	0.12151193
WV			13-Oct-14	0.12593115	NA
	7-Jan-15	0.28644095	13-Apr-15	0.05967485	0.2267661
	17-Jul-15	0.28613579	13-Oct-15	0.11344203	0.17269377
	7-Jan-16	0.27395589	12-Apr-16	0.047175	0.22678089
	16-Jul-16	0.27363428	12-Oct-16	0.10095958	0.1726747
WV boys			13-Oct-14	0.12021885	NA
	6-Jan-15	0.27925298	12-Apr-15	0.04838351	0.23086948
	18-Jul-15	0.28881385	14-Oct-15	0.11380045	0.1750134
	6-Jan-16	0.27281721	11-Apr-16	0.04195736	0.23085986
	17-Jul-16	0.28238878	13-Oct-16	0.10736197	0.17502681
WV girls			13-Oct-14	0.13195509	NA
	7-Jan-15	0.29395408	13-Apr-15	0.07130925	0.22264483
	17-Jul-15	0.28342969	13-Oct-15	0.11313929	0.1702904
	7-Jan-16	0.27513478	13-Apr-16	0.05250189	0.22263288
	16-Jul-16	0.26462633	12-Oct-16	0.09433008	0.17029626

LVZ			29-Sep-14	-0.6640548	NA
	15-Jan-15	-0.4774345	12-Apr-15	-0.6132481	0.13581365
	12-Aug-15	-0.3383301	29-Sep-15	-0.3606078	0.02227775
	15-Jan-16	-0.1739841	11-Apr-16	-0.3097995	0.13581537
	11-Aug-16	-0.0348768	28-Sep-16	-0.0571575	0.02228071
LVZ boys	21-Aug-14	-0.6407666	18-Sep-14	-0.6447258	0.00395914
	12-Jan-15	-0.4715221	12-Apr-15	-0.6013904	0.1298683
	21-Aug-15	-0.3392145	18-Sep-15	-0.3431737	0.00395917
	12-Jan-16	-0.1699777	11-Apr-16	-0.2998456	0.12986788
	20-Aug-16	-0.0376642	18-Sep-16	-0.0416232	0.00395899
LVZ girls			5-Oct-14	-0.689011	0.689011
	17-Jan-15	-0.4849534	12-Apr-15	-0.6272488	0.14229538
	7-Aug-15	-0.3363252	5-Oct-15	-0.3831186	0.04679339
	17-Jan-16	-0.1790624	11-Apr-16	-0.3213474	0.14228495
	6-Aug-16	-0.0304242	4-Oct-16	-0.0772217	0.04679749
WVZ			11-Sep-14	-0.3262105	NA
	9-Dec-14	-0.0706928	11-Mar-15	-0.3818703	0.31117753
	22-Jun-15	0.02726437	11-Sep-15	-0.1720875	0.19935188
	9-Dec-15	0.08345686	10-Mar-16	-0.2277207	0.31117756
	22-Jun-16	0.18141018	10-Sep-16	-0.017955	0.19936522
	8-Dec-16	0.237596			NA
WVZ boys			10-Sep-14	-0.3519936	NA
	8-Dec-14	-0.0935453	10-Mar-15	-0.4166707	0.32312539
	23-Jun-15	0.02285279	10-Sep-15	-0.172953	0.19580579
	8-Dec-15	0.08549952	9-Mar-16	-0.2376119	0.32311139
	22-Jun-16	0.20189455	9-Sep-16	0.00609713	0.19579741
	7-Dec-16	0.26455613			
WVZ girls			11-Sep-14	-0.2987807	0.29878069
	10-Dec-14	-0.0463477	12-Mar-15	-0.3455231	0.29917546
	22-Jun-15	0.03189721	12-Sep-15	-0.1707985	0.20269573
	10-Dec-15	0.08163884	12-Mar-16	-0.2175369	0.29917577
	21-Jun-16	0.15987912	11-Sep-16	-0.0428237	0.20270286
	9-Dec-16	0.20961513			NA
LAZ	-	-	-	-	
WAZ	23-Aug-14	-0.9917825	10-Nov-14	-1.1060873	0.11430485
	1-Feb-15	-0.9687278	24-May-15	-1.3029926	0.33426474

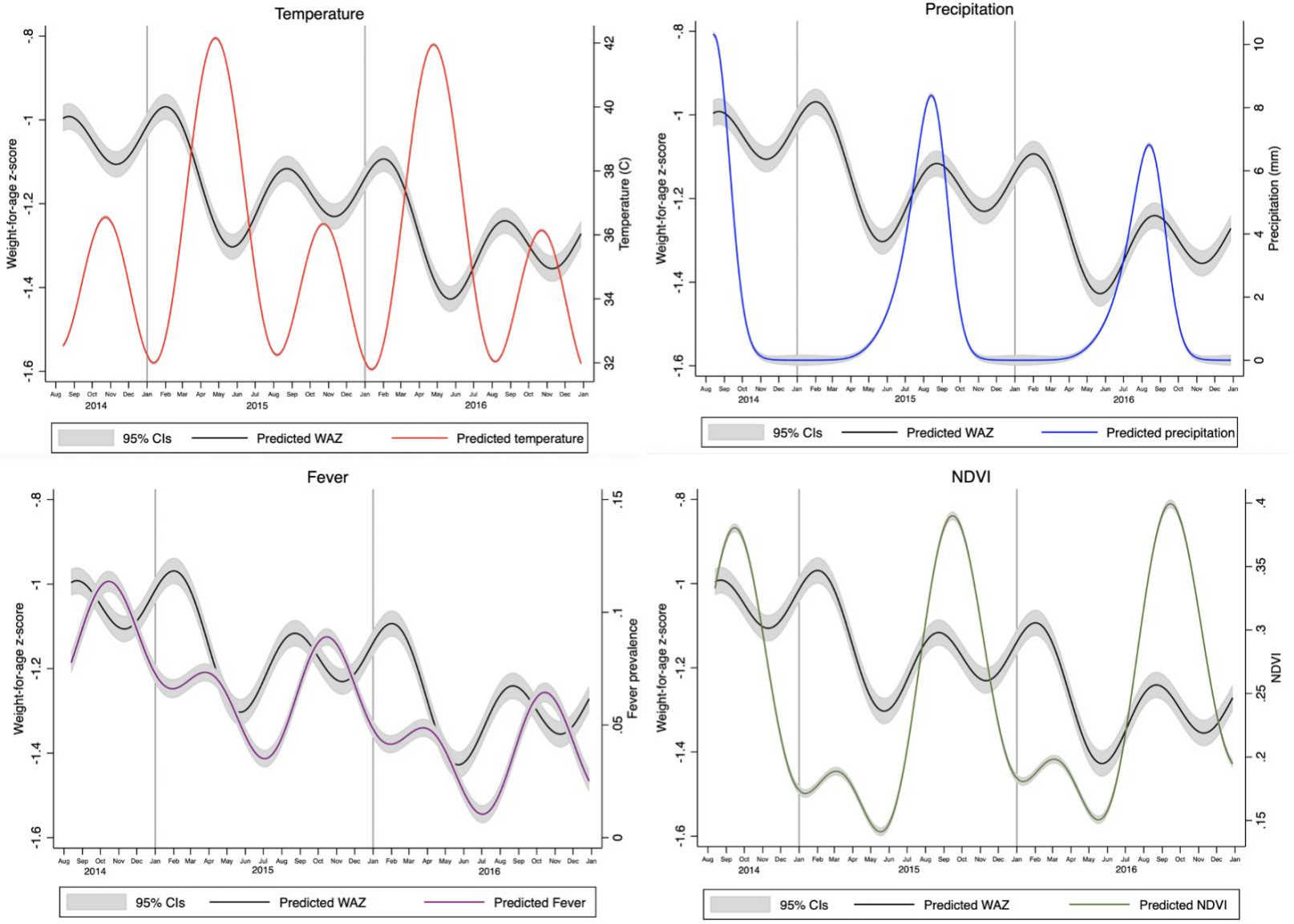
	23-Aug-15	-1.1162564	10-Nov-15	-1.2305581	0.11430166
	1-Feb-16	-1.0932093	23-May-16	-1.4274785	0.33426917
	22-Aug-16	-1.2407364	10-Nov-16	-1.3550377	0.11430134
WAZ boys	26-Aug-14	-1.1177669	10-Nov-14	-1.221762	0.10399508
	31-Jan-15	-1.0881883	23-May-15	-1.4329825	0.34479419
	26-Aug-15	-1.2266781	10-Nov-15	-1.3306718	0.1039937
	1-Feb-16	-1.1971026	23-May-16	-1.5419101	0.34480752
	25-Aug-16	-1.3355952	10-Nov-16	-1.4395963	0.10400112
WAZ girls	23-Aug-14	-0.9917825	10-Nov-14	-1.1060873	0.11430485
	1-Feb-15	-0.9687278	24-May-15	-1.3029926	0.33426474
	23-Aug-15	-1.1162564	10-Nov-15	-1.2305581	0.11430166
	1-Feb-16	-1.0932093	23-May-16	-1.4274785	0.33426917
	22-Aug-16	-1.2407364	10-Nov-16	-1.3550377	0.11430134
WLZ	23-Aug-14	-0.8333946	3-Nov-14	-0.9500705	0.11667593
	3-Feb-15	-0.7069025	18-May-15	-1.0835999	0.37669739
	24-Aug-15	-0.7943908	3-Nov-15	-0.9110656	0.11667487
	3-Feb-16	-0.6679034	17-May-16	-1.0445859	0.37668251
	23-Aug-16	-0.7553727	2-Nov-16	-0.8720533	0.11668061
WLZ boys	26-Aug-14	-0.9128666	3-Nov-14	-1.0232902	0.11042363
	2-Feb-15	-0.7870217	18-May-15	-1.1863988	0.39937712
	26-Aug-15	-0.8667388	4-Nov-15	-0.9771665	0.11042769
	3-Feb-16	-0.7408889	17-May-16	-1.1402533	0.3993644
	25-Aug-16	-0.8206189	3-Nov-16	-0.9310404	0.11042144
WLZ girls	20-Aug-14	-0.7409292	2-Nov-14	-0.8650501	0.12412082
	4-Feb-15	-0.6145759	18-May-15	-0.9680594	0.35348342
	21-Aug-15	-0.7091509	2-Nov-15	-0.8332686	0.12411772
	4-Feb-16	-0.5828004	17-May-16	-0.9362864	0.35348605
	20-Aug-16	-0.6773671	2-Nov-16	-0.8014834	0.1241163
Precipitation	14-Aug-14	10.3190376	10-Jan-15	0.00183424	10.3172033
	14-Aug-15	8.39126559	10-Jan-16	0.00149152	8.38977407
	13-Aug-16	6.82312316			6.82312316
Temp	24-Oct-14	36.5528129	12-Jan-15	31.9989155	4.55389744
	26-Apr-15	42.1561863	7-Aug-15	32.2449926	9.91119368
	24-Oct-15	36.3469243	12-Jan-16	31.7931913	4.55373305
	25-Apr-16	41.9505689	6-Aug-16	32.0391785	9.91139038
	23-Oct-16	36.1412824			NA

NDVI	25-Sep-14	0.38054476	11-Jan-15	0.17125669	0.20928807
	4-Mar-15	0.18882411	18-May-15	0.14107497	0.04774914
	15-Sep-15	0.3899636	12-Jan-16	0.18068339	0.20928021
	3-Mar-16	0.19824602	17-May-16	0.15049468	0.04775134
	15-Sep-16	0.39938359			
Fever	15-Oct-14	0.11373636	30-Jan-15	0.06608238	0.04765398
	25-Mar-15	0.0733673	3-Jul-15	0.03503504	0.03833227
	15-Oct-15	0.08908086	30-Jan-16	0.04142778	0.04765308
	25-Mar-16	0.04871307	2-Jul-16	0.01038228	0.03833079
	15-Oct-16	0.06442529			NA
Diarrhea	23-Oct-14	0.07648047	19-Jul-15	0.04634815	0.03013232
	23-Oct-15	0.04868488	18-Jul-16	0.01855257	0.03013231
	23-Oct-16	0.02088928			NA
URS	3-Jan-15	0.11484401	4-Aug-15	0.0307372	0.08410681
	3-Jan-15	0.07342445	3-Aug-16	-0.0106812	0.08410565
Malaria	30-Sep-14	0.05538407	22-Jan-15	-0.0022023	0.05758636
	28-Mar-15	0.00784941	6-Jun-15	-0.0045328	0.0123822
	30-Sep-15	0.05958276	22-Jan-16	0.00199739	0.05758537
	27-Mar-16	0.01205044	5-Jun-16	-0.0003339	0.01238434
	30-Sep-16	0.06378337			NA
Any Illness	26-Oct-14	0.49816446	28-Jan-15	0.43101168	0.06715277
	2-Mar-15	0.43478904	9-Jul-15	0.25454779	0.18024124
	25-Oct-15	0.40542455	29-Jan-16	0.33827435	0.06715021
	1-Mar-16	0.34205014	8-Jul-16	0.16180582	0.18024432
	25-Oct-16	0.31268679			NA

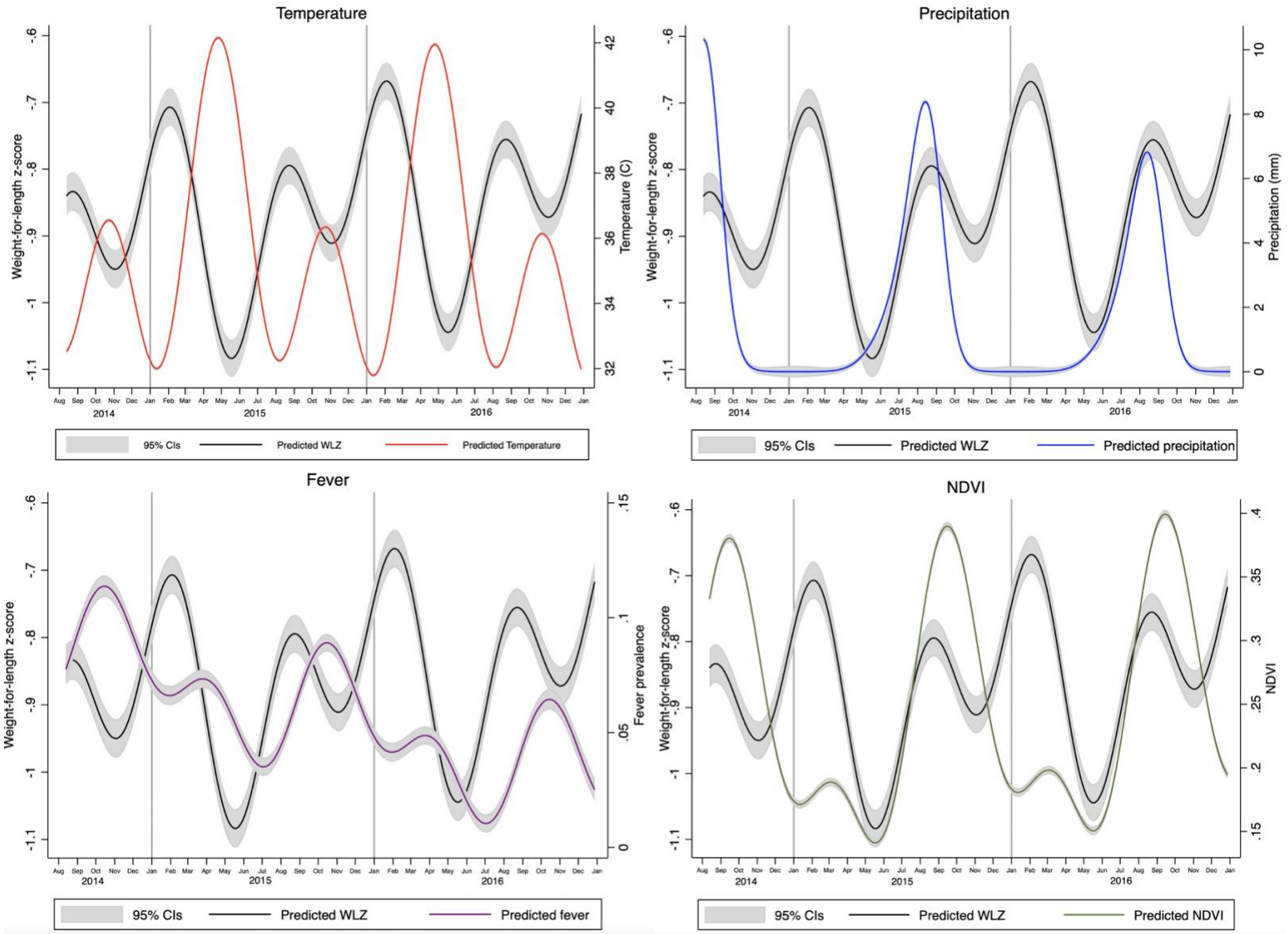
Notes: LAZ = length-for-age z-scores; WLZ=weight-for-length z-scores; LVZ = length velocity z-scores; WVZ = weight velocity z-scores; LV = length velocity (cm/month); WV = weight velocity (kg/month); URS = upper respiratory symptoms; NDVI = Normalized Difference Vegetation Index



Supplementary Figure 1. Weight velocity z-score seasonality using harmonic model predictions, overlaid on selected climatic and morbidity predictions. Light gray reference lines indicate calendar years



Supplementary Figure 2. Weight for-age z-score seasonality using harmonic model predictions, overlaid on selected climatic and morbidity predictions. Light gray reference lines indicate calendar years



Supplementary Figure 3. Weight for-length z-score seasonality using harmonic model predictions, overlaid on selected climatic and morbidity predictions. Light gray reference lines indicate calendar years

Chapter 7: Conclusions

Summary of findings

All three aims of this dissertation were centered around determining the timing of growth faltering along an individual child's growth trajectory among children 6-27 months in Sanmatenga Province, Burkina Faso. The first aim focused on the timing of onset and continued intensity of linear growth faltering, asking whether children who experience linear growth faltering end up too short for their age because of continuously slow growth or because of intermittent episodes of slow growth. The second aim was to determine the bi-directional temporal relationships between linear and ponderal growth velocities. The third and last aim was to establish the relationship between peak timing of climatic exposures (temperature, precipitation, vegetation) and peak timing of growth faltering.

Regarding the timing of onset and continued intensity of growth faltering, we found that longitudinal patterns of growth faltering appear to closely align with the patterns identified by cross-sectional studies. Children who end up short started small at 6 months of age and stayed on their initial growth trajectories, continuously growing slower than those who ended up taller. We discovered that smooth growth is important for attained length and that the most influential period for growth between 6-27 months is 9-11 months. Length velocity from 9-11 months is associated with almost twice the increase in attained length as the next most influential period from 12-14 months. Among the shortest children, growth velocities diverge further from the reference population as children age, which is even more apparent when assessed using LAD instead of LAZ. Using LAD, we identified that growth faltering continues after the 1,000-day window among the shortest children in our sample. In addition, growth tempo appears to play a key role in overall height attainment; the tallest children had already reached the ending height of

the shortest children by the time they were 10 months. Regardless, growth faltering occurs to some degree among almost all children in our sample, which can be observed by the whole-population shift in the distribution of LAZ across quintiles of attained height by the study end.

We established an important bi-directional temporal relationship between linear and ponderal growth velocities. Episodes of faster weight growth are associated with concurrent and subsequent faster length growth, showing that the same growth-limiting conditions likely affect both anthropometric growth parameters. Multiple insults to ponderal growth velocity perpetuated by the vicious cycle of infection, inadequate dietary intake, and lowered immunity will continuously lead to slower linear growth velocity. Episodes of faster length growth, however, are associated with lower subsequent weight growth. This indicates that linear growth spurts may not be accompanied by sufficient dietary intake to avoid slow-downs in ponderal growth. These temporal relationships are strongest among the youngest children and among male children, who appear more vulnerable to growth insults than female children.

Using harmonic regressions with higher-order sine and cosine terms, we improved the precision and accuracy of growth seasonality models and found that growth indicators are highly synchronized with peak temperature and the incidence of fever and diarrhea. Contrary to previous growth seasonality research, we did not find increased growth faltering during peak precipitation, but rather at the beginning and end of the rainy period. We find two seasonal peaks for all growth indicators, as well as for temperature and fever, meaning that there are two time points in the year in which children in central-northern Burkina Faso are especially vulnerable to growth faltering. Weight velocities slow down around the same time as peaks in fever and temperature, followed shortly thereafter by slowdowns in length velocities. Pathogens that cause

diarrheal disease and fever may have more opportunities to infect children when temperatures are high and precipitation is low.

Implications of findings

Findings from this dissertation highlight several key areas of potential improvement for growth faltering programs and reveal important policy implications.

Results from all three aims indicate that young children in central-northern Burkina Faso are all experiencing environmental conditions that increase their risk for infection, leading to both linear and ponderal growth faltering among a significant proportion of the population. By the time the children in our sample reach 24 months, even those in the highest attained length categories have a distribution of length-for-age z-scores that is shifted to the left of the WHO growth reference population distribution. This issue with whole-of-population undernutrition is not unique to Burkina Faso – the newest Lancet series on maternal and child undernutrition published in March 2021 revealed population-level downward shifts in both HAZ and WHZ among children from 31 low-income countries (1). That children who experience the most extreme growth faltering are consistently growing much slower than expected indicates that these children are constantly living in growth-constraining conditions. Further, the fact that smoothness of growth matters for attained length suggests that growth may be disproportionately influenced by adverse environmental and nutritional factors in these children compared to those who end up taller. Addressing environmental constraints is key to improving nutrition and health outcomes.

While these environmental growth-constraining conditions exist year-round, they are most dangerous during the hottest times of the year, when the rains are just beginning and just ending. The commonly accepted theory that growth faltering is accelerated during the rainy

season, when food is in short supply, caregivers have less time to look after their children, and disease incidence is highest, has largely been informed by studies that have considered seasonality as a categorical, usually binary, predictor of growth. Based on our harmonic regression models which identify with precision the temporal relationship among growth outcomes, climatic factors and morbidity, infection appears to be the dominant driver of nutritional status, rather than food insecurity. The combination of climatic conditions in the hottest times of the year, when rains are beginning and ending, are clearly prime for infection. Bacterial pathogens replicate faster and survive longer in higher temperatures, and the shortage of water during the hot, dry season might mean that people have to consume unsafe water and reduce their hygiene practices. In addition, results from our models of the statistical relationship between climatic factors, morbidity and anthropometry revealed morbidity to be the overwhelming driver of anthropometric indices, as well as coinciding with peak temperature.

As the climate continues to change, the high ambient temperatures in central-northern Burkina Faso that permit pathogens to thrive are only likely to increase. Climate change policy is thus central to keeping the environment safe for growing children. Programmatically, the focus should be on ways to mitigate threats of infection, especially during the highest risk periods. This means systemic, community-level improvements in infrastructure (water and sanitation, irrigation systems, road access, building design) that will allow for better access to hygienic living situations. Individual or household-level interventions are unlikely to succeed if the entire community environment is not conducive to optimal growth.

Using growth velocity indicators, we have identified that ponderal growth slows first in reaction to environmental stressors that cause infection, and that linear growth slows shortly thereafter. Thus, if environmental constraints that affect faltering in both anthropometric

parameters are addressed, programs may be effective in preventing both linear and ponderal growth deficits. However, what length growth there is in the environment of Burkina Faso is not followed by adequate weight gain, and children have slower weight growth after linear growth spurts. In addition, we identify a specific sub-period, from 9-11 months, in which children may be especially vulnerable to growth faltering, likely due to their increased reliance on household complementary foods. Our results stress the importance of adequate dietary intake during periods of intense linear growth, which may coincide with this sub-period. Structural, environmental changes as mentioned above will help ensure food safety during this period and reduce the risk of infection, but children may need extra support for diet adequacy during this most influential growth period. Complementary feeding support including provision of appropriate supplementary foods when necessary and increasing both maternal and paternal knowledge of optimal feeding practices during this brief but important period, as children transition to consumption of (ideally) 3-4 full household meals per day, could be an efficient and effective way of decreasing the burden of growth faltering.

Breaking the intergenerational cycle of undernutrition is a challenge. That children who entered the study already short at 6 months also ended up short, continuing to diverge further and further from the median length for their age as they got older stresses the importance of early intervention to prevent growth faltering from occurring in utero, and continuing support for optimal growth even after the 1,000-day window. Though we did not have data on children's growth prior to six months, if we extrapolate their growth trajectories backwards, it is likely that children who were already short at 6 months were also born smaller. The recently updated Lancet series on maternal and child undernutrition highlights the role of short maternal height and low body-mass index in determining children's nutritional status through their effects on

birth size; children who are small for gestational age account for at least a fifth of the childhood stunting burden in low- and middle- income countries (1). Putting our results into the context of the known pathways between short mothers, low birthweight, and subsequent growth faltering reveals the importance of ensuring the health of mothers long before they become pregnant. Interventions that support proper nutrition and hygiene throughout the pre-conception period during adolescence and take advantage of the opportunity for catch-up growth during this time may help break the intergenerational cycle.

In sum, large-scale systemic improvements to the structural level factors that constrain both linear and ponderal growth at all times among entire populations are needed to improve growth trajectories. Our findings, though based on a cohort of children from the relatively small geographic region of northern Burkina Faso, complement and align with studies from a variety of low-income country contexts (1–3), showing the likelihood of generalizability. Structural improvements, combined with climate change policy actions, are urgently needed to keep environments safe and conducive to growth and development while increasing population health and human capital.

Directions for future research

In this dissertation, we used unique methods to analyze high-frequency longitudinal growth data with the objective of gaining a deep understanding of the processes underlying growth faltering. In doing so, we make several observations about the trade-offs between research investments that prioritize more frequent data points collected during longitudinal studies versus larger, often cross-sectional sample sizes. Though ideal study design would combine large sample sizes with frequent data collection, in reality, logistical and financial constraints often force a choice between the two.

In making that choice, the central consideration should be the factors driving the research question. First, researchers should consider the trade-offs between generalizability of their results and depth of understanding of an issue. Though high-frequency data points certainly allow for a deeper understanding of growth processes, the generalizability of large cross-sectional studies that assess multiple contexts at once must be weighed against more focused longitudinal cohort studies that are less generalizable by nature due to their relatively smaller sample sizes. If the objective is to understand within-population or within-individual differences in growth patterns, cross-sectional data is insufficient; however, if the objective is to observe differences in growth metrics between populations, using cross-sectional data may be more appropriate.

Second, longitudinal studies require large enough sample sizes to account for within-subject correlation, with increasing sample sizes needed for higher internal autocorrelation between repeated measurements within a single participant, but smaller required sample sizes as the number of repeated measurements increases. If autocorrelation between measurements is very high, repeated measurements may not provide additional information in relation to cross-sectional data. However, if repeated measures are not closely correlated to each other, the additional statistical power of longitudinal studies is an advantage.

That our longitudinal study of the timing of growth faltering among individuals was so closely aligned with previous cross-sectional studies is encouraging in terms of the likely utility of assessing growth trends with accessible, lower-cost cross-sectional data. However, such cross-sectional studies on any emerging research area related to growth faltering should be compared with longitudinal data that provides more information on individual-level growth trajectories whenever possible.

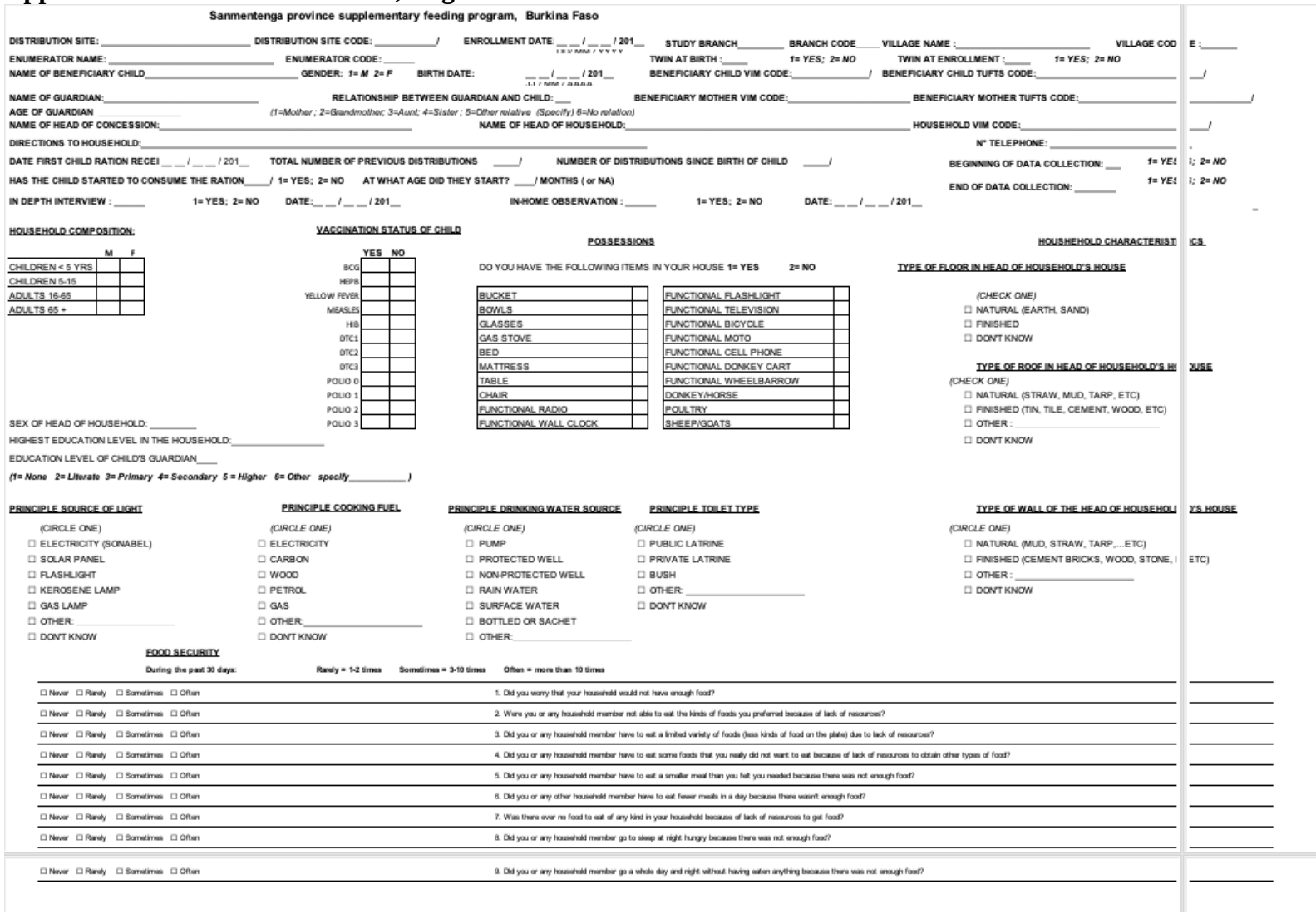
Future studies in longitudinal growth faltering should seek to understand the factors that contribute to periods of slow growth and measure the duration of slow growth episodes. In addition, gender disparities in longitudinal growth trajectories between males and females require further study, especially to understand how the infection-undernutrition cycle may differ between them. High-frequency data collection is needed on food security, diet diversity, breastfeeding, and infection exposures to further explain the underlying pathways between slow growth of different types. In these future endeavors, longitudinal growth researchers should take care to use suitable indicators for studying longitudinal growth; in addition to assessing growth outcomes using attained size indicators that include information on all growth up to the point of measurement, researchers should use velocity indicators that provide information on current growth-limiting conditions. Appropriate methods should also be used for modeling growth seasonality that consider the spatial and temporal variability in climatic factors and check for multiple yearly peaks of undernutrition.

References

1. C. G. Victora, *et al.*, Revisiting maternal and child undernutrition in low-income and middle-income countries: variable progress towards an unfinished agenda. *Lancet* (2021).
2. J. Benjamin-chung, *et al.*, Early childhood linear growth failure in low- and middle-income countries. *Pre-print*, 1–40 (2020).
3. A. Mertens, *et al.*, Child wasting and concurrent stunting in low- and middle-income countries. *medRxiv Pre-print*, 2020.06.09.20126979 (2020).

Appendices

Appendix 1. Enrollment/Exit form, English translation



Sanmentenga province supplementary feeding program, Burkina Faso

DISTRIBUTION SITE: _____ DISTRIBUTION SITE CODE: _____/ ENROLLMENT DATE: __ __ / __ __ / 201__ (DD / MM / YYYY) STUDY BRANCH_____ BRANCH CODE____ VILLAGE NAME :_____ VILLAGE COD E :_____

ENUMERATOR NAME: _____ ENUMERATOR CODE: _____ TWIN AT BIRTH :____ 1= YES; 2= NO TWIN AT ENROLLMENT :____ 1= YES; 2= NO

NAME OF BENEFICIARY CHILD_____ GENDER: 1= M 2= F BIRTH DATE: __ __ / __ __ / 201__ (JJ / MM / AAAA) BENEFICIARY CHILD VIM CODE:_____/ BENEFICIARY CHILD TUFTS CODE:_____ ___/

NAME OF GUARDIAN:_____ RELATIONSHIP BETWEEN GUARDIAN AND CHILD: ___ BENEFICIARY MOTHER VIM CODE:_____ BENEFICIARY MOTHER TUFTS CODE:_____ _____/

AGE OF GUARDIAN _____ (1=Mother ; 2=Grandmother; 3=Aunt; 4=Sister ; 5=Other relative (Specify) 6=No relation)

NAME OF HEAD OF CONCESSION:_____ NAME OF HEAD OF HOUSEHOLD:_____ HOUSEHOLD VIM CODE:_____ ___/

DIRECTIONS TO HOUSEHOLD:_____ N° TELEPHONE: _____

DATE FIRST CHILD RATION RECEI __ __ / __ __ / 201__ TOTAL NUMBER OF PREVIOUS DISTRIBUTIONS _____/ NUMBER OF DISTRIBUTIONS SINCE BIRTH OF CHILD _____/ BEGINNING OF DATA COLLECTION: ___ 1= YES ; 2= NO

HAS THE CHILD STARTED TO CONSUME THE RATION_____/ 1= YES; 2= NO AT WHAT AGE DID THEY START? ____/ MONTHS (or NA) END OF DATA COLLECTION: _____ 1= YES ; 2= NO

IN DEPTH INTERVIEW : _____ 1= YES; 2= NO DATE:__ __ / __ __ / 201__ IN-HOME OBSERVATION : _____ 1= YES; 2= NO DATE: __ __ / __ __ / 201__

HOUSEHOLD COMPOSITION:

	M	F
CHILDREN < 5 YRS		
CHILDREN 5-15		
ADULTS 16-65		
ADULTS 65 +		

SEX OF HEAD OF HOUSEHOLD: _____

HIGHEST EDUCATION LEVEL IN THE HOUSEHOLD:_____

EDUCATION LEVEL OF CHILD'S GUARDIAN____

(1= None 2= Literate 3= Primary 4= Secondary 5 = Higher 6= Other specify_____)

VACCINATION STATUS OF CHILD

	YES	NO
BCG		
HEP B		
YELLOW FEVER		
MEASLES		
HIB		
DTC1		
DTC2		
DTC3		
POLIO 0		
POLIO 1		
POLIO 2		
POLIO 3		

POSSESSIONS

DO YOU HAVE THE FOLLOWING ITEMS IN YOUR HOUSE 1= YES 2= NO

BUCKET		FUNCTIONAL FLASHLIGHT	
BOWLS		FUNCTIONAL TELEVISION	
GLASSES		FUNCTIONAL BICYCLE	
GAS STOVE		FUNCTIONAL MOTO	
BED		FUNCTIONAL CELL PHONE	
MATTRESS		FUNCTIONAL DONKEY CART	
TABLE		FUNCTIONAL WHEELBARROW	
CHAIR		DONKEY/HORSE	
FUNCTIONAL RADIO		POULTRY	
FUNCTIONAL WALL CLOCK		SHEEP/GOATS	

HOUSEHOLD CHARACTERISTICS

TYPE OF FLOOR IN HEAD OF HOUSEHOLD'S HOUSE

(CHECK ONE)
- ☐ NATURAL (EARTH, SAND)
- ☐ FINISHED
- ☐ DON'T KNOW

TYPE OF ROOF IN HEAD OF HOUSEHOLD'S HOUSE

(CHECK ONE)
- ☐ NATURAL (STRAW, MUD, TARP, ETC)
- ☐ FINISHED (TIN, TILE, CEMENT, WOOD, ETC)
- ☐ OTHER : _____
- ☐ DON'T KNOW

PRINCIPLE SOURCE OF LIGHT

(CIRCLE ONE)
- ☐ ELECTRICITY (SONABEL)
- ☐ SOLAR PANEL
- ☐ FLASHLIGHT
- ☐ KEROSENE LAMP
- ☐ GAS LAMP
- ☐ OTHER: _____
- ☐ DON'T KNOW

PRINCIPLE COOKING FUEL

(CIRCLE ONE)
- ☐ ELECTRICITY
- ☐ CARBON
- ☐ WOOD
- ☐ PETROL
- ☐ GAS
- ☐ OTHER:_____
- ☐ DON'T KNOW

PRINCIPLE DRINKING WATER SOURCE

(CIRCLE ONE)
- ☐ PUMP
- ☐ PROTECTED WELL
- ☐ NON-PROTECTED WELL
- ☐ RAIN WATER
- ☐ SURFACE WATER
- ☐ BOTTLED OR SACHET
- ☐ OTHER:_____

PRINCIPLE TOILET TYPE

(CIRCLE ONE)
- ☐ PUBLIC LATRINE
- ☐ PRIVATE LATRINE
- ☐ BUSH
- ☐ OTHER: _____
- ☐ DON'T KNOW

TYPE OF WALL OF THE HEAD OF HOUSEHOLD'S HOUSE

(CIRCLE ONE)
- ☐ NATURAL (MUD, STRAW, TARP,...ETC)
- ☐ FINISHED (CEMENT BRICKS, WOOD, STONE, ETC)
- ☐ OTHER : _____
- ☐ DON'T KNOW

FOOD SECURITY

During the past 30 days: Rarely = 1-2 times Sometimes = 3-10 times Often = more than 10 times

☐ Never ☐ Rarely ☐ Sometimes ☐ Often	1. Did you worry that your household would not have enough food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	2. Were you or any household member not able to eat the kinds of foods you preferred because of lack of resources?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	3. Did you or any household member have to eat a limited variety of foods (less kinds of food on the plate) due to lack of resources?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	4. Did you or any household member have to eat some foods that you really did not want to eat because of lack of resources to obtain other types of food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	5. Did you or any household member have to eat a smaller meal than you felt you needed because there was not enough food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	6. Did you or any other household member have to eat fewer meals in a day because there wasn't enough food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	7. Was there ever no food to eat of any kind in your household because of lack of resources to get food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	8. Did you or any household member go to sleep at night hungry because there was not enough food?	
☐ Never ☐ Rarely ☐ Sometimes ☐ Often	9. Did you or any household member go a whole day and night without having eaten anything because there was not enough food?	

Appendix 2. Enrollment/Exit form, English translation

Sanmentenga province supplementary feeding program, Burkina Faso

NAME OF BENEFICIARY CHILD:_____ SEX: ____ 1= M 2= F BENEFICIARY CHILD VIM CODE:_____ BENEFICIARY CHILD TUFTS CODE:_____

BENEFICIARY MOTHER VIM CODE:_____ BENEFICIARY MOTHER TUFTS CODE:_____

DISTRIBUTION SITE: _____ DISTRIBUTION SITE CODE: _____/ BIRTHDATE:__ __/ __ __/ 201__ TWIN AT BIRTH :____ 1= YES; 2= NO TWIN AT INCLUSION :____ 1= YES; 2= NO

NAME OF GUARDIAN: _____ RELATIONSHIP BETWEEN CHILD AND GUARDIAN: _____ VILLAGE NAME :_____ VILLAGE CODE:_____

1=Mother ; 2=Grandmother; 3=Aunt; 4=Sister ; 6=No relation; 5=Other relation (Specify)_____

INCLUSION DATE: ____/ ____/ 201__ DD / MM / YYYY IN-DEPTH INTERVIEW : _____ 1= Yes; 2= No IN-HOME OBSERVATION : _____ 1=Yes; 2= No DATE:__ __/ __ __/ 201__

NAME OF CHIEF OF THE CONCESSION:_____ N° TELEPHONE: _____

DIRECTIONS TO THE HOUSE:_____

QUESTIONS TO COMPLETE AT EACH MEASURE :

Distribution	Place	Distribution Date (always fill in)	Date of measurement	Child not seen (reason)		LENGTH	WEIGHT	MUAC	Breastfeeding	CURRENTLY OEDEMA	CURRENTLY FEVER	CURRENTLY DIAHRREA	Illness in the last 2 weeks 1 = YES 2 = NO									Vitamin A in the last 2 weeks	COMMENTARY (about the symptoms, treatment, health center (appetite)	CSB+	OIL	ENUMERATOR CODE
	0. Child not seen 1. Seen at distribution site 2. Seen at home	(dd/mm/yy)	(dd/mm/yy)	1. Hospitalized for SAM 2. Hospitalized for another reason 3. Travelling 4. Moved 5. Died 6.Refusal 9. Other (Specify)		(cm) (_ _.)	(kg) (_ _.)	(mm) (_ _)	1 = Yes 2= No	1 = Yes 2= No	1 = Yes 2= No	1 = Yes 2= No	M1	M2	M3	M4	M5	M6	M7	M8	M9	1 = Yes 2= No		1 = Yes 2= No	1 = Yes 2= No	
**START Distribution 1					1																					
					2																					
Distribution 2					1																					
					2																					
Distribution 3					1																					
					2																					
Distribution 4					1																					
					2																					
Distribution 5					1																					
					2																					
Distribution 6					1																					
					2																					
Distribution 7					1																					
					2																					
Distribution 8					1																					
					2																					

Illness in the last 2 weeks : M1. Diarrhea M2. Persistant Cough M3. Respiratory Difficulties M4. Rapid breathing M5. Fever M6. Burn M7. Accident M8. Confirmed Malaria M9.Other (Specify)

QUESTIONS COMPLETED AT EACH MEASURE:																									
NAME OF BENEFICIARY CHILD:_____ CODE OF BENEFICIARY CHILD:_____																									
Distribution	Place	Distribution date (always fill-in)	Measurement date	Child not seen (reasons)	LENGTH		WEIGHT	MUAC	Breastfeeding	CURRENT OEDEMA	CURRENT FEVER	CURRENT DIARRHEA	Illness in the last 2 weeks 1 = YES 2 = NO									Vitamin A in the last 2 weeks	COMMENTARY (about the symptoms, treatment, health center (appetite)	CSB+	OIL	ENUMERATOR CODE
	0. Child not seen 1. Seen at distribution site 2. Seen at home	(dd/mm/yy)	(dd/mm/yy)	1. Hosptilalized for SAM 2. Hospitlized for another reason 3. Travelled 4. Moved 5. Death 6.Refusal 9. Other (Specify)	(cm) (_ _.-_)		(kg) (_ _.-_ _)	(mm) (_ _ _)	1 = Yes 2= No	1 = Yes 2= No	1 = Yes 2= No	1 = Yes 2= No	M1	M2	M3	M4	M5	M6	M7	M8	M9	1 = Yes 2= No		1 = Yes 2= No	1 = Yes 2= No	
Distribution 9					1																				
					2																				
Distribution 10					1																				
					2																				
Distribution 11					1																				
					2																				
Distribution 12					1																				
					2																				
Distribution 13					1																				
					2																				
Distribution 14					1																				
					2																				
Distribution 15					1																				
					2																				
Distribution 16					1																				
					2																				
Distribution 17					1																				
					2																				
Distribution 18					1																				
					2																				
Distribution 19					1																				
					2																				
Distribution 20					1																				
					2																				
Distribution 21					1																				
					2																				
Follow-up 1					1																				
					2																				
Follow-up 2					1																				
					2																				
Follow-up 3					1																				
					2																				
Illness in the last 2 weeks : M1. Diarrhea M2. Persistant Cough M3. Respiratory Difficulties M4. Rapid breathing M5. Fever M6. Burn M7. Accident M8. Confirmed Malaria M9.Other (Specify)																									

Appendix 3. In-depth interview, dietary diversity section, English translation

Dietary Diversity for Burkina Faso

Question	Information Requête	Date
Ask the respondent: "I would like to ask you some questions about feeding [CHILD]. First I need to know if you will be able to tell me about feeding [CHILD] yesterday."		
1	Do you know what [CHILD] ate yesterday? **1 = Yes, 2 = No**	|___| **Code If 1 (Go to Question 2). If 2, STOP.**
Allaitement et liquide		
2	Is the child still breastfeeding? 1 = Yes, 2 = No	|___| Code If 1, (Go to Question 3 and continue to question 5) If 2, (Go to Question 4)
3	Now I would like you to tell me how many times [CHILD] breastfed yesterday. I am going to read you some answers and I want you to please tell me which you think is closest. *Read all of these choices to the respondent (except "don't know"):* 0 = Not at all 1 = Only at night 2 = Very little, only 1 or 2 times during the day 3 =Moderately, about 3-5 times during the day 4 = Very often, at least 6 times during the day 99 = Don't know	|___| Code
4	If no, how old was the child the last time he/she was breastfed? [Note the age in months, or 99 if unknown]	|___|___| mois
Now explain to the caregiver: "I would like to ask you about liquids that [CHILD] may have had yesterday during the day or at night. I am interested in whether your child had the item even if it was combined with other foods.		
5	Did [CHILD] have any fresh milk or milk from a can or box (Bonnet Rouge or Bonnet Blue)? 1 = Yes, 2 = No, 9 = Unknown	|___| Code

6	Did [CHILD] have any powdered milk (such as Nido or Bonnet Rouge)? 1 = Yes, 2 = No, 99 = unknown	|___| Code
7	Did [CHILD] have any infant formula (such as Nursie or France Lait)? 1 = Yes, 2 = No, 99 = unknown	|___| Code
8	Did your child eat in an unusual manner yesterday, compared to other days of the week? (Was there a party, ceremony, or conversely an unusual lack of food?) 1. Yes 2. No	|___| code
9	If YES, has your food consumption/that of your child been somewhat more or less than usual? 1. More 2. Less	|___| code
10. Discuss the food groups that compose what the mother/her child consumed yesterday **==>** **Note 1. Yes 2.No**		CHILD
a	**Cereals:** millet, sorghum, rice, corn, wheat, fonio, (including bread, pasta, couscous, flour in donuts or cakes, etc.) [**DO NOT PUT CSB IN THIS LINE ; SEE BELOW FOR ITS OWN LINE]**	|___|
b	**Orange sweet potato**	|___|
c	**Roots and tubers:** cassava, yams, white potatoes, taro, fabirama, (including banana/plantain)	|___|
d	**Legumes:** beans, groundnut, peas, chick pea, lentils, legumes, soy, etc.	|___|
e	**Peanuts** as a snack	|___|
f	**Peanut butter** in a sauce	|___|
g	**Sesame** paste or with grains as a sauce, or with galette/pancake/crepe	|___|
h	**Oil Seed/Oleaginous Seed:** cashew, wild nuts, other oil-rich seeds (except cola nuts for chewing)	|___|
i	**Dark Green Leafy Vegetables**: sorrel, amaranth, spinach, baobab, onion, beans, etc.	|___|
j	**Dark Red or Orange Vegetables**: pumpkin, squash, carrots, red peppers	|___|
k	**Tomato Concentrate**	|___|

l	**Other Vegetables:** fresh tomato, okra, zucchini, eggplant, onions, cabbage, cucumbers, salad, etc.	|___|
m	**Fruit rich in Vitamin A** : mango, dark red or orange papaya, dark orange melon,,néré (including fruit juice)	|___|
n	**Other Fruits:** bananas, pineapples, tamarind, and all other wild fruit (including fresh fruit juice)	|___|
o	**Liver** (beef, veal, mutton, poultry…)	|___|
p	**Meat** Skewer or stew (beef, mutton, chicken and poultry, goat, pig, dog, etc. (Including giblets -except liver)	|___|
q	**Meat or poultry or giblets as a condiment** in the sauce or in the soup	|___|
r	**Insects,** small rodents and other small animals	|___|
s	**Dried Fish Powder** (or crushed dried fish used as a condiment in the sauce)	|___|
t	**Small fish** dried, salted, or smoked, consumed whole/intact	|___|
u	**Other fish** (fresh, canned…) and seafood	|___|
v	**Eggs** (from chicken, poultry, etc.)	|___|
w	**Milk** (from a goat, a cow, a camel…), powdered milk, condensed milk, yogurt and curds, cheeses	|___|
x	**Red palm oil** or fruits/pulp from red palm	|___|
y	**Other oils and grease** (vegetable oil, butter, shea butter, margarine, mayonaise, fried foods…)	|___|
z	**Cakes** and pasteries from the store	|___|
aa	**Tea or Coffee** (to clarify whether with milk - except "a drop of milk" - and sugar)	|___|
ab	**Sugar,** honey, jam, candies...	|___|
ac	**Sugary Drinks**: Fanta and other soda, ZomKom, ginger juice, tamarind juice, bissap juice, bouye juice, etc.	|___|

ad	**Alcoholic drinks** beer, dolo, chiapalo palm wine, hard alcohol…)	|___|
Ae	**CSB+ flour**	|___|
Af	**Lipid based nutrient supplement** (RUSF, Plumpynut, etc)	|___|

……

RECORD

	Time interview finished	__ __: __ __ h h m m	Use 24 hours format.

Thank you so much for your time and patience with this interview. Before we end, is there anything you would like to add.

If you have any questions for me I will be glad to respond.

Appendix 4. In-depth interview, water sample collection, English translation

WATER SAMPLE COLLECTION

CHECK THAT THE SAMPLE WAS COLLECTED 1. Yes 2. No |___|

1. When did you collect water sample?

Date: __ __ / __ __ / 201 __
dd / mm / yyyy
Time: __ __: __ __ (Use 24 hours format)
h h m m

Name_____ Code |___||__|

Signature_____

PERFORMING THE TEST

When was the test performed?
Date: __ __ / __ __ / 201 __
dd / mm / yyyy

Time: __ __: __ __ (Use 24-hour format)
h h m m

Person who performed the test
Name_____ Code |___||__|

Signature_____

READING TEST RESULTS

When was the reading done ?
Date: __ __ / __ __ / 201 __
dd / mm / yyyy

Time: __ __: __ __ (Use 24-hour format)
h h m m

What are the Aquagenx results?
1. Positiive Concentration of E Coli : |___|___|___|. |___|
2. Negative
3. Inconclusive

Person who read the test:
Name_____ Signature_____ Code |___||__|

Appendix 5. In-home observation, breastfeeding time section, English translation

Effectiveness and Cost-Effectiveness of Four Formulations of Food Supplements for the Prevention of Wasting and Stunting in children 6-23 months in Burkina Faso._

Province du Sanmentenga

In-home observation guide : CSB+

Study Arm _____ Code of study arm : |___||
Observer name _____ _____Observer Code : |___|
Village name _____ _____Village Code : |___|___||___|

Household code :_____/

Household GPS Coordinates:

N: |__|___| |___|___| |___|___|.|___| º	W/E: |___|___||___| |___|___| |___|___|.|___| º
Altitude: |___|___|___| m	

Name of Beneficiary Child:_____ Beneficiary Child Code: _____/
Child's Tufts Code : _____/ Mother's Tufts code :_____/

Start date of observation __ __ / __ __ / 201 __ End date of observation __ __ / __ __ / 201 __

(dd / mm / yyyy) (dd / mm / yyyy)

Observation Day : D1 / ____/ D2 / ____/ D3 / ____/ D4 / ____/
Ration present in the household this day ? _____Yes _____No

Time	**6:00**	**6:30**	**7:00**	**7:30**	**8:00**
20. Is the child breastfeeding? 1. Yes 2. No 88.NA **(Specify the exact times of start and finish of each breastfeeding and describe the type of breastfeeding in the general notes)**	**Code [ ]** **Times : ST1 :___** **SE1 :____** **ST2 :____** **SE2 :____** **ST3 :____** **SE3 ____**	**Code [ ]** **Times : ST1 :___** **SE1 :____** **ST2 :____** **SE2 :____** **ST3 :____** **SE3 ____**	**Code [ ]** **Times : ST1 :___** **SE1 :____** **ST2 :____** **SE2 :____** **ST3 :____** **SE3 ____**	**Code [ ]** **Times : ST1 :___** **SE1 :____** **ST2 :____** **SE2 :____** **ST3 :____** **SE3 ____**	**Code [ ]** **Times : ST1 :___** **SE1 :____** **ST2 :____** **SE2 :____** **ST3 :____** **SE3 ____**
21. Other foods consumed by the beneficiary child 1. Cereals 2. Roots/Tubers 3. Legumes 4. Peanuts 5. Dark leafy vegetables 6.Other vegetables 7. Milk 8. Eggs 9. Meat/fish 77.Other **(specify in the notes)**	**Code [ ][ ][ ]** **[ ][ ][ ][ ]** **Notes**	**Code [ ][ ][ ]** **[ ][ ][ ][ ]** **Notes**	**Code [ ][ ][ ]** **[ ][ ][ ][ ]** **Notes**	**Code [ ][ ][ ]** **[ ][ ][ ][ ]** **Notes**	**Code [ ][ ][ ]** **[ ][ ][ ][ ]** **Notes**

Appendix 6. Informed consent form, enrollment, English translation

Effectiveness and cost effectiveness of four formulations of supplementary foods in the prevention of moderate acute malnutrition and stunting among children 6-23 months in Burkina Faso

Province du Sanmentenga

Local Research Firm: Institut de Recherche en Sciences de la Santé (IRSS)
Contacts: Dr LANOU Hermann: Tel +[redacted]
Dr GARANET Franck : Tél +[redacted]
CLIFFER Ilana: Tél +[redacted]

INFORMATION SHEET FOR BENEFICIARY MOTHERS CSB+ BRANCH

You have been enrolled in a supplementary feeding program at this food distribution site that provides a nutritious food supplement to you while you are pregnant and lactating, and to your child after s/he reaches the age of six months, to help your child grow better and to prevent malnutrition. Your child will receive the food supplement until s/he reaches two years of age.

This food distribution site is part of a research study being conducted by Institut de Recherche en Sciences de la Sante of Burkina Faso, in collaboration with Tufts University in Boston, United States, in cooperation with the ViM program. The study will assess four different supplementary foods used for the prevention of malnutrition in children. Each food distribution site will be providing one of these foods. This site will be providing Corn Soy Blend Plus (CSB+) to you and your child.

If you choose to participate in the study, your child will have his height, weight, and MUAC measured monthly at the distribution site to assess his growth. We will also obtain general information about your child and household today, which should take about 20 minutes. We may also contact you in the future to ask for your participation in an interview or group discussion about your experience with the food given by the program.

Your participation in the study is voluntary. You can choose to accept the food supplement or not. You can choose whether or not your child's measurements will be taken and recorded as part of the study. You can stop participating in the study at any time. Your agreement to have your child measured will not affect your continued receipt of the supplementary food.

There is no cost to participating in the study. The benefit to you is that you will receive the food supplement (if you choose to do so); we hope the study will benefit future nutrition programs by giving information about the most effective way to prevent malnutrition in children. Your information will not be shared with anyone outside of the research team. The results of the study will not be connected to you as an individual or to your responses. All information will be kept private.

The records of this study will be kept securely, in locked cabinets in the IRSS office.

The foods used in this study have been used in other nutrition programs, and we do not anticipate any risks to your child's participation. If you have concerns, you can communicate them with the study team: Dr LANOU Hermann (+226 [redacted]), Dr GARANET Franck (+226 [redacted]) and CLIFFER Ilana (+226 [redacted]). If you have questions about your rights in terms of participating in the research, communicate with the ethics committee for health research (00226 50 32 41 59) or the Minister of Health of Burkina Faso or the Institutional Review Board for health sciences of Tufts University (IRB) at 00-1-617-636-7512.

A description of this clinical trial will be available on http://www.Clinical Trials.gov, as required by US Law. This Web site will not include information that can identify you. At most, the Web site will include a summary of the results. You can search this web site at any time.

GUARDIAN CONSENT FOR HER CHILD'S PARTICIPATION

YOUR SIGNATURE OR THUMBPRINT, BELOW, WILL SHOW THAT YOU HAVE DECIDED TO VOLUNTEER YOUR CHILD AS A RESEARCH PARTICIPANT AND THAT YOU HAVE READ OR RECEIVED CLEAR DESCRIPTION OF THE STUDY, AND UNDERSTOOD THE INFORMATION PROVIDED ABOVE, AND YOUR RIGHTS AS A PARTICIPANT.

Signature/Thumbprint  Mother/Guardian

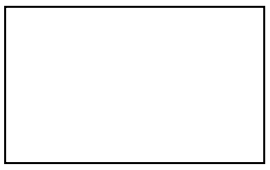
Name_____

Signature of Interviewer/ _____ Name _____

GUARDIAN CONSENT FOR A MINOR

[INSTRUCTIONS FOR ENUMERATOR: If the beneficiary's primary caretaker is under 18 years of age and not their mother then the caretaker's guardian must provide consent. IF A GUARDIAN'S SIGNATURE IS REQUIRED, THEY WILL CONSENT FOR THE CARETAKER ON ALL OTHER AREAS OF THIS FORM.]

The signature or thumbprint below will indicate that the guardian of the caretaker has allowed the caretaker to be a research participant. It also indicates that a clear explanation of the study and the rights of the participant are understood.

Signature/Thumbprint  Mother/Guardian

Name_____

PHOTO

Consent for photos

There may be photos taken during the measurements. These will not identify you by name. You can still participate if you choose to not have your photo taken.

YOUR SIGNATURE OR THUMBPRINT, BELOW, WILL SHOW THAT YOU CONSENT TO YOUR CHILD BEING PHOTOGRAPHED DURING THE INTERVIEW.

Signature/Thumbprint  Mother/Guardian

Name_____

Date _____ Time_____

Participants CODE: _____(*Fill only after participant voluntarily agrees to participate)*

Appendix 7. Informed consent form, in-depth interview, English translation

Effectiveness and cost effectiveness of four formulations of supplementary foods in the prevention of moderate acute malnutrition and stunting among children 6-23 months in Burkina Faso

Province du Sanmentenga

Local Research Firm: Institut de Recherche en Sciences de la Santé (IRSS)
Contacts: Dr LANOU Hermann: Tel +226 [redacted]
Dr GARANET Franck : Tél +226 [redacted]
CLIFFER Ilana: Tél +226 [redacted]

INFORMATION SHEET FOR BENEFICIARY MOTHERS

You are being asked to voluntarily participate in an interview that is being conducted by Institut de Recherche en Sciences de la Santé (IRSS) in collaboration with Tufts University, in Boston, USA, because your child has been receiving a food ration from the Victory Against Malnutrition (ViM) Program. We would like to get your views on the food ration you have been receiving. The whole interview will take about 60 minutes. The reason for the interview is to know what you think about the food you have received, and also how you prepare it and how your child eats it.

If you decide to take part in this interview, then we will do the following:
We will ask you questions about how you prepare and use the food you receive. We may also want you to show us how you usually store and eat the food. We may ask you questions about your child's participation in the program. We will ask to collect a small (2 Tablespoon) sample of the cooked/prepared ration and a sample of your household's water.

If you choose to not participate in the interview, your child will continue participating in the ViM Program and receiving the same food. We do not think there will be any risks from participating in this interview. We will do everything to protect your privacy (see below for more detail).Although there is no direct benefit to participation, the study will benefit other women and children in Burkina Faso and elsewhere by helping us understand how to improve their nutrition and health.

The records of this study will be kept securely, in locked cabinets in study coordinator's office. Your information will not be shared with anyone outside of the research team. The results of the study will not be connected to you as an individual or to your responses. If you take part in this study, it will not cost you or any member of your family any money. If you become a participant, you have the right to change your mind on being interviewed or stop the study at any time. If you stop, it will not change your child will still continue getting the food ration.We will be happy to answer any questions you have about this study.

If you have a project worry, you may contact the research team: Dr LANOU Hermann (+226 [redacted]), Dr GARANET Franck (+226 [redacted]) and CLIFFER Ilana (+226 [redacted]). If you have questions about your rights as a research study subject, call the ethics committee for health research (00226 50 32 41 59) or the Ministry of Health of Burkina or the Tufts University Health Sciences Review Board (IRB) at 00-1-617-636-7512.

BENEFICIARY MOTHER'S CONSENT FOR HER PARTICIPATION

PUTTING YOUR SIGNATURE OR THUMBPRINT BELOW WILL SHOW THAT YOU HAVE DECIDED TO VOLUNTEER AS A RESEARCH PARTICIPANT AND THAT YOU HAVE READ OR RECEIVED CLEAR DESCRIPTION OF THE STUDY, AND UNDERSTOOD THE INFORMATION PROVIDED ABOVE, AND YOUR RIGHTS AS A PARTICIPANT.

Signature / Thumbprint of participant
Name_____

Signature of Interviewer_____ Name_____

GUARDIAN CONSENT FOR A MINOR

[INSTRUCTIONS FOR ENUMERATOR: If the beneficiary's primary caretaker is under 18 years of age and not their mother then the caretaker's guardian must provide consent. IF A GUARDIAN'S SIGNATURE IS REQUIRED, THEY WILL CONSENT FOR THE CARETAKER ON ALL OTHER AREAS OF THIS FORM.]

The signature or thumbprint below will indicate that the guardian of the caretaker has allowed the caretaker to be a research participant. It also indicates that a clear explanation of the study and the rights of the participant are understood.

Signature / Thumbprint of Guardian Name_____

Signature of Interviewer _____ Name _____

CONSENT FOR GPS COORDINATES

We would also like to record the location your household for study purposes. Likewise, all information will be securely stored and you to not connect you to this information we are recording. You may also not allow the use of this information and still participate in the interview.

Woman's consent for the recording of her GPS coordinates

PUTTING YOUR SIGNATURE OR THUMBPRINT BELOW, WILL SHOW THAT YOU HAVE DECIDED TO ALLOW THE DATA COLLECTOR TO RECORD THE LOCATIONOF YOUR HOUSEHOLD.

Participant or Guardian

Signature / Thumbprint
Name_____

Signature of Interviewer_____ Name _____

PHOTO

Le consentement de la femme pour des photos

There may be photos taken during the interview. These will not identify you by name. You can still be interviewed if you choose to not have your photo taken.

Woman's consent for photographs
PUTTING YOUR SIGNATURE OR THUMBPRINT BELOW WILL SHOW THAT YOU AGREE TO BEING PHOTOGRAPHED DURING THE INTERVIEW.

Signature / Thumbprint Guardian
Name_____

Signature / Thumbprint of Interviewer _____Name _____

Date _____ Time_____

Participants CODE: _____(*Fill only after participant voluntarily agrees to participate)*

Appendix 8. Informed consent form, in-home observation, English translation

Effectiveness and cost effectiveness of four formulations of supplementary foods in the prevention of moderate acute malnutrition and stunting among children 6-23 months in Burkina Faso

Province du Sanmentenga

Local Research Firm: Institut de Recherche en Sciences de la Santé (IRSS)
Contacts: Dr LANOU Hermann: Tel +226 [redacted]
Dr GARANET Franck : Tél +226 [redacted]
CLIFFER Ilana: Tél +226 [redacted]

FICHE D'INFORMATION OBSERVATION A DOMICILE

You are being asked to voluntarily participate in a study that is being conducted by Institut de la Recherche en Science de la Sante, in collaboration with Tufts University in Boston, USA. This is a study that is looking at your daily household living practices . We would like to ask you to allow one of our research team members to be in your home daily, from morning until evening, for five days, to observe your household practices. At the end of the week we would then like to take 60 minutes of your time to ask you some questions. The reason for the observation and interview is to understand your daily household practices. We hope that the results from this study will allow us to learn more about household practices.

If you decide to take part in this observation and interview, then we will do the following:

1. You will have one of our research team members in your home every day for five days, from waking hours until evening. They will not stop you from doing your daily activities and will not ask you to do anything for them.

2. At the end of the week we will ask for one hour of your time to ask you some questions.

3. We may also take some pictures during the observation. These pictures will not identify you or reveal your home by name. You can still participate in the observation even if you do not consent to have your picture taken.

If you choose to not participate in the interview, your child will still continue receiving the same food. We do not think there will be any risks from participating in this interview. We will do everything to protect your privacy. We will be happy to answer any questions you have about this study. If you have a project worry, you may contact the research team : Dr LANOU Hermann (+226 [redacted]), Dr GARANET Franck (+226 [redacted]) et CLIFFER Ilana (+226 [redacted]). If you have questions about your rights as a research study subject, contact the ethics commmittee for health research (00226 50 32 41 59) or the Burkina Faso Ministry of Health or the Tufts University Health Sciences Institutional Review Board (IRB) at 00-1-617-636-7512.
Although there is no direct benefit to participation, the study will benefit other women and children in Burkina Faso and elsewhere by helping us understand how to improve their nutrition and health. The discussion will be audio-recorded, but the recordings will only be used to transfer the information into a computer. The records of this study will be kept securely, in locked cabinets in study coordinator's office. Your information will not be shared with anyone outside of the research team. The results of the study will not be connected to you as an individual or to your responses. You can still participate in the discussion if you do not consent to be audio-recorded, the device will be turned off while you speak.

If you take part in this study, i twill not cost you or any member of your family any money. You will be invited to take a few mintues at the end of the observation period to respond to some questions for about 60 minutes.

You have the right to refuse participation in the observation. You also have the right not to respond to questions that are posed to you. You can change your mind at any time in terms of your participation in the study, or stop at any time. If you stop, this will not change anything about your child's participation in the ViM program, and they will continue to receive rations.

A description of this clinical trial will be available on http://www.Clinical Trials.gov, as required by US Law. This Web site will not include information that can identify you. At most, the Web site will include a summary of the results. You can search this web site at any time.

CONSENT FOR PARTICIPATION FOR IN-HOME OBSERVATIONS

PUTTING YOUR SIGNATURE OR THUMBPRINT, BELOW, WILL SHOW THAT YOU HAVE DECIDED TO VOLUNTEER AS A RESEARCH PARTICIPANT AND THAT YOU HAVE READ OR RECEIVED CLEAR DESCRIPTION OF THE STUDY, AND UNDERSTOOD THE INFORMATION PROVIDED ABOVE, AND YOUR RIGHTS AS A PARTICIPANT.

.

Signature / Thumbprint of participant | Name _____

Signature of Interviewer _____ Name_____

CONSENT FOR GPS COORDINATES

Consent for recording GPS coordinates

We would also like to record the location your household for study purposes. The same privacy actions will be used with this information as well. All information will be securely stored and coded as to not connect you to your information. You may also not allow the use of this information and still participate in the interview.

PUTTING YOUR SIGNATURE OR THUMBPRINT, BELOW, WILL SHOW THAT YOU HAVE DECIDED TO ALLOW THE DATA COLLECTOR TO RECORD THE LOCATION OF YOUR HOUSEHOLD

Signature / Thumbprint participant | Name_____

PHOTO

Consentment for photos

There may be photos taken during the observation. These will not identify you by name. You can still participate if you choose to not have your photo taken.

Consent for photographs

PUTTING YOUR SIGNATURE OR THUMBPRINT, BELOW, WILL SHOW THAT YOU CONSENT TO BEING PHOTOGRAPHED DURING THE OBSERVATION.

Signature / Thumbprint | Name_____

Date_____ Time _____

(*Fill only after participant voluntarily agrees to participate)*

Participants CODE: _____