Diet and Disease: Examining the Seasonal Determinants of Children's Health in Senegal

Karan S. Shakya*, Leah E. M. Bevis*, and Andrew L. Thorne-Lyman†

Abstract

Seasonal changes in food availability and disease incidence put pressure on children's health in Sub-Sahara Africa. Using year-round survey data from Senegal, we examine how seasonality in key health inputs (dietary diversity, diarrhea, and fever) helps predict seasonality in children's health (weight-for-height z-score). We first parameterize seasonal variation in health and health inputs using second-order trigonometric polynomials, then decompose the seasonal curve of children's health into component parts explained by seasonality in each health input. We find that lagged seasonality in disease incidence predicts seasonality in child health, while seasonality in dietary diversity does not – likely because diets are poor in Senegal even during the most food-plentiful part of the year. We also observe noticeable heterogeneity in the way these health inputs predict children's health across different wealth levels and regions.

Keywords: malnutrition, seasonality, diet, diarrhea, fever, Senegal

*Department of Agricultural, Environmental and Development Economics, The Ohio State University. Corresponding author: Karan Shakya (shakya.11@osu.edu)

†Center for Human Nutrition, Department of International Health, Johns Hopkins Bloomberg School of Public Health.
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1 Introduction

Children's health exhibits considerable seasonal variation in Sub-Sahara Africa. Typically, children are healthiest directly after the local harvest when households experience an influx of food and income but become vulnerable during the lean season when these resources become scarce (Dercon and Krishnan 2000). Children's health also often declines during the rainy season, when there is a rise in water-related diseases such as diarrhea and malaria (Dostie, Haggblade, and Randriamamonjy 2002; Kemajou 2022). These seasonal environments contribute to child malnutrition and mortality and can have detrimental impacts on long-term development and human capital (Egata, Berhane, and Worku 2013; Bhagowalia, Chen, and Masters 2011; Christian and Dillon 2018, Lokshin and Radyakin 2009).

We model and compare the seasonality of multiple inputs to children's health in the context of Senegal, then ask which health input best predicts seasonality in children's health. Specifically, we first use a flexible trigonometric polynomial to model both seasonality in children's health (weight-for-height z-score, a proxy for short-term nutritional status) and the seasonality in three key health inputs (incidence of diarrhea, a proxy for water-borne disease; incidence of fever, a proxy for malaria; and dietary quality as proxied by dietary diversity). We then decompose the seasonal curve of children's health into component parts explained by seasonality in each health input. This methodology is enabled by Senegal's "continuous" Demographic and Health Survey (DHS) data, which are collected year-round across the country rather than in a 2 or 3-month period as is typical for DHS. These data are not a panel and we do not observe any single child more than once.

Most studies examining the seasonality of children's health have used high-frequency panel surveys that track children over time, thus directly observing monthly changes in each child. These studies have linked variations in children's health to changes in key health inputs such as food consumption, diarrhea, and fever (Becker, Black, and Brown 1991; Checkley et al. 2003). However, such high-frequency panel surveys are expensive and thus rare, and often restricted in temporal or geographic availability. (Our data are nationally representative.) Researchers working with more typical cross-sectional datasets often resort to discretizing seasons into blocks, then comparing average child health during the monsoon or the lean season to that during the harvest season.[1] These studies find strong associations between the seasonal differences in diet quality (Guizzo Dri et al. 2022; Belayneh, Loha, and Lindtjørn 2021), diarrhea (Richard et al. 2013), and malaria (Touré et al. 2016) and children's health. However, no study has yet examined the relative importance of seasonality in multiple health inputs for children's health, nor compared the distinct seasonal patterns of various health inputs across sub-groups.

Our paper makes three contributions to the literature that studies seasonality in children's health. First, ours is the first paper that we know of to simultaneously examine the relative importance of multiple seasonal health inputs. We find that, in Senegal, diseases, rather than diet quality, are the primary predictors of seasonality in weight-for-height z-score. Although in many contexts children's health is strongly correlated with diet, these children often have better diet quality on average (Belayneh, Loha, and Lindtjørn 2021; Guizzo Dri et al. 2022). In Senegal, dietary quality is so low that even directly after harvest, the average child is only eating 2 to 3 different food groups, which is far below the threshold used to define dietary adequacy of at least 5 food groups in the past 24 hours. While we do observe seasonal variation in dietary quality, the range of variation may be too low to have any effect on children's health.

Second, our paper highlights the role of household and geographical characteristics in the seasonality of children's health. Households have varying abilities to cope with seasonal shocks (Devereux, Sabates-Wheeler, and Longhurst 2011). In Senegal, we find that richer households experience limited dry season diarrhea incidence, highlighting the role of adequate water infrastructure in mitigating seasonal water-borne illnesses. This difference in diarrhea incidence changes the seasonal pattern in richer children's health, relative to poorer children. Additionally, we show that children in southern Senegal experience higher incidences of both diarrhea and fever, highlighting the sensitivity of health inputs

[1] A notable exception is Sassi 2015 who studies seasonality in children's health using highly tailored cross-sectional, limiting analysis to the Dowa district in Malawi.

to environmental conditions.

Third, our study makes a methodological contribution by not only modeling seasonal patterns in child health and health inputs but also decomposing seasonality in child health into component parts driven by those inputs. We follow previous work when modeling seasonality in child health using flexible trigonometric polynomials (Bevis, Naschold, and Rao 2019; Saville et al. 2021; Gilbert, Christiaensen, and Kaminski 2017). However, we are the first to decompose the seasonality in children's health into seasonal curves representing the association with seasonal health inputs. In this process, we estimate (rather than assume) the temporal lags between each health input and health itself. This exercise is descriptive rather than causal but suggests likely channels of impact.

The paper proceeds as follows. Section 2 describes the setting, data, and key variables. Section 3 outlines the empirical strategy, including the trigonometric parameterization of seasonal variables and the decomposition method. Section 4 presents and discusses the results, and Section 5 concludes.

2 Data and Setting

In Senegal, the seasonal cycle consists of one rainy season from June to September, and a harvest season from October to January (Figure 1). As agriculture in Senegal is primarily rain-fed, the timing and quality of rainfall during the rainy season are critical for agricultural productivity. The harvest, which immediately follows the rains, is marked by a high supply of food and income, particularly from crops such as millet, sorghum, and maize. After the harvest is the dry season when many rural households temporarily migrate for work. During these months, food stores and income dwindle, culminating in the 'lean season' – a period of high food scarcity and poor diet from June to August. These three months are a vulnerable period for children as this coincides with the rainy season when children experience high incidences of diarrhea and malaria.

2.1 Demographic and Health Survey

We pool several rounds (2012-13 to 2019) of the continuous Demographic and Health Survey (DHS) of Senegal to obtain data on child health in every month of the year, across seven years. DHS surveys are nationally representative, and samples are selected using a stratified two-stage cluster design. In the first stage, enumeration areas within each region are selected using a census. Then, within each enumeration area, a sample of households is drawn from a complete list of households.[2] While most DHS surveys are conducted every 5 years within a period of a few months, the continuous DHS survey in Senegal was collected every year and across 8 to 10 months, providing consistent, almost uninterrupted data to capture underlying seasonal variation. We focus on children between 6 to 23 months, a subgroup vulnerable to growth faltering due to malnutrition and seasonal shocks (Victora et al. 2010; Thurstans et al. 2023; Madan et al. 2018). We exclude observations in the capital and highly urbanized region of Dakar, as we expect the seasonality in Dakar to be different from other regions of the country. All analyses are weighted to account for the stratified sampling employed by DHS using the provided population weights, probability sampling units, and sampling strata.[3]

Figure 2 illustrates the frequency of survey observations across different months. Despite the 'continuous' nature of the DHS survey, observations per month are not uniformly distributed, with January, February, and December having the fewest observations. This imperfect data collection becomes relevant for subsequent analysis choices. Although recent DHS surveys were mostly conducted in the latter months of the year (Table A1), survey timing does not appear to be strongly correlated with geographical regions (Figure A1). We also formally test whether survey timing predicts key household and parental characteristics and find no significant effect for nearly all major characteristics (Table A2).

Since we are pooling observations to present seasonal variations in children's health and

[2] Methodology and modules of the DHS survey are explained further in: https://dhsprogram.com/Methodology.

[3] Survey strata for Senegal's DHS also changed midway in 2013. We account for these changes by using year-specific stratified household survey weights.

inputs, we assume the seasonal environments do not change considerably during our sample years. While we cannot test this with the DHS survey directly, we can examine whether key climatic indicators, such as rainfall, temperature, and vegetation, vary across years. These indicators, though varying slightly year by year, follow an average pattern, suggesting a relatively consistent seasonal environment in Senegal during our sample period (Figure A2).[4]

2.2 Seasonality in Children's Health

Our primary child health outcome of interest is weight-for-height z-score, which measures the deviation in a child's weight against the weight of a child from a healthy reference group with the same height (WHO 2006). Weight-for-height z-score is a short-term indicator of child malnutrition that is sensitive to recent shocks and events and therefore is an appropriate measure of seasonally varying health.[5] When a child's weight-for-height z-score is less than 2 standard deviations, they are considered extremely thin for their height, a condition known as wasting. We choose to model the seasonality in weight-for-height z-score, as opposed to a binary wasting indicator, since weight-for-height z-score is a continuous variable and provides more variation to model seasonal patterns.

Generally, wasting is a function of poor diet and frequent illness (Olofin et al. 2013; Bhutta et al. 2017). To assess the seasonality in dietary quality, we measure the dietary diversity of children by tabulating the number of different food groups consumed within the past 24 hours out of a total of 8 groups – an indicator validated to reflect diet

[4] Conversely, the timing of Ramadan – the largest religious event in Senegal – does vary slightly across sample years; it began in July in 2013 and moved to beginning in May in 2019. (This shift is because the Islamic calendar is 11 days shorter than the Gregorian one.) If dietary diversity and child health are impacted by Ramadan, we might be accidentally picking up this early summer effect as "seasonal". However, only 5% of our sample children were interviewed during Ramadan. Adding a control for Ramadan in our analysis makes a negligible difference to results (available upon request).

[5] Following DHS guidelines, children with weight-for-height z-score above or below 5 SD are considered to have invalid observations. Approximately 7.5% of children between 6 to 23 months had invalid or missing weight-for-height z-scores. These flagged observations are uncorrelated with survey timing.

quality in developing countries (Ruel, Harris, and Cunningham 2013).[6] Although dietary diversity provides a suitable proxy for the quality of food consumed, it does not capture the quantity of caloric intake in children. Nonetheless, several studies have found a positive association between the seasonality in dietary diversity and child wasting rates (Bonis-Profumo, Stacey, and Brimblecombe 2021; Belayneh, Loha, and Lindtjørn 2021; Guizzo Dri et al. 2022; Hirvonen, Taffesse, and Worku Hassen 2016).

To measure the seasonality of illness, we rely on the reported incidences of both diarrhea and fever. These measures are constructed by asking mothers if their child showed symptoms of diarrhea or fever within the past 14 days. Since malaria is rarely diagnosed via a test in sub-Saharan Africa, the incidence of fever is the best proxy for the incidence of malaria.[7]

We further examine the seasonality in child health and health inputs for a few subpopulations. First, we compare households with different levels of wealth. Wealthier households are likely to have better living conditions, such as improved sanitation, better drinking water facilities, and greater income sources, which can help mitigate the negative impacts of seasonal shocks. The DHS provides a wealth index, which is a composite measure of household wealth based on a household's ownership of assets, the physical quality of home, and the availability of water and sanitation facilities. We classify households in the lowest two wealth index groups as poorer households and those in the highest three wealth index groups as richer households.[8] Second, we compare children from different regions in Senegal. The geographical characteristics of Senegal vary primarily by lati-

[6] The food groups are based on WHO's assessment of child feeding practices (WHO 2021). The food groups are (1) breast milk, (2) grain, roots, and tubers, (3) legumes and nuts, (4) dairy products, (5) flesh food, (6) eggs, (7) vitamin A-rich fruits, and (8) other fruits and vegetables.

[7] There is valid concern regarding the overlap of symptoms between diarrhea and fever. In our sample, the correlation between diarrhea and fever is around 0.35. However, we later show that the seasonal patterns between diarrhea and fever are distinct, and fever does, indeed, align with the expected seasonal patterns of malaria. Sey et al. 2020 conduct a thorough review of the relationship between malaria and diarrhea, but they are unable to establish any direct link between these two illnesses. Thus, we model the seasonality of diarrhea and fever separately.

[8] The DHS creates these wealth index groups by assigning each household a standardized asset score, which is generated by using principal component analysis on various household assets and infrastructures. They then divide this into population quntiles and allocate each household member to the respective quntile. Since wealthier households have fewer children on average, we have chosen to allocate the highest 3 groups into the richer household category to balance sample sizes between richer and poorer households.

tude. To assess regional variation in seasonal patterns, we therefore separate households belonging to the northern and southern regions of Senegal (Figure 3). This division is loosely based on the observed seasonal patterns in rainfall, temperature, and vegetation (Figure A3).

Table 1 summarizes the statistics of all relevant seasonal variables across Senegal and different groups of households. The total number of children in our sample is 15,379. The mean weight-for-height z-score is negative for all groups, indicating that, children in Senegal are less healthy than the reference group. The mean dietary diversity across Senegal is around 3, indicating that children consume an average of 3 food groups. Approximately one-fourth of the sample children experienced diarrhea or fever in the last two weeks. Around 60% of children are from poorer households, where children tend to have lower weight-for-height z-scores and dietary diversity while experiencing higher incidences of both diarrhea and fever. Finally, roughly half the household belong to the northern region, where children are marginally healthier and report greater dietary diversity and lower levels of diseases than children from southern regions.

3 Empirical Strategy

We first parameterize all seasonal variables using a second-order trigonometric polynomial. Gilbert, Christiaensen, and Kaminski 2017 show that when samples are short and seasonal patterns are not well defined, trigonometric polynomials outperform the more conventional and flexible month dummies approach by reducing bias and enforcing cyclicality. Our sample is not perfect; we have more data in some months than in others, which means some month dummies will be poorly estimated. A flexible trigonometric polynomial overcomes this data scarcity issue by being a parametric approach, while simultaneously providing a more accurate representation of seasonal patterns by enforcing smooth cyclicality. Additionally, a second-order trigonometric polynomial is more parsimonious than month dummies (requiring 4 rather than 12 degrees of freedom), while providing almost the same level of flexibility.[9] The use of these sinusoidal curves also allows us to easily decompose weight-for-height z-score into the amplitudes and lags of dietary diversity, diarrhea, and fever.

A few previous studies have used trigonometric polynomials to identify seasonal relationships in health outcomes and health inputs. For instance, Bevis, Naschold, and Rao 2019 use second-order trigonometric polynomials to show that seasonal variations in both dietary quality and agricultural labor hours explain seasonal patterns in adult BMI. Saville et al. 2021 use a first-order trigonometric polynomial to detect seasonality in pregnant mothers and newborn children, emphasizing the importance of accounting for seasonality when designing public health surveys. Trigonometric polynomials have also been used to model seasonality in non-health outcomes such as food prices (Gilbert, Christiaensen, and Kaminski 2017; Bai, Naumova, and Masters 2020), rainfall (Norzaida, Zalina, and Fadhilah 2016), and suicide rates (Bramness et al. 2015).

Equation 1 presents the second-order trigonometric polynomial used in this paper, where Y represents the pooled values of children's health and health inputs. t represents months of the year, which is transformed to range from 0 (January 1) to 1 (December 31). For a second-order polynomial $\tau_1 = 1$ and $\tau_2 = 0.5$, which allows us to have multiple, non-symmetric peaks and troughs throughout the year. We estimate Equation 1 using ordinary least squares.

$$Y_t = \alpha_1 \sin\left(\frac{2\pi t}{\tau_1}\right) + \alpha_2 \cos\left(\frac{2\pi t}{\tau_1}\right) + \alpha_3 \sin\left(\frac{2\pi t}{\tau_2}\right) + \alpha_4 \cos\left(\frac{2\pi t}{\tau_2}\right) + \varepsilon_t \tag{1}$$

By estimating Equation 1 for each health input and for child health, we obtain predicted sinusoidal curves for each variable. That is, each seasonal variable is predicted for each day (t) in a dataset of 365 days: predicted weight-for-height z-score ($\widetilde{\text{WHZ}_t}$), dietary diversity ($\widetilde{\text{Diet}_t}$), diarrhea incidence ($\widetilde{\text{Diarrhea}_t}$), and fever incidence ($\widetilde{\text{Fever}_t}$).

[9] Note that a first-order trigonometric polynomial does not provide the same flexibility, as it enforces symmetry and only 1 rise per year. Malnutrition indicators and health inputs can have non-symmetrical seasonal variations (Marshak et al. 2021; FAO and Tufts 2019), thus requiring a second-order rather than first-order trigonometric polynomial.

Next, we model the sinusoidal curve of the weight-for-height z-score as a linear combination of the sinusoidal curves of the health inputs, as shown in Equation 2. This equation is estimated in the day-specific dataset. Each estimated $\hat{\beta}$ represents the predicted strength (or amplitude) of the relationship between the health input in question and the child's weight-for-height z-score. Each estimated $\hat{\delta}$ measures the predicted lag before a seasonal health input rise/dip is associated with a seasonal health rise/dip. I.e., $\hat{\delta}_D = 30$ implies that a month elapses between a seasonal change in diarrhea incidence and a corresponding change in the weight-for-height z-score.

$$\widetilde{\text{WHZ}}_t = \beta_F \widetilde{\text{Diet}}_{t-\delta_F} + \beta_D \widetilde{\text{Diarrhea}}_{t-\delta_D} + \beta_V \widetilde{\text{Fever}}_{t-\delta_V} + \widetilde{\mu}_t \tag{2}$$

We allow for lags (δ_F, δ_D, δ_V) since we expect that dietary diversity, diarrhea, and fever incidences may have a delayed impact on weight-for-height z-score. In studies examining the effects of food consumption and diet on children's health, researchers often include a lag term to account for potential benefits or consequences observed later on (Lakkam et al. 2014; Quisumbing 2003). These lags can vary, ranging from a lag of 0 (having an immediate effect) to a lag of nearly 2 months. Similarly, lags for diseases depend on the disease in question. Studies that have tracked cohorts of children to study the effects of diarrhea on their health have observed lags of around 1 to 2 months (Checkley et al. 2003; Richard et al. 2013). On the other hand, fever incidence is found to have a more immediate and larger effect on children (Becker, Black, and Brown 1991). While none of these studies have definitively estimated the "correct" lag for any given health input, they provide a plausible range within which to expect the lags to persist in children.

We estimate the βs and δs jointly using a 'grid-search' method, meaning that we estimate Equation 2 over a specified range of the parameters. We first identify all reasonable values of lags, based on nutrition literature: we consider weekly lags for each seasonal health input for up to 2 months. Specifically, each considered $\hat{\delta}$ takes a value representing weekly lags from 0 to 8 weeks. Then, for each combination of lags, we estimate the βs using constrained least-squares where the constraints are $\beta_F \geq 0$ and $\beta_D, \beta_V \leq 0$. (I.e., dietary quality must have a positive association with health, and disease incidence a negative one.) This grid search procedure identifies an optimal solution set for each combination of $\hat{\delta}$ values: $(\hat{\beta}_F, \hat{\beta}_D, \hat{\beta}_V | \hat{\delta}_F, \hat{\delta}_D, \hat{\delta}_V)$. We choose our final solution $(\hat{\beta}^*_F, \hat{\beta}^*_D, \hat{\beta}^*_V, \hat{\delta}^*_F, \hat{\delta}^*_D, \hat{\delta}^*_V)$ by minimizing the Residual Standard Error (RSE) across all solutions sets from all $\hat{\delta}$ values.[10]

Motivated by Broderick, Giordano, and Meager 2021, we run a robustness check to see how susceptible our final solutions are to sampling noise in the full dataset. We re-estimate both Equations 1 and 2 ten times after randomly dropping approximately 10% of our data, reproducing both the underlying sinusoidal curves for health inputs and child health and the decomposition parameters. If these sinusoidal curves and the decomposition parameters linking seasonality in health inputs to seasonality in child health remain stable, we know that our results are not driven by sampling noise or outliers.

4 Results and Discussions

4.1 Seasonality in Children's Health in Senegal

Table 2 presents the results of estimating Equation 1 for each outcome, in the entire sample of children. The F-statistic presents the joint significance of the model and indicates that children's health and health inputs have a significant seasonal component that the trigonometric polynomial captures. These predicted coefficients are more effectively visualized as sinusoidal curves, and Figure 4 graphs these curves against the raw monthly means for each seasonal variable. Most of the sinusoidal curves fall within the 95% confidence interval of the monthly means, indicating that our model suitably approximates observed seasonal patterns, while (unlike monthly dummies) enforcing cyclicality. A more parsimonious first-order trigonometric polynomial fails to adequately capture the seasonal variations in these variables (Figure A4).

[10] If $\hat{\beta}_I$ for input I is zero, then the same RSE will be achieved under any corresponding $\hat{\delta}_I$. I.e., an input's lag value is inconsequential if the input's amplitude is zero. In such cases, we choose $\hat{\delta}_I = 0$ arbitrarily.

The sinusoidal curve for the weight-for-height z-score is highest during March and lowest during November, aligning with the expectation that children are healthiest in the periods after harvest. Dietary diversity is greatest during January and has two troughs in April and September. The dip in dietary diversity during April does not coincide with the traditional lean season. This suggests that the period of food insecurity, at least in terms of dietary diversity, may begin earlier than the growing/lean season in Senegal.

The curve for diarrhea has two peaks corresponding to the months of low rainfall (in February) and high rainfall (in August), which is consistent with our expectations. During the monsoon season, there is an increase in surface runoff and water contamination, which increases exposure to pathogens that cause diarrhea (Horn et al. 2018). Conversely, during the dry season when water is scarce, households in Sub-Sahara Africa are more likely to consume water from unhygienic sources increasing rates of diarrhea (Bandyopadhyay, Kanji, and Wang 2012; Chao et al. 2019). The curve for fever incidence peaks from August to November, coinciding directly with the rainy season in Senegal. This supports our assumption that fever reflects the incidence of malaria, which also peaks during the rainy season. Additionally, the curves for diarrhea and fever are visually distinct, providing evidence that these two variables capture different seasonal variations in diseases.

Table 3, column 1, holds the parameter solutions found by estimating Equation 2 via a grid-search. The optimal (RSE-minimizing) solution was found when the contribution of diarrhea to child health was lagged by 8 weeks, with the contribution of dietary diversity and fever being lagged not at all. Notably, the amplitude of dietary diversity is extremely small, suggesting a negligible contribution to the seasonality in children's health. The amplitudes of diarrhea and fever are larger, at -1.58 and -2.73 respectively. This suggests that seasonality in both diarrheal (likely waterborne) diseases and fever (likely driven by malaria) contributes to shaping the seasonality in children's health, with fever playing a more pronounced role.[11]

[11] The RSE (model fit) for the optimal solution is 0.04. To better contextualize this, Figure A5 displays the original and predicted sinusoidal curve of the weight-for-height z-score. Our model does a good job of capturing the variation in weight-for-height z-score in the first half of the year but only roughly matches the decline observed after July.

To test the sensitivity of our solutions to sampling noise or outliers, we re-estimate the health and health input sinusoids (Equation 1) and then re-run the decomposition grid-search (Equation 2) using reduced samples. While the health and health input sinusoids are statistically indistinguishable from the full sample sinusoidal curves (Figure 5), they are perturbed enough to check if our decomposition solutions are stable. Figure 6 plots the optimal solutions derived from the full and reduced samples, with darker colors indicating overlapping solutions across multiple grid-search results. Notably, the reduced sample amplitudes of dietary diversity consistently remain close to 0, while the amplitudes for diarrhea and fever cluster around the full-sample amplitudes, providing assurance that our health input amplitudes and lags are robust to sampling noise.

4.2 Seasonality in Children's Health Across Sub-groups

The sinusoidal curves for children in wealthier households are different than those for poorer children in two ways (Figure 7).[12] First, as expected, the weight-for-height z-score is higher for wealthier households, indicating that children from wealthier households are generally healthier throughout the year. This level shift in child health might stem from a level shift in dietary quality: richer children also experience improved dietary diversity throughout the year, relative to their poorer counterparts. (No such year-round shift in disease incidence is observed.) However, the improvement in health might also stem from better medical care or other unobserved, non-seasonal health inputs.

Second, and perhaps more surprising, children from wealthier households still experience significant seasonality in their health. In fact, they experience greater seasonality than poorer children, driven by a greater health boost during the post-harvest (January-April) dry season. Relatedly, children from wealthier households do not experience the dry-season diarrhea spike during January-April that poorer children experience. This makes sense since dry-season diarrhea is associated with poor water and sanitation infrastructure, and in our sample, richer households were more likely to have improved

[12]The regression coefficients that generate these curves are presented in Table A3.

drinking water sources and sanitation facilities (Table A5). Lastly, children from wealthier households also experience low fever incidence during January-April, whereas poorer children experience a slight rise in fever during this period, relative to the middle of the year.

Decomposition results in Table 3, columns 2 and 3, show that the seasonality of children's health in poorer households is strongly associated with the seasonality of both diarrhea and fever. For richer households, only the seasonality of fever incidence is strongly associated with children's health. The amplitude for dietary diversity is close to zero for both sub-samples, just like in the national sample.

In our sample, approximately two-thirds of richer households and one-third of poorer households live in Northern Senegal. Because the seasonality of children's health across wealth gradients could be shaped by geography (and vice-versa), we also examine differences in the seasonality of health inputs and child health across regions. Figure 8 illustrates these seasonal variations, showing that children from Northern households are healthier than those from Southern households in the post-harvest months (January-April) and consistently have greater dietary diversity.[13] The incidence of both diarrhea and fever is higher year-round in the South, possibly due to the more tropical environment increasing exposure to vector-borne diseases or perhaps due to greater poverty.

Decomposition results in Table 3, columns 4 and 5, show that as with richer children, the seasonality of child health in Northern Senegal is primarily associated with the seasonality of fever incidence. Both diarrhea and fever are significant predictors of child health in Southern Senegal, with effect sizes (amplitudes) of comparable magnitudes. These magnitudes are in fact larger than those observed for poorer households, further highlighting the pronounced role of illnesses in this region. While the seasonal patterns of both diarrhea and fever incidence are almost identical in the South and among poorer children generally (Figures 7 and 8 (c) and (d)), the association between seasonal patterns in disease and health is greatest in the South. This suggests less health resilience to disease

[13] The regression coefficients that generate sinusoidal curves for the North and South are in Table A4.

in Southern Senegal. Once again, seasonality in dietary diversity did not significantly predict seasonality in child health outcomes for either group.

Table 3 estimates sub-group specific lags as well as health input amplitudes. For disease incidence – the health inputs that actually predict child health – these lags do not vary by sub-group. For the country as a whole and for each sub-group, 8 weeks pass between correlated shifts in diarrhea incidence and child health. For the country as a whole and for each sub-group besides the South, there is no lag between shifts in fever incidence and associated child health; in the South, the lag is estimated to be 1 week.

4.3 Policy Implications

Our findings show that improving child health during July-October in Senegal would go a long way towards reducing wasting rates. This is important because while advancement has been made towards reducing stunting rates in Senegal, high wasting rates persist (Brar et al. 2020). Wasting is a key aspect of the Sustainable Development Goal to "end all forms of malnutrition by 2030". We find that weight-for-height z-scores fluctuate seasonally by approximately 0.3 standard deviations in Senegal, causing wasting rates to vary from 6.3% to around 11.3% within an average year. This 5 percentage point gap is large – it is approximately twice the gap between Senegal's average wasting rates (8.1%) and the average wasting rates in Sub-Saharan Africa (2.2%), or between Sub-Saharan Africa and South Africa (2.3%) (World Bank 2022). Furthermore, this variation is notable for policy, as the WHO categorizes regions with wasting rates greater than 10% as high-risk and priority areas (WHO 2018). A large portion of Senegal's population is at risk of surpassing the 10% threshold during certain times of the year, emphasizing the need for improved assessment and management of seasonal environments.

Diarrhea and fever jointly, strongly predict seasonality in children's health in Senegal, highlighting the need to manage disease incidence during both the dry and wet periods. Diarrhea peaks in both seasons. Wet season diarrhea is thought to be driven by contaminated rainwater running into wells and other drinking water sources, while dry season diarrhea is thought to be caused by families switching to dirtier water sources as their preferred, cleaner sources of drinking water run dry. We show that household amenities may mitigate dry season diarrhea rates; wealthier households, with improved sanitation and drinking water sources, exhibited substantially lower levels of dry season diarrhea. Yet even these households remain susceptible to wet season diarrhea. Improved infrastructure is therefore needed to ensure that standard sources of drinking water are protected from rainwater runoff during the wet season and that all families have a safe source of drinking water during the dry season. Investment in such infrastructure should alleviate diarrheal disease and its impact on seasonal wasting in Senegal.

Addressing malaria, which peaks during the monsoon, is challenging as the rains create more stagnant waters for mosquitoes to breed. Studies have emphasized the role of bed nets, particularly insecticide-treated bed nets, as a cost-effective solution for managing malaria rates in children in Sub-Sahara Africa (Snow et al. 1988; Curtis et al. 2006; Bradley et al. 1986). Yet in our sample, even households with bednets – about 60% of households, regardless of wealth (see in appendix Table A5) – displayed a rise in fever during the monsoon. As fever strongly predicts seasonality in child health for all sub-groups examined, this raises the question of alternate malaria management strategies, including more rigorous bed net implementation and spatial repellent strategies (Sougoufara et al. 2018).

Our findings also provide evidence of alternative pathways contributing to seasonality in malnutrition indicators. Traditionally, many policies aimed at addressing malnutrition have suffered from a "food-first" bias where the emphasis was on increasing children's food intake (Pelletier et al. 1995; Venkat et al. 2023). However, academic studies have firmly identified disease incidence as a key contributor to malnutrition (Marshak et al. 2021; Belayneh, Loha, and Lindtjørn 2021). The average child in Senegal consumes around 2 to 3 food groups and remains at this level even right after the harvest (with just half a food group improvement in dietary diversity score compared to the low point of the year). Given that the World Health Organization defines 'minimum dietary diversity' for children under 2 years as the consumption of at least 5 food groups (WHO 2017), it is perhaps unsurprising that seasonal variation in diets, in our sample, was too weak to predict seasonality in child health. (Poor diet is likely a constraining factor for year-round health, however.) Instead, the seasonal variation in weight-for-height z-scores was driven primarily by changes in diarrhea and malaria, highlighting the key role of these illnesses and the need for targeted interventions to address them in order to combat malnutrition in Senegal.

However, households with consistently greater dietary diversity, such as richer and northern households, show better weight-for-height z-score. This suggests a possible sustained benefit of a better diet throughout the year on child health. Recent studies underscore the positive impact of frequent consumption of animal-sourced food on children's nutrition (Ramahaimandimby et al. 2023; Farnworth et al. 2023). Raising children's average dietary diversity score from 2 to an acceptable standard of 5 will undoubtedly take time, but introducing a few key food groups during the most vulnerable periods could improve children's health throughout the year.

5 Conclusion

We pooled several rounds of the continuous DHS for Senegal and parameterized the seasonality in child weight-for-height z-score, dietary diversity, diarrhea, and fever incidences using a second-order trigonometric polynomial. As expected, weight-for-height z-score, a proxy for short-term child health, and dietary diversity, a proxy for dietary quality, are both highest after the annual harvest. Incidence of diarrhea (a proxy for water-borne illness, among other things) and fever (a proxy for malaria) both rise during the rainy season. Incidences of diarrhea also rise during the dry season, particularly for poorer households, likely because households switch to dirtier drinking water sources as their primary sources dry up.

We then decomposed the seasonality in children's health into components predicted by seasonality in dietary diversity, diarrhea, and fever. We did this using a grid-search method that simultaneously estimates both the lags and the amplitudes between the seasonality in health inputs and children's health. We found that seasonality in the two illnesses – fever, having an immediate effect, and diarrhea, having a lagged effect after two months – strongly predicts seasonality in children's health, with dietary diversity adding no additional predictive power.

It is heartening that our data-driven approach to identifying the amplitudes and lags of health inputs provides results consistent with those from several longitudinal studies that assess the effects of health inputs on children's health. Becker, Black, and Brown 1991 tracked a cohort of Bangladeshi children between the ages of 5 to 18 months and measured how variations in several health inputs affected their weight. They found that incidences of both diarrhea and fever were significant in reducing children's weight, with fever having a greater and more immediate effect. Similarly, our findings suggested a 2-month lag between the rising incidence of diarrhea and its impact on child health, consistent with Checkley et al. 2003 who found that, among Peruvian children, the effect of diarrhea on children's growth was most prominent after 2 months. Similar results were also found by Richard et al. 2013 who assessed how diarrhea impacted children's weight using samples from Peru, Brazil, Guinea-Bissau, and Bangladesh.

Finally, it is important to note that our results are specific to the Senegalese context. The lack of association between dietary diversity and children's health is likely due to the poor diet in Senegal, and this association would likely differ in regions where children have better diets year-round. The magnitude and lags of other health inputs also, of course, depend on a region's monsoon, harvest, and lean seasons. For a more comprehensive understanding of how seasonality in health inputs affects children's health globally, studies from various contexts are needed.

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Tables and Figures

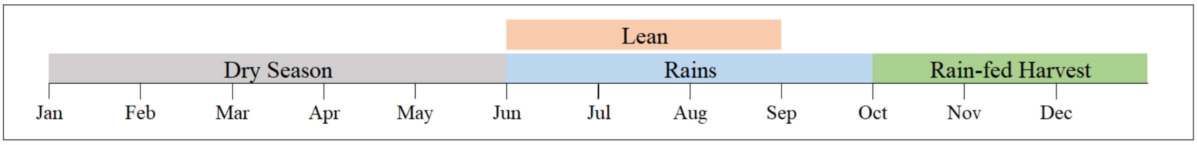


Figure 1: General seasons model for Senegal (adapted from Nene 2018).

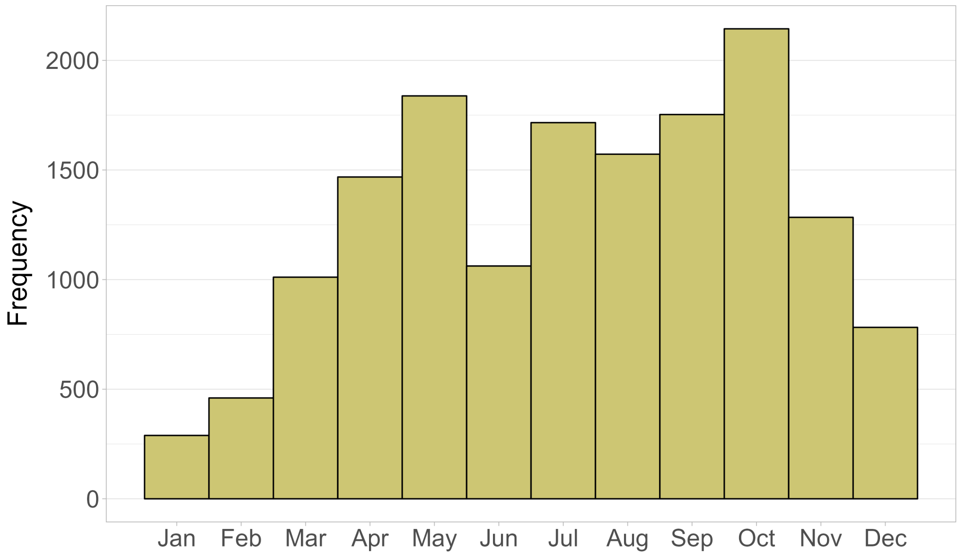


Figure 2: Number of children surveyed in each month after pooling all rounds of the DHS surveys.

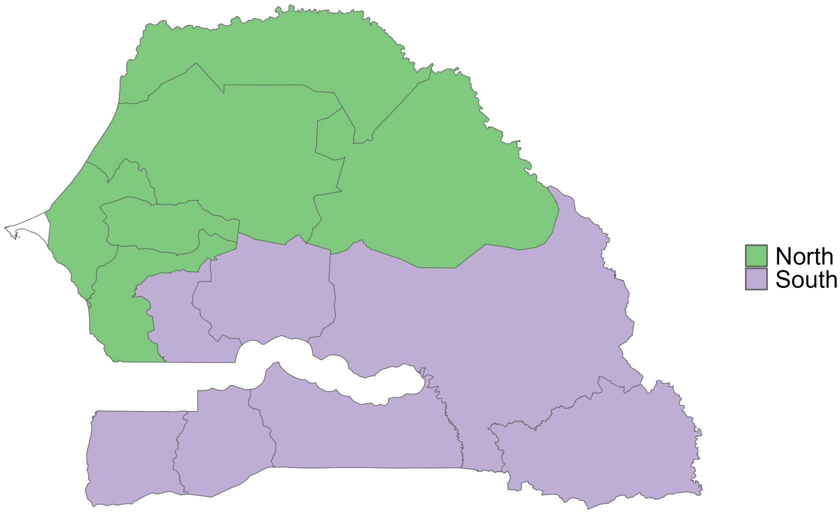


Figure 3: Division of northern and southern household in Senegal. Omitted region is Dakar, the capital city excluded from the study.

Table 1: Summary statistics for children between 6-23 months.

		Houshold Wealth		Regions	
	Senegal	Poorer	Richer	Northern	Southern
Observations	15379	9442	5937	7059	8320
Weight-for-height z-scores	-0.56 (1.14)	-0.65 (1.13)	-0.45 (1.14)	-0.54 (1.14)	-0.60 (1.13)
Dietary diversity (0-8)	2.98 (1.41)	2.80 (1.34)	3.20 (1.47)	3.08 (1.41)	2.83 (1.41)
Diarrhea incidence (0-1)	0.27 (0.44)	0.29 (0.45)	0.24 (0.43)	0.24 (0.43)	0.31 (0.46)
Fever incidence (0-1)	0.24 (0.43)	0.25 (0.43)	0.23 (0.42)	0.21 (0.41)	0.27 (0.45)

Standard deviations presented in parenthesis.

Table 2: Results of the trigonometric parameterization (Equation 1) for Senegal.

	Weight-for-Height Z-score	Dietary Diversity	Diarrhea	Fever
$\alpha 1$	0.109***	0.031	-0.007	-0.036***
	(0.021)	(0.027)	(0.008)	(0.007)
$\alpha 2$	-0.018	0.091***	0.001	0.004
	(0.023)	(0.034)	(0.009)	(0.007)
$\alpha 3$	0.037*	0.062**	0.044***	-0.002
	(0.022)	(0.028)	(0.008)	(0.007)
$\alpha 4$	-0.045**	0.048*	-0.030***	-0.016**
	(0.020)	(0.029)	(0.007)	(0.007)
Constant	-0.543***	2.876***	0.272***	0.229***
	(0.015)	(0.021)	(0.006)	(0.005)
Observations	14226	15379	14668	14651
F-Statistics	8.6	2.7	13.6	8.4

Standard errors in parenthesis. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Children with missing or invalid observations are omitted from analysis. Standard errors are clustered at the DHS cluster level.

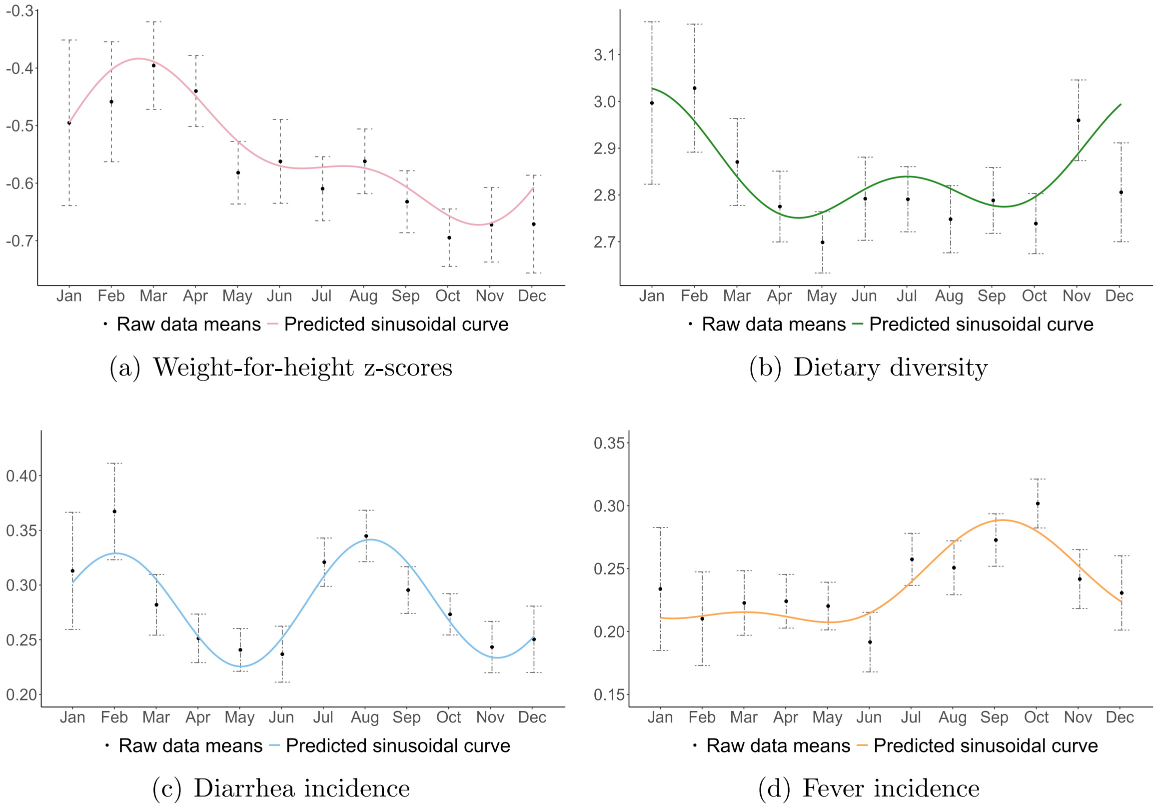
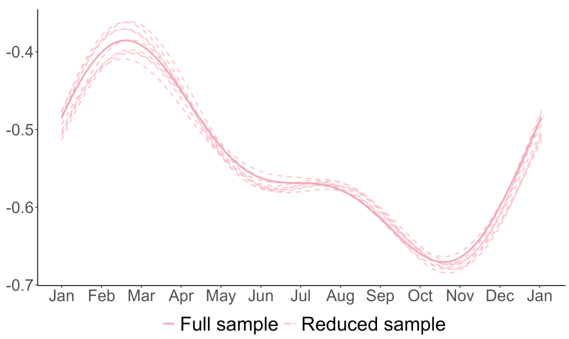


Figure 4: Raw monthly means (points) with 95% confidence intervals compared with predicted sinusoidal curves (line). Sinusoid predictions result from estimating Equation 2.

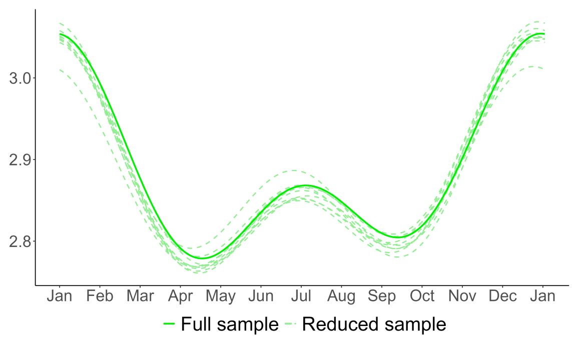
Table 3: Amplitudes and lags of all households using the grid-search.

		Senegal (1)	Poorer (2)	Richer (3)	North (4)	South (5)
Amplitude	Dietary diversity	0.09 (0.024)	0.24 (0.000)	0.00 (0.024)	0.54 (0.037)	0.00 (0.004)
	Diarrhea	-1.58 (0.057)	-2.03 (0.000)	-0.67 (0.063)	-0.82 (0.070)	-3.69 (0.020)
	Fever	-2.73 (0.094)	-2.53 (0.001)	-3.88 (0.078)	-4.34 (0.105)	-3.19 (0.027)
Lags (weeks)	Dietary diversity	0	3	0	0	0
	Diarrhea	8	8	8	8	8
	Fever	0	0	0	0	1
RSE		0.04	0.00	0.04	0.06	0.00

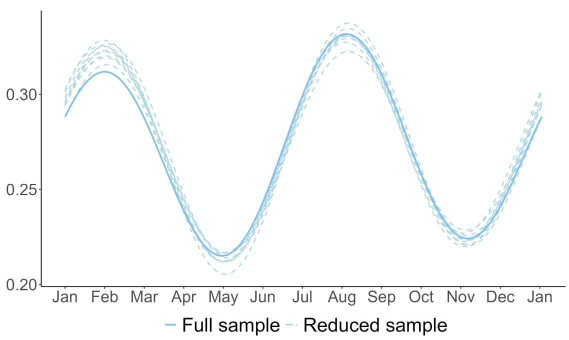
Standard deviations are presented in parenthesis.



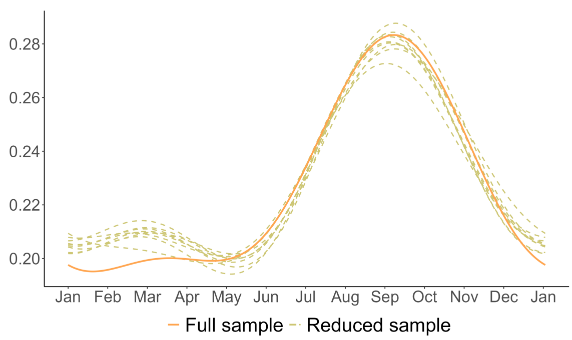
(a) Weight-for-height z-scores



(b) Food group score



(c) Diarrhea incidence



(d) Fever incidence

Figure 5: Full sample sinusoidal curves (solid lines) compared with 10 sinusoidal curves (dotted lines) generated by randomly dropping 10% of the data for Senegal.

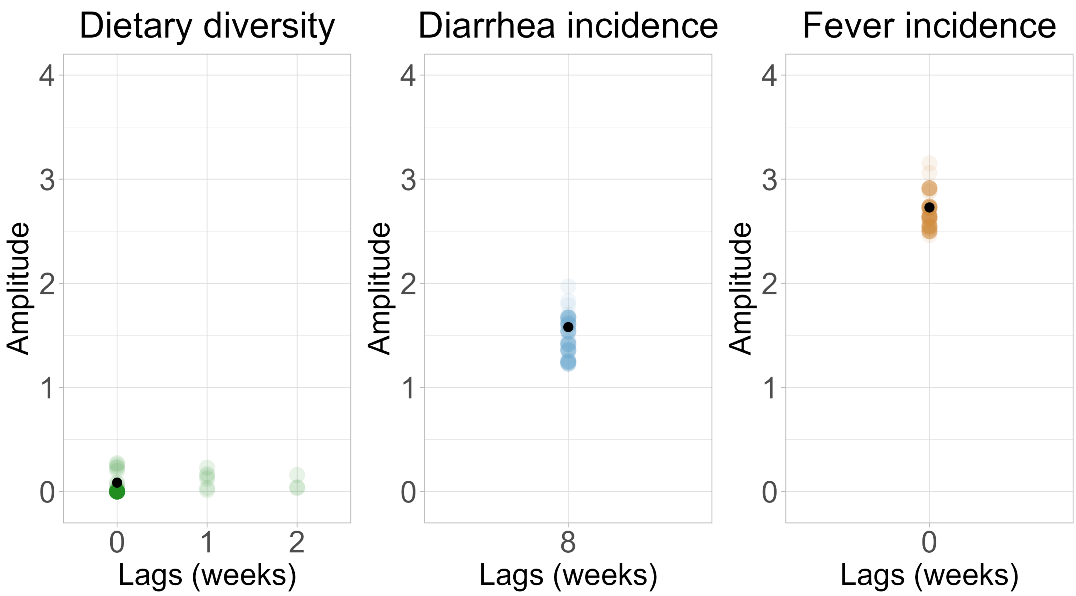
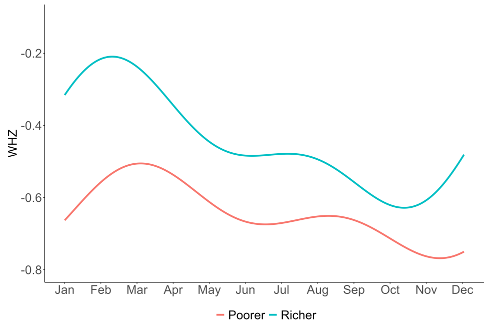
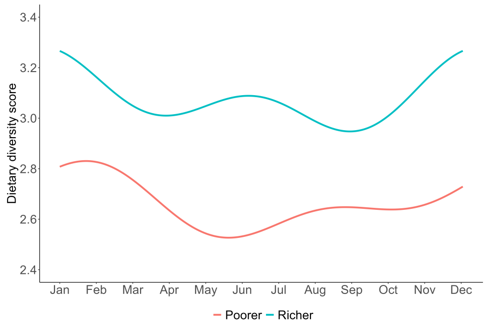


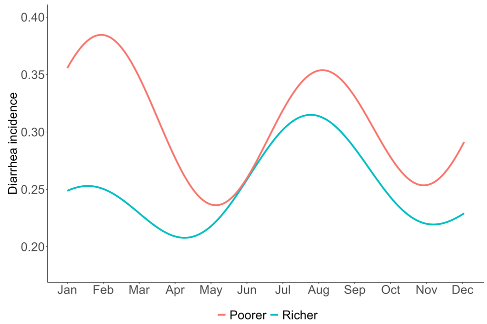
Figure 6: Sub-samples robustness check for the decomposition results for Senegal. Dark point indicates solution from the full sample and colored points indicate solutions from each iteration using reduced samples.



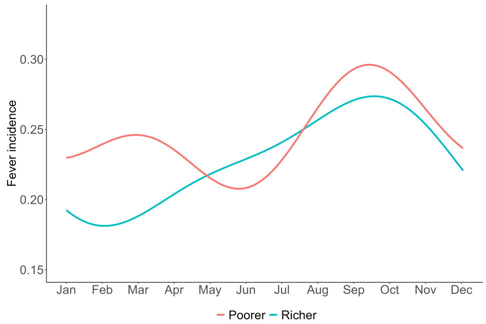
(a) Weight-for-height z-scores



(b) Dietary diversity

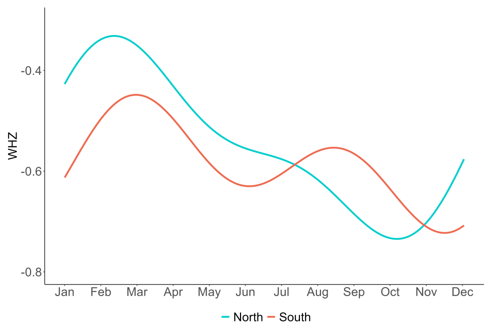


(c) Diarrhea incidence

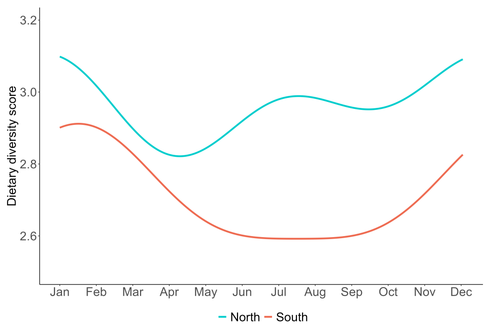


(d) Fever incidence

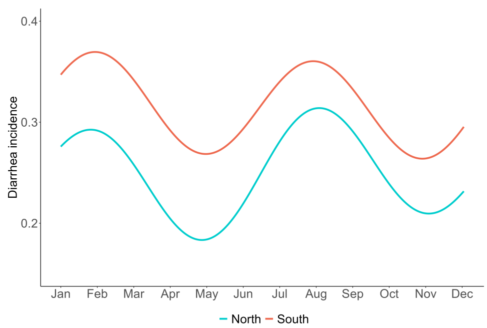
Figure 7: Sinusoidal curves for children from poorer and richer households.



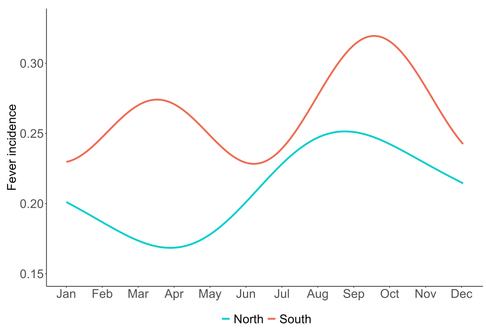
(a) Weight-for-height z-scores



(b) Dietary diversity



(c) Diarrhea incidence



(d) Fever incidence

Figure 8: Sinusoidal curves for children from northern and southern Senegal.

Online Appendix

Table A1: Survey observations across years and months.

	Month												
	1	2	3	4	5	6	7	8	9	10	11	12	Total
2012	0	0	0	0	0	0	0	0	0	196	245	277	718
2013	257	0	222	301	342	163	0	0	0	0	0	0	1285
2014	32	248	322	327	52	232	222	190	212	144	0	0	1981
2015	0	212	285	278	306	1	127	361	227	248	14	0	2059
2016	0	0	181	347	356	113	86	333	205	291	101	0	2013
2017	0	0	1	172	441	10	530	482	379	558	517	430	3520
2018	0	0	0	0	3	331	469	185	446	381	167	22	2004
2019	0	0	0	43	338	212	282	21	284	326	240	53	1799
Total	289	460	1011	1468	1838	1062	1716	1572	1753	2144	1284	782	15379

The first survey cycle covers half the years of 2012 and 2013.

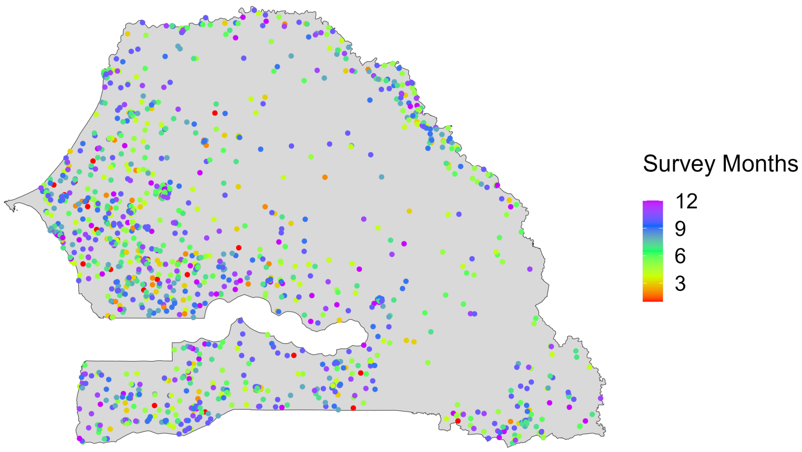
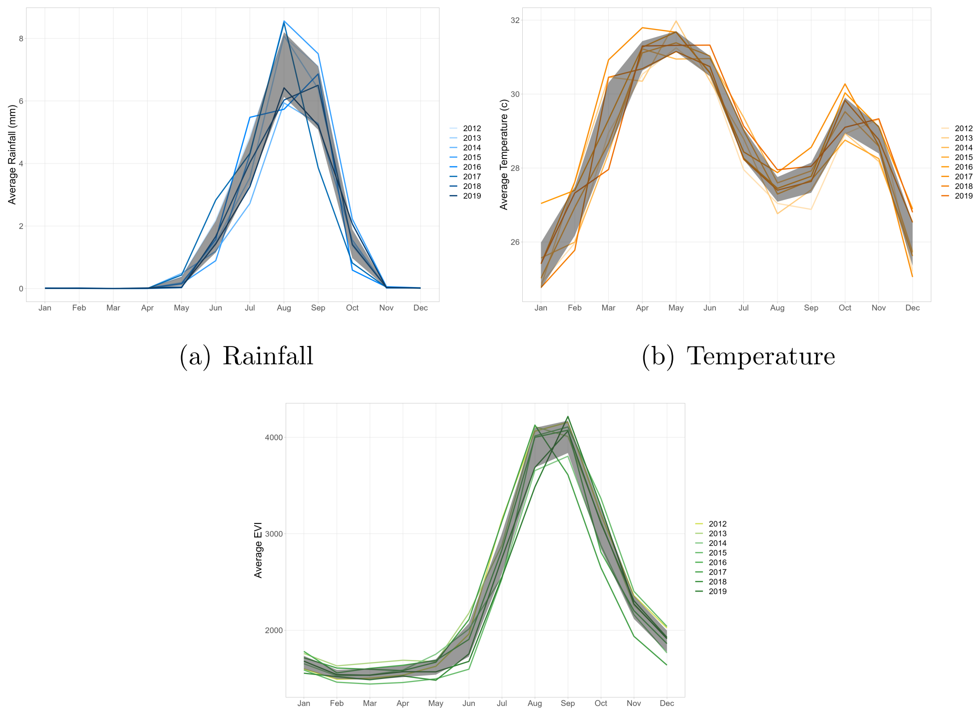


Figure A1: Average month of interview for each DHS cluster across all survey years.

Table A2: Predicting major household characteristics across survey months in Senegal.

	(1) Age of child	(2) Child is girl	(3) Mother's age	(4) Mother's education	(5) Children in household	(6) Total children born	(7) Poorer households	(8) Rural residence
Jan	0.272	-0.042	-0.861*	-0.096	0.084	-0.169	-0.017	0.072
	(0.324)	(0.072)	(0.442)	(0.080)	(0.251)	(0.181)	(0.129)	(0.083)
Feb	0.022	-0.018	-0.207	-0.180***	0.238	0.095	-0.032	0.043
	(0.279)	(0.031)	(0.464)	(0.058)	(0.214)	(0.165)	(0.085)	(0.068)
Mar	0.244	0.006	-0.360	-0.134***	0.136	0.127	-0.040	-0.008
	(0.211)	(0.022)	(0.303)	(0.047)	(0.215)	(0.119)	(0.062)	(0.062)
Apr	0.124	-0.005	-0.011	-0.121***	0.145	0.103	-0.011	0.010
	(0.225)	(0.019)	(0.304)	(0.045)	(0.196)	(0.121)	(0.062)	(0.066)
May	-0.312	0.005	-0.669**	-0.120***	0.181	-0.027	-0.006	0.048
	(0.195)	(0.018)	(0.277)	(0.043)	(0.212)	(0.097)	(0.054)	(0.047)
Jun	-0.109	-0.025	-0.012	-0.020	-0.047	-0.032	-0.053	0.040
	(0.207)	(0.024)	(0.355)	(0.058)	(0.170)	(0.126)	(0.063)	(0.054)
Jul	0.236	-0.001	-0.163	0.011	-0.081	-0.167	-0.101*	-0.044
	(0.201)	(0.019)	(0.292)	(0.049)	(0.163)	(0.110)	(0.054)	(0.055)
Aug	0.088	-0.026	-0.523*	-0.044	-0.077	-0.069	-0.000	0.010
	(0.202)	(0.018)	(0.287)	(0.047)	(0.152)	(0.101)	(0.050)	(0.049)
Sep	0.094	-0.020	0.199	-0.033	0.305*	0.014	-0.024	0.029
	(0.197)	(0.019)	(0.294)	(0.056)	(0.178)	(0.111)	(0.050)	(0.051)
Nov	0.103	-0.006	0.168	0.002	0.165	0.026	-0.089	-0.003
	(0.211)	(0.021)	(0.324)	(0.053)	(0.180)	(0.117)	(0.055)	(0.053)
Dec	0.230	-0.009	-0.018	-0.122**	0.382	0.076	0.020	0.108**
	(0.261)	(0.022)	(0.406)	(0.051)	(0.233)	(0.123)	(0.065)	(0.050)
Constant	14.275***	0.509***	28.625***	0.500***	3.565***	3.686***	0.592***	0.741***
	(0.126)	(0.012)	(0.194)	(0.032)	(0.118)	(0.069)	(0.033)	(0.031)
Joint F-stat	1.01	0.56	1.71	2.87	1.19	0.87	0.73	0.94
p-value	0.436	0.862	0.066	0.001	0.291	0.573	0.705	0.500
N	15379	15379	15379	15378	15379	15379	15379	15379

Asterisks indicates significance: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.



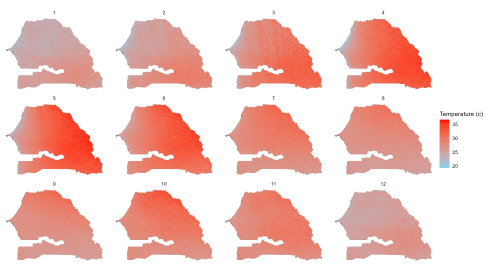
(a) Rainfall

(b) Temperature

(c) EVI

Figure A2: Average values of (a) Rainfall, (b) Temperature, and (c) EVI across years. Darker lines indicate more recent years and shaded regions indicate the 95% confidence interval across months for our sample period. Rainfall data was accessed from the CHIRPS data, temperature data from ECMWF, and vegetation was measured through EVI using the MODIS product.

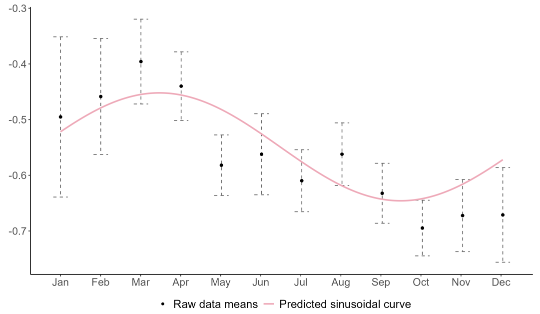
(a) Rainfall



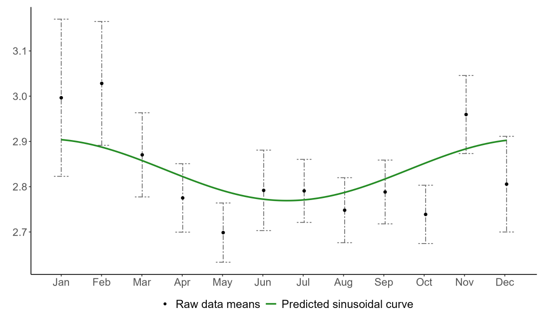
(b) Temperature

(c) EVI

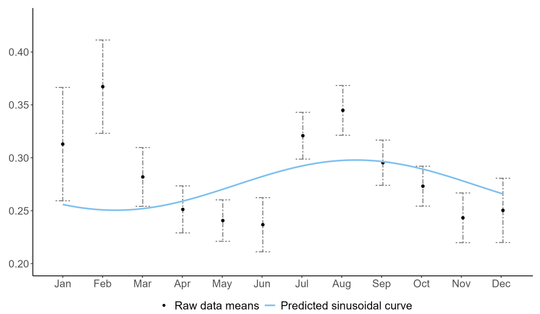
Figure A3: Average seasonal variations in (a) rainfall, (b) temperature, and (c) vegetation across Senegal.



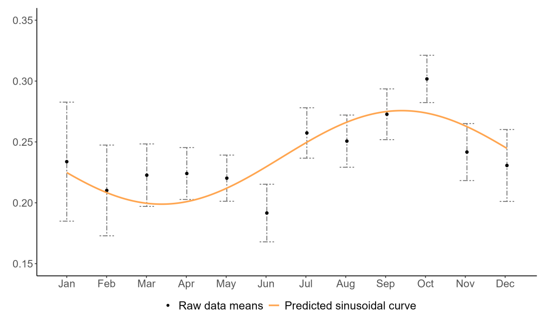
(a) Weight-for-height z-scores



(b) Food group score



(c) Diarrhea incidence



(d) Fever incidence

Figure A4: Raw monthly means (points) with 95% confidence intervals compared with the predicted curve generated using first-order Fourier series. These curves are limited to one trough/peak a year and fails to adequately capture the complex seasonal variations in diarrhea and fever incidences.

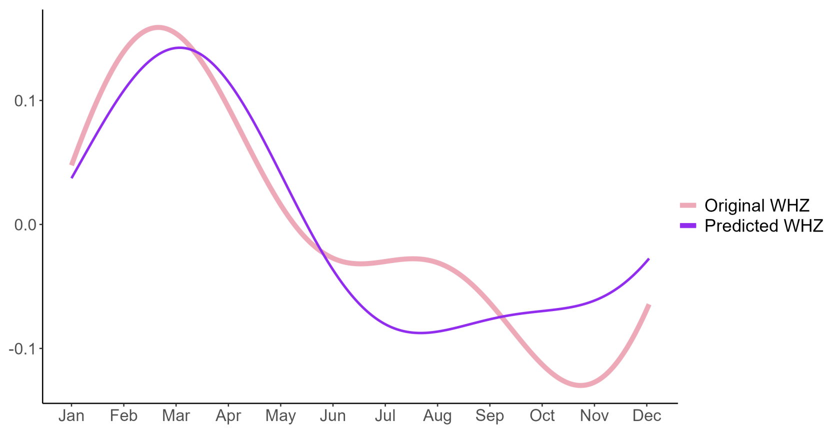


Figure A5: Predicted sinusoidal curve compared with the sinusoidal curve for weight-for-height z-score.

Table A3: Results of the trigonometric parameterization for children consuming in poorer households.

	WHZ	Dietary diversity	Diarrhea	Fever
Richer	0.224***	0.379***	-0.068***	-0.022**
	(0.028)	(0.041)	(0.011)	(0.010)
$\alpha 1 \times$ Richer	0.106***	-0.016	-0.037**	-0.019
	(0.039)	(0.055)	(0.015)	(0.014)
$\alpha 2 \times$ Richer	0.022	0.011	-0.048***	-0.015
	(0.042)	(0.062)	(0.015)	(0.014)
$\alpha 3 \times$ Richer	0.046	-0.003	-0.025*	0.009
	(0.039)	(0.056)	(0.015)	(0.013)
$\alpha 4 \times$ Richer	0.004	0.129**	0.013	0.022
	(0.037)	(0.053)	(0.014)	(0.015)
Observations	14226	15379	14668	14651

Standard errors in parenthesis. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Only interaction effects are presented. Children with missing or invalid observations are omitted from analysis. Standard errors are clustered at the DHS cluster level.

Table A4: Results of the trigonometric parameterization for children from north and south regions.

	WHZ	Dietary diversity	Diarrhea	Fever
North	0.086***	0.219***	-0.069***	-0.061***
	(0.029)	(0.038)	(0.011)	(0.010)
$\alpha 1 \times$ North	0.079**	-0.125**	-0.016	-0.018
	(0.040)	(0.051)	(0.015)	(0.014)
$\alpha 2 \times$ North	0.055	-0.044	-0.011	-0.016
	(0.044)	(0.062)	(0.016)	(0.014)
$\alpha 3 \times$ North	0.031	0.037	-0.004	0.021
	(0.041)	(0.053)	(0.015)	(0.014)
$\alpha 4 \times$ North	0.065*	0.034	-0.012	0.024*
	(0.038)	(0.055)	(0.014)	(0.014)
Observations	14226	15379	14668	14651

Standard errors in parenthesis. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. Only interaction effects are presented. Children with missing or invalid observations are omitted from analysis. Standard errors are clustered at the DHS cluster level.

Table A5: Differences in drinking water quality, sanitation facilities, and use of bednets between richer and poorer households.

	Improved drinking water	Improved sanitation	Use bednets
Richer households	0.284***	0.565***	0.063***
	(0.014)	(0.013)	(0.016)
Constant	0.634***	0.379***	0.491***
	(0.013)	(0.012)	(0.012)
Observations	14858	12058	15252
R^2	0.109	0.352	0.004

Standard errors in parenthesis. $^{*}p < 0.1$, $^{**}p < 0.05$, $^{***}p < 0.01$. 'Improved drinking water' is a binary outcome that includes households with either piped water, tube well, protected well, protected spring, tank water, bottled water or access to public taps. Unimproved drinking water includes households who use unprotected wells, springs, or surface water. 'Improved sanitation' is a binary outcome that consists of households with latrine that flushes into a sewer system, septic tank, or pit, or households that use improved pit latrines. Unimproved sanitation includes households with no flush toilet or households that use bucket toilets or poorly build pit latrines. 'Use bednets' is a binary outcome indicating households where all children sleep under a bed net. Standard errors are clustered at the DHS cluster level.