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Extreme Weather Events and Undernutrition

A Critical but Constructive Review of the Literature

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ABSTRACT

Climate change is resulting in increased frequency of extreme weather events, especially in low- and middle-income countries (LMICs) already characterized by highly vulnerable malnourished populations. Unsurprisingly, there are many empirical studies of the linkages between extreme weather events and undernutrition, especially stunting and wasting in early childhood, and several existing reviews of this literature. However, the quality of empirical studies in this highly multi-disciplinary literature is uneven, and existing reviews do exhaustively illustrate the potential pitfalls of climate-nutrition analyses. In this more critical review, we therefore have five objectives. First, to map out the existing literature, particularly in terms of the types of dependent and independent variables used, the geographies in which different studies focus their analysis, and the types of statistical methods used. Our second objective is to illustrate the empirical limitations and pitfalls of this literature through a more critical review. Our third objective is to be critically constructive, by developing a checklist of good practices for analytical studies in this literature, which we hope will be formalized and broadly adopted. Our fourth objective is to illustrate the usefulness of these good practices through a deep dive into what we consider an exemplary study in the literature from Blom et al. (2022). Our final objective is to identify possible steps for new types of survey methods and data collection, actions for the adoption of best-practice analytical methods and identify important research questions for future research.

Key words: Climate change; extreme weather; undernutrition; stunting; wasting.

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1. Introduction

Anthropogenic climate change has resulted in higher temperatures across land, sea, and atmosphere, as well as increased frequency of weather extremes such as heatwaves, extreme precipitation, droughts, and tropical cyclones; changes directly affecting 3.3-3.6 billion people (IPCC, 2022). Since low- and middle-income countries (LMICs) already have high burdens of multiple forms of malnutrition – including stunting, wasting and multiple micronutrient deficiencies – and fewer household, community and national level resources to cope with shocks, there are justified concerns that climate change and extreme weather events may seriously slow or even reverse progress against malnutrition.

The effects of extreme weather during infancy and early life are of particular interest due to the importance of this stage of life for child growth and development. The most immediate humanitarian concern is that various forms of malnutrition, particularly wasting, are significant risk factors for mortality in early childhood (Olofin et al., 2013), with malnutrition in early childhood estimated to account for 45% of mortality in children under five (Black et al., 2013a). Shocks and stressors during critical growth periods can have lifelong impacts (Barker, 1994). Growth faltering in early life can lead to lower human capital development (Abiona, 2017; Rosales-Rueda, 2018), cognitive development (Aguilar and Vicarelli, 2022; Ampaabeng and Tan, 2013; Dewey and Begum, 2011; Rosales-Rueda, 2018), educational attainment (Aizer, Stroud and Buka, 2016; Alderman, 2006; Almond and Currie, 2011), reduced income and wealth (Maccini and Yang, 2009; Shah and Steinberg, 2017), and poor health in adulthood (Black et al., 2013b; Isen, Rossin-Slater and Walker, 2017). The first thousand days thus remains a critical window for anthropometric attainment (Black et al., 2013b), since poor nutrition during this period can affect both immediate health and life-long outcomes (Alderman and Headey, 2018; Roth et al., 2017; Tusting et al., 2020).

The impacts of climate change and extreme weather events on malnutrition are complex and still not fully understood, however, and it is the objective of this critical review to:

1. Provide an updated mapping of the state of the empirical literature on the links between extreme weather events and nutrition through a targeted review designed to map out the different kinds of dependent and independent variables used in this literature and the geographies of study (Section 2);
2. Critically evaluate the challenges this literature faces in establishing evidence that meets internal and external validity criteria (Section 3);
3. Develop a checklist for climate-nutrition research that researchers, reviewers and editors can use to assess quality, but also to just assess what a given study does and does not do (Section 4);
4. Dig deeper into a recent high-quality study from Blom et al. (2022) on heat exposure and child nutrition in West Africa, using this study as something of an exemplar, and applying the aforementioned checklist to assess what the study does and does not do (Section 5); and
5. To identify important knowledge and data gaps that need to be addressed by future research and some practical steps towards closing these gaps, such as improving data collection and strengthening inter-disciplinary collaboration and peer review (Section 6).

It is important, at this point, to justify why we engage in this review, given that other reviews of this literature have already been published in peer-reviewed journals and in the grey literature. Phalkey et al. (2015b) provided an earlier review, while Stanke et al. (2013) and Belesova et al. (2019) review drought exposure and child undernutrition studies, Agabiirwe et al. (2022) look at floods and child undernutrition;

Lieber et al. (2022) look at droughts, flood and climate variability and nutrition, Helldén et al. (2021) look at a range of health outcomes including child nutrition, both Syed, O'Sullivan and Phillips (2022) and Chersich et al. (2020) look at extreme heat and pregnancy outcomes, and Brown et al. (2020) review both climate events and conflict as risk factors for child undernutrition. There are also separate reviews on climate and diarrheal diseases (Carlton et al., 2015; Levy et al., 2016), which are a well-known risk factor for child undernutrition. Since there are now quite a number of reviews on extreme weather events and undernutrition, why undertake another?

First, as we show below, this is a rapidly growing literature in terms of the number of studies produced every year. Second, this is an evolving literature. Many early studies focused on drought impacts in rural populations, largely with agricultural mechanisms in mind, but the past decade has seen a huge surge in interest on the physiological effects of ambient heat on both maternal nutrition (including during pregnancy), birth outcomes and early life nutrition in children. Etiological pathways between extreme temperatures and fetal growth include fetal oxidative stress, less effective thermoregulation and increased water demands during pregnancy (Bakhtsiyarava et al., 2022; Rocha and Soares, 2015). However, the third and most important justification for this new review is that, in our view, most previous reviews – almost all following systematic review protocols – have been insufficiently critical of this literature. Previous reviews rightly point to one of the most important problems in this literature – the challenge of identifying impact pathways linking climate events to nutrition outcomes (e.g. agricultural impacts versus etiological pathways), but discussion on the range of internal validity challenges related to confidently identifying impacts between weather events and nutrition (as opposed to associations) is sometimes quite light. Finally, previous reviews tend not to discuss some problems facing the literature taken as a whole, including external validity issues and the potentially heterogenous impacts of climate events on different populations, as well as the under-recognized problems of publication bias.

In this paper we therefore first provide an updated mapping of the existing literature and the indicators and methods most commonly used, before undertaking a much more critical review of the literature. However, we also aim to be constructively critical by proposing a checklist for quality control assessment in the empirical literature on climate change and undernutrition, analyzing what we consider to be a recent exemplar study in this literature, and identifying priority areas for future research.

2. Mapping out the existing literature on extreme weather events and nutrition

Event key words

To look for studies that sought to test and quantify associations/impacts between weather extremes and nutrition, a broad literature search was conducted for peer-reviewed articles using Web of Science, PubMed, Scopus, and EconLit databases. Each extreme event and its synonyms were used to develop event keywords as shown in

Table ***1***. A query consisted of each event keyword in the title of the publication AND any of the following nutrition-related keywords in the article abstract: stunt*, wast*, weight, vitamin*, deficien*, diet*, food security, or food consumption. Further keywords were added to the title and abstract fields to limit the scope of the study to those conducted at the child or household level (AND [child* OR household*]), and those that specifically addressed nutrition or health outcomes (AND nutrition OR health).

Table 1. Event Keywords

Flood	***Landslide***	***Storm***	***Temperature***	***Drought/Fire***	***Other Hazards***
Flood*	Landslide*	Storm*	Temperature*	Drought*	Shock*
Inundate*	Mudslide*	Typhoon*	Heat*	Fire*	Disaster*
Rainfall	Rockslide*	Hurricane*	Cold*	Wildfire*	Catastroph*
Precipitation	Rockfall	Cyclone*	Frost*	Forest Fire	
			Freez*		

Source: Authors' construction.

This approach has several distinctions compared to existing reviews,[1] with more focus on extreme weather events than continuous environmental factors, and an exclusive focus on regression analyses of historical data (not simulation studies) on the subject of climate and undernutrition. Second, although much of our subsequent analysis focuses on height-for-age Z scores (HAZ) stunting and weight-for-height Z scores or wasting, we also wanted to understand how well populated the literature is with other nutrition indicators. Finally, in a critical augmentation to all existing reviews, we characterize the spatial and temporal extent and resolution of each study to enable future comparisons on similar topics.

Screening Process

The initial search yielded a total of 992 unique entries. Of these, 990 (99% of original) English language publications were retained. Subsequently we excluded surveys, interviews, editorials, guidelines, protocols, editorials (including letters, notes, and comments), event-specific outputs (documents from congresses, conferences, or proceedings), and any retracted publications or errata. These criteria yielded 788 original publications (79% of the original sample), which were further narrowed down to 238 publications (for details, see Appendix A), including 10 reviews excluded from the main analysis but retained as supporting studies for cross-referencing of included publications. Several characteristics were gathered from each included study to inform the mapping analysis below. A complete list of identified characteristics is presented in Table 2.

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[1] Compared to Brown et al 2020 and Belesova et al 2019, we employ narrower search queries on a range of specific environmental extremes and hazards rather than continuous environmental factors. Although papers on the continuous environment are included in this analysis, the underlying search query is different. We further focus on studies at the child- and household-level rather than country- and regional studies. This criterion effectively excludes several simulation studies on crop yield and downstream food security outcomes, which are not the subject of our review. In contrast to Brown et al 2020 and Phalkey et al 2015, we include nutrition outcomes related to physiological malnutrition including vitamin and mineral deficiencies per Belesova et al 2019, as well as diet diversity, food security, and food consumption.

Table 2. Data Extraction Sheet Fields

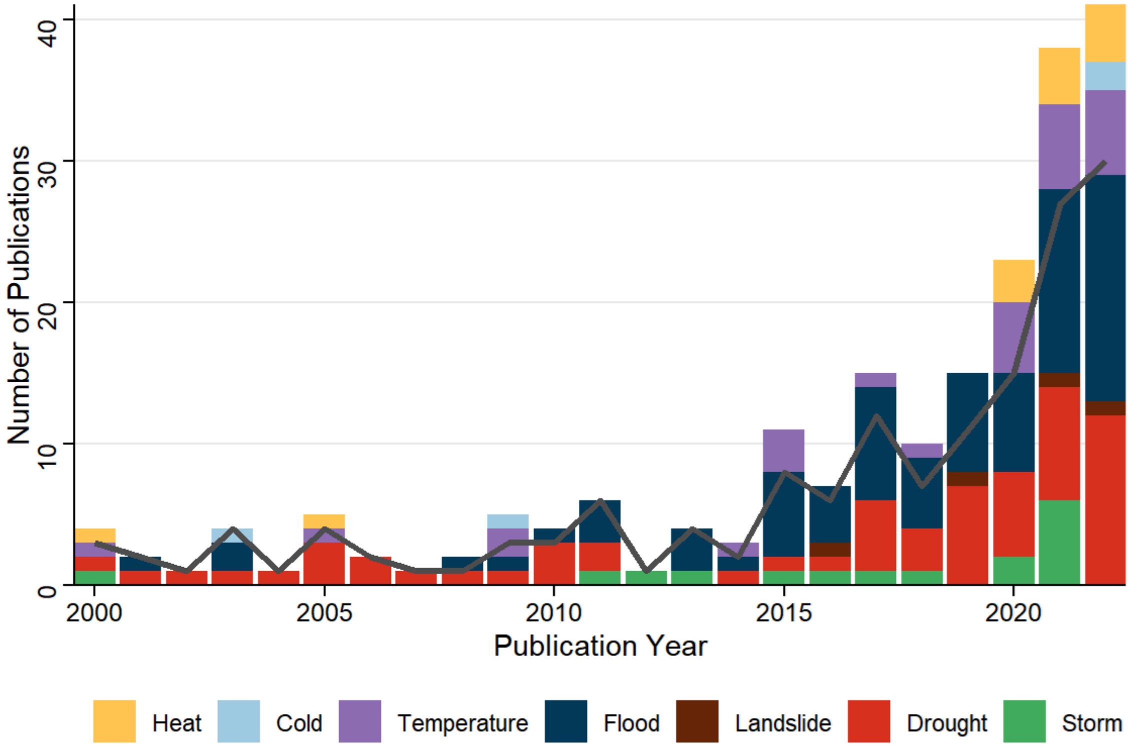
Category	*Field Name*	*Operational Definition*	*Options (if any)*
Spatial Extent	Country of study	Country or countries where study was conducted	Any
	Location of study	Names of study sites or geographic regions included in study	Any
	Spatial Resolution	Administrative level classification of study unit according to Geonames	ADM1 – ADM5
Temporal Extent	Study Period	Study period as defined by authors	
	Time of Data Collection	Time when survey was administered	Month, Year
	Recall Period of Survey	Recall period of survey if applicable	*n* days, *n* weeks, *n* months, long-term
Study Summary	Outcome Category	Type of undernutrition addressed in study (Belesova et al., 2019)	Acute, Chronic, Mixed, Micronutrient Deficiency
	Outcome Measure(s)		WHZ, MUAC, GAM, HAZ, WAZ, Blood measure, Diet Score
	Independent Variables	Categories of independent variables addressed (Phalkey et al., 2015a)	Environment, Agriculture, Crop, Livelihoods, Socioeconomics, Demography, Diet, Morbidity
	Methodology	Categories of how the relationship between variables is assessed	Group comparisons, Association, Advanced Association, Causal (Observational), Causal (Experimental), Prediction
Hazard Characteristics	Hazard	Specific hazard or shock studied	Flood, Landslide, Drought, Temperature Extremes, Storm,
	Hazard Measure	Measure used to characterize hazard/shock	Any

Source: Authors' construction.

Publication trends over time by the types of extreme weather events studied

Descriptive statistics from the 238 publications included in this review are presented below. As seen in Figure 1, the number of relevant publications has notably increased since 2014, with a parallel increase in the types of weather phenomena being studied. Floods (79 studies, 33%) and droughts (62 studies, 26%) are the most frequent extreme events studied. Continuous measures of temperature, including hot and cold extremes comprise 44 studies or 18% of the sample. 16 studies (7%) were found involving storms or tropical cyclones, and only four studies were found addressing landslides and their impacts on nutrition.

Figure 1. Counts of reviewed publications by year and weather phenomena studied. Grey line indicates total number of publications. Studies investigating multiple phenomena (e.g. heat and cold) are included multiple times in underlying bar graph.

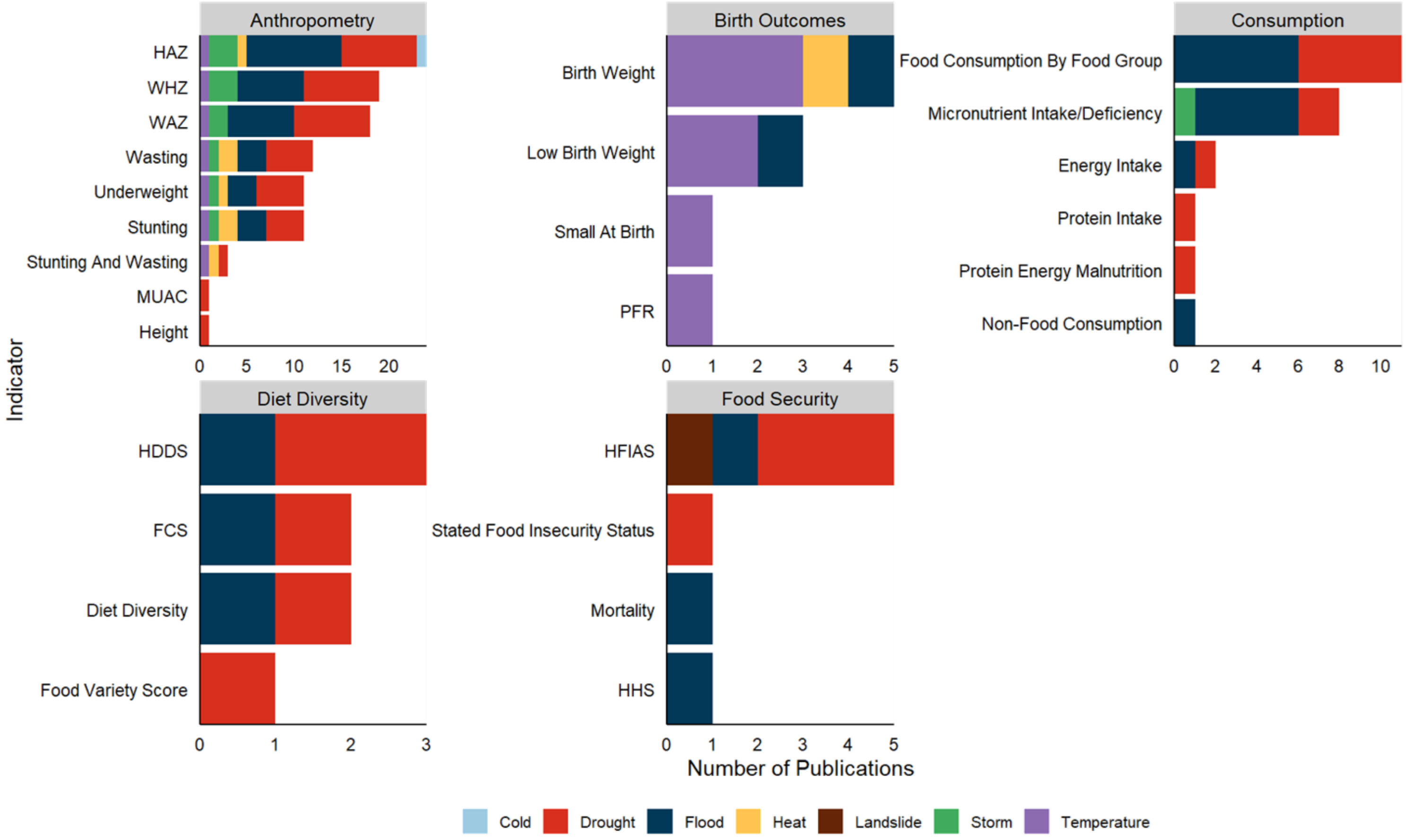


Source: Authors' estimates from the targeted review.

The diversity of dependent variables analyzed in the literature

Figure 2 presents the variety of nutrition indicators studied across reviewed articles. Anthropometric indicators are the most frequent outcome measure, utilized in 42% of reviewed publications. Among these indicators, a small difference is observed between frequency of Height-for-Age Z score (HAZ) and Weight-for-Height Z Score (WHZ), indicating comparable research interest in both chronic undernutrition (stunting) and acute undernutrition (wasting). Perhaps surprisingly, weight-for-age Z scores (WAZ) are often analyzed even though this measure (and "underweight") confounds both chronic nutrition and acute nutrition since weight is a function of height. Nutritionists therefore no longer regularly report or analyze "underweight" or WAZ. Food consumption-based indicators and birth outcomes are the next most frequent indicator category, appearing in 10% and 4% of studies respectively. Indexed and self-reported measures of diet diversity and food security are the rarest in our analysis, comprising less than 6% of reviewed publications.

Figure 2. Counts of publications by nutrition indicator and extreme weather phenomenon studied



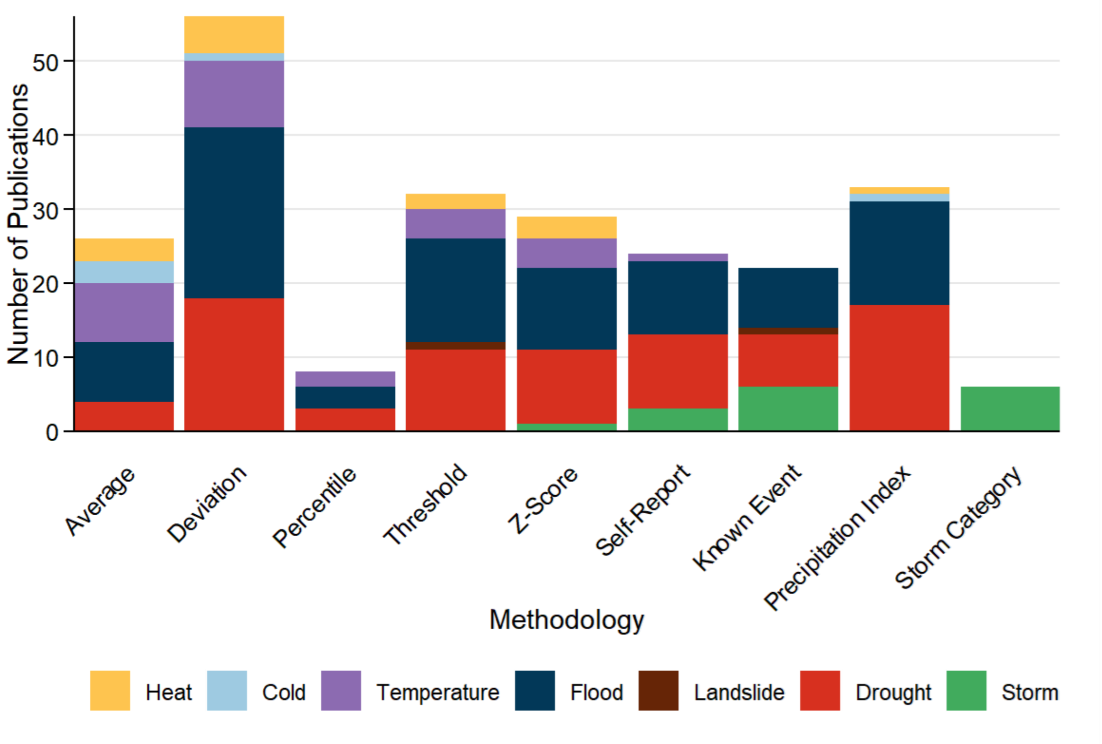
Source: Authors' estimates from the targeted review.

As in *Figure 1*, floods and droughts are the most well-studied extreme weather phenomena and comprise the greatest diversity (over 18) of associated nutrition indicators. The majority of these studies utilized anthropometric indices or binary assessments of stunted or wasted status (n=25). Studies of temperature impacts on nutrition utilized 11 unique nutrition indicators, with four studies investigating birth outcomes. A particular research focus on temperature influences on birth outcomes is therefore observed in the literature. Studies of storm impacts on nutrition utilized 7 unique nutrition indicators mostly related to anthropometry.

The diversity of climate indicators analyzed in the literature

Figure 3 presents the variety of environmental measures utilized in reviewed publications. Deviation or anomaly measures, e.g. standard deviation from historic average precipitation, is the most frequently used climate indicator. Positive and negative rainfall anomalies from varied reference periods are often used to study household impacts of floods and droughts. Recent multi-county studies (n = 25) favor precipitation indices such as the Standardized Precipitation Index (SPI) and the Standardized Precipitation and Evapotranspiration Index (SPEI) as a more reliable measure of flood and drought across geographies. Three studies were found to utilize both continuous SPEI and threshold SPEI values to create different categories of severity (Dimitrova, 2021; Freudenreich, Aladysheva and Brück, 2022; Rustad, Rosvold and Buhaug, 2019). Threshold-based indicators are also frequently utilized in temperature studies to operationalize increasing severity of heat stress (Isen et al., 2017; Tusting et al., 2020). Averages and Z-scores are similarly common; however, few studies utilize percentile-based climate indicators, perhaps due to the higher data demands of this measure (Block et al., 2021). Finally, there is a large degree of overlap between Self-Report and Known Event measures, as the surveys that seek to identify whether households experienced a shock or not are targeted to particular regions and time frames.

Figure 3. Counts of publications by type of climate indicator utilized and extreme weather phenomenon studied. Note: studies utilizing multiple indicators for one or more variables are included as multiple entries



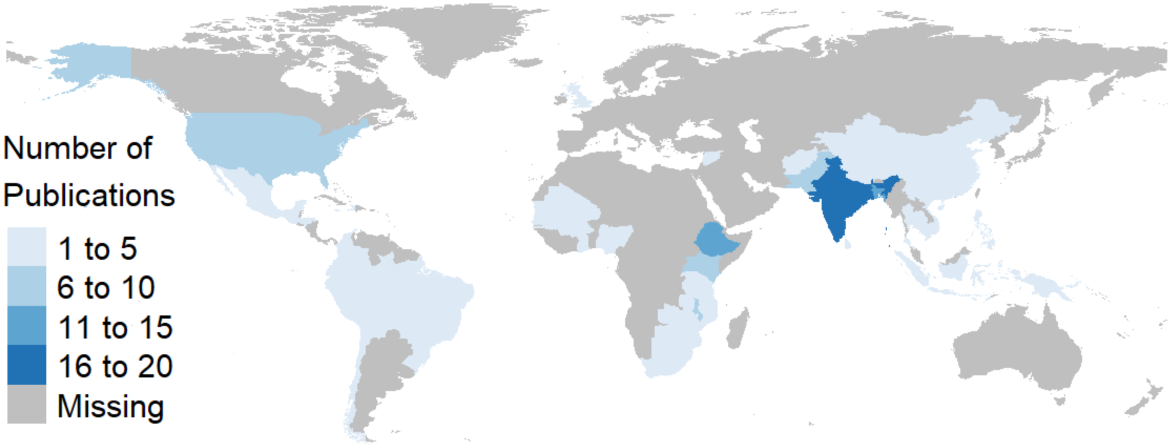
Source: Authors' estimates from the targeted review.

Notes: Studies utilizing multiple indicators for one or more variables are included as multiple entries

Geographical Distribution of Studies

This review includes studies conducted in 51 countries (Figure 4), most of them in the global south. India (n=19), Bangladesh (n=14), and Ethiopia (n=14) are the most well-represented countries in this review. Among these countries, droughts (25 studies) and floods (20 studies) are the most frequently studied extreme weather events, and anthropometric outcomes are the best studied (n=35).

Figure 4. Counts of publications by study location. Note: Multi-country studies are not included in this map.



Source: Authors' estimates from the targeted review.

3. Methodological challenges in the literature on extreme weather and child undernutrition

Since most of the studies in this literature focus on child stunting (or HAZ) and wasting (or WHZ), we focus our discussion of the methodological challenges in this literature on those pertaining to child anthropometric outcomes specifically, although many of the problems we discuss apply to analyses that use other dependent variables. We also note that the questions and problems we pose below are often interconnected; one type of problem (e.g., a small sample size) can compound other problems (e.g., precise quantification of interaction effects).

Question 1. Do studies specify regression models that plausibly identify causal impacts between weather events and nutrition outcomes? As noted above, studies use a variety of analytical methods to examine associations between extreme weather events and nutrition outcomes, but the underlying interest in all cases is a causal relationship. However, many studies fall short of establishing associations that can plausibly be thought of as causal in nature. Part of this problem may be inter-disciplinary disconnects. In economics, for example, there is a stronger tradition of using regression analysis of observational data for quasi-experimental studies, such as through instrumental variables (IV) approaches or difference-in-difference approaches. The most common regression models in this literature use nutrition outcomes on the left-hand side as a function of GIS-based weather indicators on the right-hand side. However, in those circumstances it is critical to control for geographical fixed effects at the spatial unit of the weather variables of interest (e.g. the pixel or grid), for variation in weather to be entirely temporal in nature.

If sufficient granular fixed effects are not specified, then variation in weather at least partially comes from spatial variation weather and climate, and this is almost certain to lead to seriously biased estimates of the impact coefficients. To see why, consider that locations that are more likely to face extreme weather events may also be more likely to have other characteristics – e.g. remoteness, poor infrastructure, poor access to services and so on – that are difficult to observe and control for, and which affect nutrition outcomes independently of extreme weather. In practice, it seems that many studies in this literature do not adequately control for fixed effects at the unit of weather measurement.

How well do different studies distinguish the correlated dimensions of extreme weather events? As we observed above, there are many different ways to measure extreme weather events, and some of these may be correlated. Drought is modelled as a function of dry weather, but that can often include hot spells, so any "impact" of drought through a presumed agricultural channel like crop failure may also be picking up impacts from heat stress. Most studies that look at temperature also control for rainfall, and vice versa.

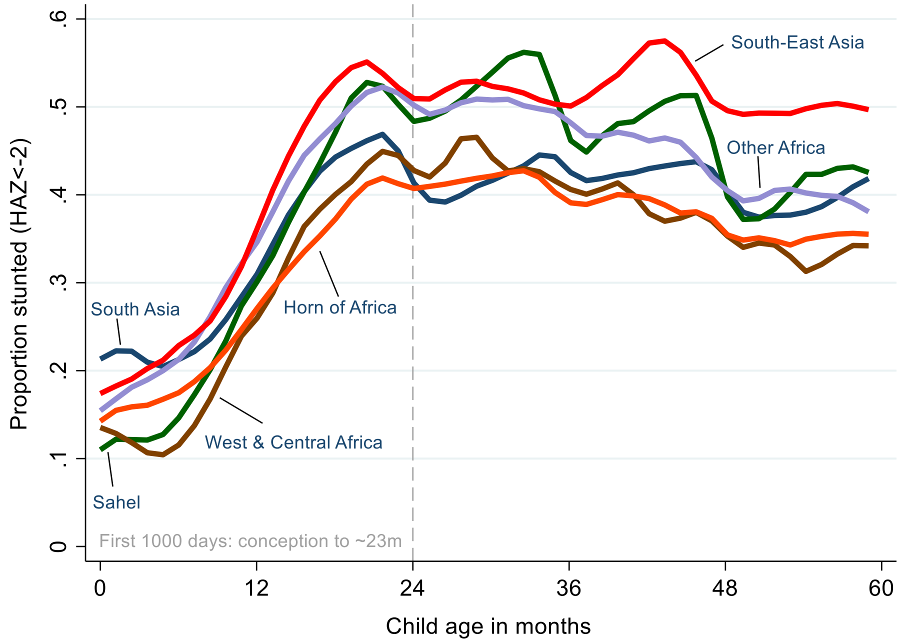
Do studies appropriately allow for non-linear associations between weather indicators and nutrition? The relationship between weather variables and undernutrition is self-evidently non-linear, irrespective of the mechanism hypothesized. Physiologically, the human body becomes stressed by heat (and humidity) as ambient temperatures approach the internal temperature of the human body (e.g., 37 degrees Celsius), so a number of studies have tried to model extreme heat as temperatures that approach 37 degrees. Crop yields also have a highly non-linear relationship with temperature; maize yields rise modestly with temperature until a robust threshold of around 29 degrees Celsius (Block et al., 2022); above that threshold, yields plummet precipitously. That said, there may not be any precise hypotheses regarding turning points or thresholds when the mechanisms are unclear or if context-specific factors matter. In such cases it may be best to flexibly account for non-linear relationships, such as through binning; for example, 5-degree temperature bins (Blom et al. 2022). Studies should avoid inflexible linear specifications, use flexible approaches, and check that those specific non-linear specifications (e.g. based on theory) do indeed provide the best fit.

Do studies appropriately account for the different dynamics of stunting and wasting and their lagged relationships with weather events? Stunting or low height-for-age is a chronic measure of the impacts of cumulative nutrition insults. It is well known that stunting emerges in the first 1000 days of life, including in utero and the first 2 years after birth (Victora et al., 2009). Panel A in Figure 5 illustrates this for different regions. In all regions between 10-20 percent of children are born stunted, largely reflecting poor maternal nutrition during pregnancy. However, stunting then increases rapidly soon after birth until just before 2 years of age, then stabilizes or even declines somewhat as growth velocity is relatively low from 2-5 years of age. Indeed, linear growth velocity is so low from 2-5 years of age that weather shocks in this age range may not leave a strong "signal" on child height even if there are impacts on nutrient intake or other aspects of health. Conversely, including very young children in a sample (e.g., 1-2 months of age) could attenuate coefficients if young children are protected from shocks, because of exclusive breastfeeding, for example. Alderman and Headey (2018) therefore caution analysts to be careful in how they analyze stunting and HAZ data. In the case of weather shocks, the most sensible core specification might regress HAZ or stunting in the 24-59 age bracket against weather shocks in utero and in the first 2 years of life, but it also makes sense to conduct regressions on age-based sub-samples, as in Blom et al. (2022).

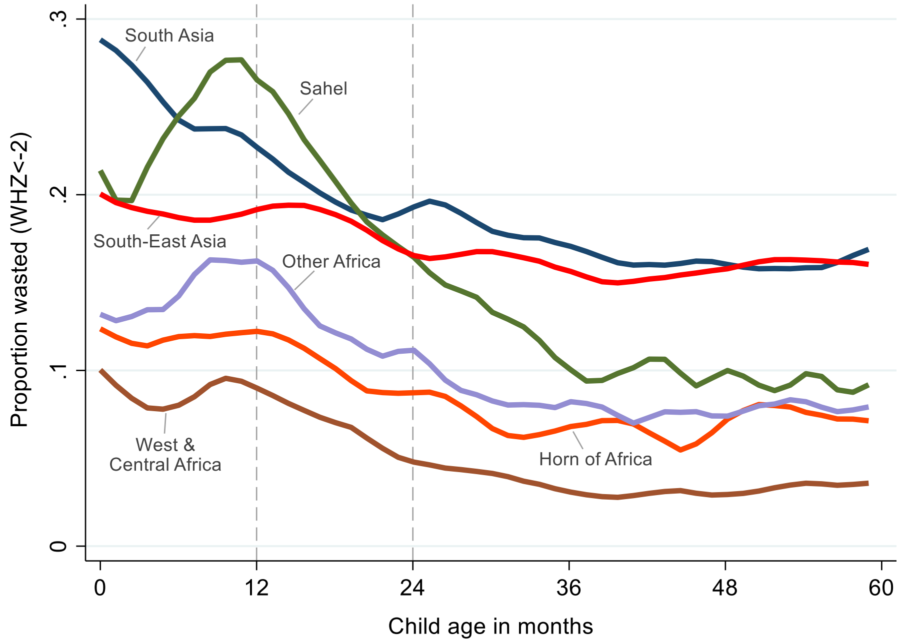
Wasting presents other challenges, as it is normally thought of as a measure of acute malnutrition influenced by recent shocks, though "How recent?" is unclear and lag sensitivity should be checked. Moreover, while some part of a child's thinness at a given point of time may be "acute" (i.e., explained by recent exposure to shocks), some of it may be chronic. As panel B in Figure 5 illustrates, wasting in South Asia peaks at birth and then declines (Headey and Ruel, 2022), pointing to poor maternal nutrition as the primary cause of wasting, and indeed South Asian women are unusually thin as well as short (Coffey, 2015).

Figure 5. Variations in age dynamics of stunting and wasting in LMICs for Demographic Health Survey (DHS) regions with high undernutrition burdens

Panel A: Stunting (HAZ<-2) by age and region



Panel B: Wasting (WHZ<-2) by age and region



Source: Headey and Ruel (2022).

In sub-Saharan Africa, in contrast, wasting is only highly prevalent in the more arid Sahel and Horn of Africa regions and tends to peak at 10-12 months of age, not at birth. However, as comparisons across Panels A and B illustrate, stunting is high throughout sub-Saharan Africa's different regions. Hence, African regions can be categorized into high stunting-high wasting (e.g. the Sahel and the Horn of Africa) and high stunting-low wasting (the rest of Africa). A naïve approach to wasting analysis could therefore easily lead to inferences that weather shocks do not influence nutrition. For example, it would be unrealistic to expect significant impacts of weather shocks on wasting in Malawi because the condition is not prevalent there, even though stunting rates are very high. In contrast, it makes more in sense to find impacts on both stunting and wasting in Burkina Faso (a high stunting and high wasting region).

Finally, researchers need to bear in mind that wasting also has seasonal patterns that also differ across regions. Wasting in South Asia is thought to peak during monsoons, but in the arid parts of sub-Saharan Africa it may peak during the dry lean seasons. Issues of survey timing therefore need to be considered in wasting analyses. For stunting, short-term seasonality is likely very small, but there may be seasonal variation in the timing of birth that at least needs to be controlled for. Stunting and wasting are therefore both complicated, but in different ways.

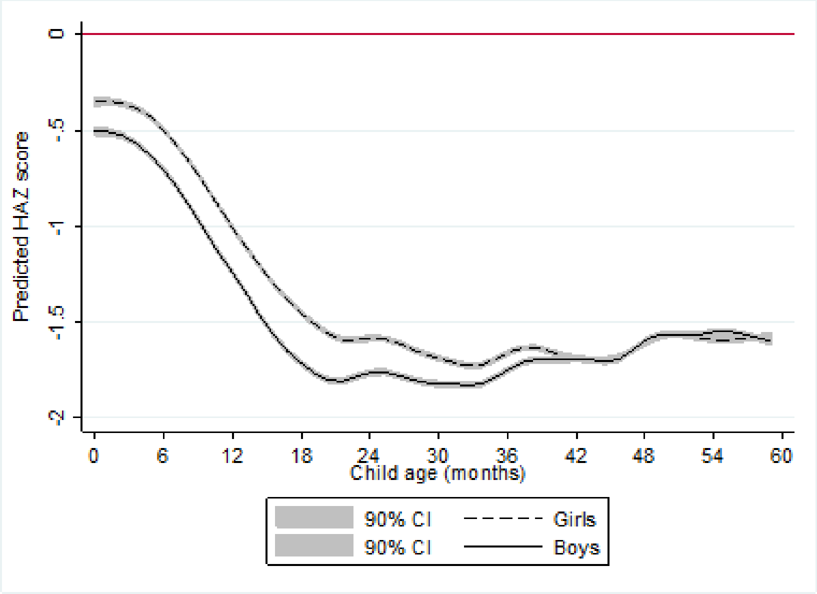
Do studies test interaction effects by gender? Gender-specific impacts of extreme weather events are not only possible, they are arguably probable, but not always intuitive given preconceived notions that girls are more discriminated against in many LMIC settings. As noted above, nutritional insults can begin in utero, but a well-known finding from biological sciences is that male fetuses, and even male infants, are more vulnerable to various shocks than their female counterparts (Kraemer, 2000; McCarthy, 2019). Unfortunately, some LMICs have strong son preferences and other cultural norms that discriminate against girls and women, so it possible that as children get older the biological disadvantage of boys is overturned by socioeconomic and cultural advantages, including access to better food and health care, with discrimination in favor of boys perhaps especially strong during shocks (Behrman, 1988; Bhalotra, 2010).

On the basis of greater biological vulnerability of male fetuses and infants, it is not surprising that many studies on different types of shocks on early childhood health outcomes have found larger impacts of shocks on boys, especially in utero or early life, and sometimes insignificant effects of shocks on girls (Block et al., 2022; Headey and Ruel, 2023). At the same time, girls do face discrimination in some LMICs, so the biological disadvantages that boys face in utero and early childhood may be reversed by social norms at later ages.

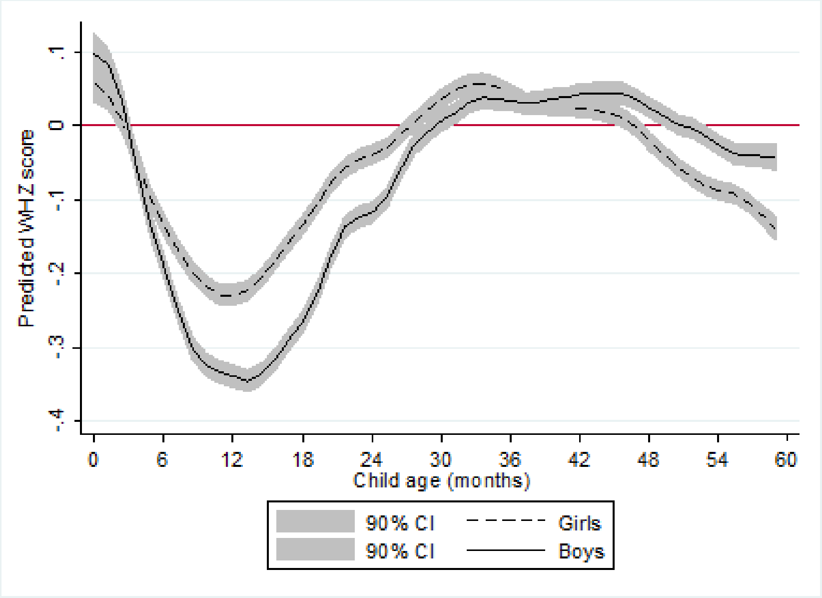
Figure 6 illustrates general patterns in predicted HAZ by age (with 90% confidence intervals) for boys and girls separately, pooling results for almost 700,000 children across 58 LMICs surveyed under the DHS . Panel A shows that female HAZ is higher at birth by around 0.15 standard deviations and the difference is statistically significant. Higher HAZ scores for girls persist at around that magnitude until around 2 years of age, when they start to disappear by age three and a half. For India – a country known for strong son preference, which is hypothesized to explain stunting outcomes (Jayachandran and Pande, 2017) – Alderman and Headey (2018) show that male HAZ is also lower than female HAZ at birth, but overtakes female HAZ in later childhood. Panel B in Figure 6 also confirms that the average male child has a much larger decline in WHZ scores in the first two years of life. However, by ages 4 and 5 girls have lower WHZ scores. Figure 6 draws on all children in the DHS regardless of whether they are exposed to shocks or not, but it illustrates the need to test for shock interaction effects by gender, and indeed by gender and age. Based on existing evidence, it is likely that boys are generally more nutritionally vulnerable to shocks in utero and in early childhood, while girls may be more vulnerable in later childhood.

Figure 6. Predicted HAZ and WHZ for girls and boys 0-59 months of age in 58 countries

Panel A: HAZ scores by age and gender



Panel A: WHZ scores by age and gender



Source: Alderman and Headey (2018). The sample includes 699,421 children from 125 Demographic Health Surveys for 57 countries. 90% confidence intervals (CI) are reported in grey shading.

Do studies account for measurement error in nutrition outcomes and extreme weather event data? Random measurement error in a dependent variable (i.e., nutrition outcomes) creates imprecision in coefficient estimates, while measurement error in an independent variable (i.e. weather outcomes) can produce both imprecision and attenuation of the coefficient to zero (Wooldridge, 2012), making it more difficult to uncover a true relationship between nutrition and weather outcomes because of fuzzy signals. This could be particularly problematic for smaller samples, for lower quality surveys with larger measurement error in anthropometric data and age, and for testing interaction effects (e.g., by gender, child age, livelihood, location, and so on). For the DHS it has been shown that there is significant error in height-for-age z scores due as much to mismeasurement of child age as of height (Larsen, Headey and Masters, 2019), and quality of anthropometric and child age data in the DHS and other major survey initiatives is variable across countries and may have deteriorated over time as survey questionnaires have lengthened.

The quality of weather data, in contrast, is continually improving and evolving, but often involves imputation, which can be especially problematic for indicators reliant on sparse weather stations. Measurement error in weather data could be especially problematic for more remote communities, creating systematic problems for quantifying average effects and interaction effects (e.g., with remoteness, livelihoods, etc). In summary, measurement error in weather indicators needs better documentation in this literature.

Do studies account for spatial correlation in errors? The clustered survey design in many nutrition surveys (e.g., DHS) normally leads researchers to use cluster robust standard errors, but when the key variable of interest is a community level climate variable, then errors in climate variables can be correlated across nearby clusters. In that case, it is advised to use Conley standard errors (Conley, 1999). Just like clustered standard errors consider observations with a survey clustered to be correlated with each other within groups (e.g., DHS clusters), Conley standard errors recognize potential correlation of errors based on spatial proximity (e.g., proximity of DHS clusters to each other). While this adjustment to standard errors, confidence intervals and significance tests does not affect coefficient point estimates on the effects of extreme weather, the adjustments could be large enough to affect inferences on statistical significance, especially in surveys where there are relatively few survey sites, or little heterogeneity in weather patterns.

Are studies on weather shocks and nutrition statistically powered to detect impacts? Often only explicitly experimental studies reflect on statistical power considerations, but statistical power is important for observational or quasi-experimental studies also, especially in the context of weather events measured at a geocoded pixel level rather than the household level, and in the context of significant measurement error in HAZ, stunting, WHZ and wasting. An analysis with low power is unlikely to produce sufficiently precise effect sizes even when a true effect does exists, but it is also possible that a low-powered analysis can produce statistically significant estimates that are of the wrong size or magnitude. On the face of it, many nutrition surveys appear to be large in terms of the sample size of individual children, but almost all employ clustered survey designs where children from the same community are surveyed. The DHS, for example, typically surveys 25-30 households per cluster, so any given cluster could have just a handful of children under 5 years of age or as many as 40 children in higher fertility clusters. In a typical study, each child in each community is matched to some kind of community-level weather data, such that it is the sample size of communities (survey clusters) and variation in weather events across communities that is of importance for attaining sufficient variation in the right-hand side weather variables.

How can analysts better consider power issues? Simulating statistical power in observational studies can be done but can also be quite complex (Black et al., 2022). However, there are also some relatively simple ways to reduce problems with low power. The DHS, for example, are conducted in multiple countries, often contiguous to each other, and in most countries, there are multiple survey rounds; the more survey clusters across space and time, the more variation in weather events, and the less likely that the study is underpowered. For stunting and HAZ it is also possible to exploit variation in child age to increase variation in exposure to extreme weather events. Exploiting variation in child age is less feasible for wasting (acute malnutrition), however, and in addition to all the other aforementioned challenges of identifying the impacts of extreme weather on wasting, researchers should be aware of the risk of their WHZ/wasting regressions being underpowered. Lack of statistical power will also often be a problem for testing interaction effects or sub-sample stratification. In summary, before starting an analysis, researchers should consider whether their sample is powered to detect impacts by focusing on standard errors in the dependent and independent variables in their geography of interest, as well as spatial and temporal variation in weather events.

Do studies use continuous measures of height-for-age and weight-for-height as well as stunting and wasting? From a public health standpoint it is tempting to focus regression analysis on stunting (HAZ<-2) and wasting (WHZ<-2), or severe stunting or wasting (z-scores<-3), as these are well-known risk factors for mortality (Olofin et al., 2013), and also predictive of other health, cognitive, schooling and economic outcomes (Black et al., 2013a). However, using dichotomous variables effectively discards some of the information contained in their continuous counterparts, and can reduce precision (Royston, Altman and Sauerbrei, 2006), which – as noted above – can already be a problem in these types of analyses.

How large are the effects of extreme weather events on the risk of various types of undernutrition? Empirical analyses not only need to establish causality; they also need to quantify the magnitude of extreme weather's effects on undernutrition indicators with some precision, and to assess whether those affect sizes are plausible. Early reviews in econometrics found that many studies in high end economic journals only discussed statistical significance and not effect sizes (McCloskey and Ziliak, 1996; Ziliak and McCloskey, 2004), and this poor scientific habit still persists in economics and other disciplines to this day. However, quantifying the nutritional impacts of weather shocks has obvious policy importance. In the past, highly cited reviews of the underlying causes of undernutrition focus little attention on extreme weather events for lack of evidence, and many national nutrition strategies are articulating effective means of building nutritional resilience to extreme weather events. Yet as at least one study has claimed, climate change is arguably a more sizable risk factor for undernutrition than poverty, women's education, clean water or sanitation. Magnitudes matter; precision matters.

What are the mechanisms linking extreme weather events to undernutrition? As noted in our introduction, this is the most widely discussed limitation of this literature. There are many types of extreme weather events, but also a range of individual, household, community and economywide contextual factors that could condition impacts. Studies that look at the impacts of droughts, floods, monsoon failures, or crop-specific heat stresses typically motivate their analysis in terms of hypothesized impacts on agricultural production, but rarely established agricultural pathways. A major challenge here is the lack of agricultural data in survey initiatives such as the DHS. This has led some analysts to use economic or agricultural household surveys with anthropometric data to attempt to better identify mechanisms, such as heat-induced crop failure in Tanzania (Block et al., 2022). However, economic surveys such as the LSMS-ISA typically lack indicators on alternative pathways like water-borne diseases (e.g. diarrhea), malaria, or maternal or child heat stress. All of these factors are very difficult to directly observe or measure accurately in large scale surveys. Analysts also need to recognize the possibility of multiple mechanisms linking climate shocks to nutrition. Many extreme weather events will affect household income, and income is an important determinant of diet quality, but those extreme weather events could simultaneously have physiological impacts as well.

How large is the extent of sample selection bias, by which shock-affected children/households are simply not surveyed because extreme weather events reduce the likelihood of a survey taking place? While disasters can sometimes prompt special survey efforts, it is likely often the case that at least some types of extreme weather events disrupt or delay survey efforts. We conjecture that this bias is especially problematic in settings where extreme weather events coincide with conflict, poor or damaged infrastructure and weak governance. Moreover, while it may be possible to identify to the longer term impacts of a shock on HAZ or stunting through surveys conducted several years after the shock, gauging impacts on wasting would require a survey to be conducted quickly after the event, or ideally a long-standing high frequency survey, such as those implemented by Helen Keller International in Bangladesh in the 1990s and 2000s (Bloem, Moench-Pfanner and Panagides, 2003), which were useful in gauging the impacts of the 1998 floods. Furthermore, in principle, even when a survey can be conducted after an extreme natural disaster, such disasters can also elevate child mortality rates to the point where child deaths may create selection biases, leading to underestimates of the true impacts of the disaster on malnutrition (Alderman, Lokshin and Radyakin, 2011).

How extensive is misclassification of an individual or household's exposure to extreme events, due to phenomenon such as migration? A mostly implicit assumption in this research is that current location at the time of a survey accurately represents individual exposure to extreme weather events because they resided in the same location during those weather events. In practice, however, most surveys are cross-section with limited information on a household's history of residence changes (the DHS sometimes asks this question). In many cases migration rates may not be high enough to seriously bias coefficients, but this will not necessarily be the case in more extreme natural disasters or circumstances where disasters coincide with conflict, since migration is a very common means of coping with extreme shocks. The bias may also be worse with longer lags between exposure to shocks and the timing of the survey.

Do studies explore potential coping mechanisms or sources of nutritional resilience? As with mechanisms of impact, identifying coping mechanisms or sources of resilience will often be exceedingly difficult. As an extension of other interaction effects discussed above, however, analysts should try to assess whether certain household or community characteristics dampen the harmful impacts of weather shocks. Examples include access to irrigation, larger cropping areas or herd sizes, crop diversification, improved agricultural practices, access to remittances, improved water or sanitation services. For example, in a recent study on the impacts of food price shocks on child wasting, Headey and Ruel (2023) use the DHS's limited agricultural data to show that children from landless rural households were more affected by real food prices increases than children from households that owned farmland and presumably were able to produce some of their own food or benefit somewhat from higher agricultural sales prices. In many contexts, it also appears that receiving remittances is an important source of resilience, while other studies have examined nutritional resilience in terms of proximity to towns and markets or access to sanitation services. In agriculture, a key research question pertains to adoption of best practices for coping with extreme weather events. While that is a large but distinct area of research – for example, trailing drought-resistance rice varieties – more work is needed on the potential for agricultural infrastructure or improved practices to protect child nutrition in rural households. However, it is also worth noting that regressions that that are unable to control for coping mechanisms are estimating coefficient that represent an average across potentially heterogeneous impact: some households may be able to mitigate the impacts of shocks, and some may not. Moreover, the mitigation of shocks may come at a long-term cost, such as sale of assets. Hence, understanding the mechanisms linking extreme weather events to nutrition is important from both a policy point of view, as well as a statistical point of view.

Finally, we pose two questions for the broader literature rather than individual studies:

What types of extreme weather events elevate risks of undernutrition, and which merit more research? In some of the earlier research on extreme weather events and nutrition there was a strong focus on major disasters, such as droughts in Africa (Hoddinott and Kinsey, 2001) or major floods in Bangladesh (del Ninno and Lundberg, 2005). However, with growing interest in climate change and empirical proof that temperatures have already increased significantly in many LMICs, research has started to shift to more subtle weather events such as heat shocks that might affect human physiology directly (Deschenes, Greenstone and Guryan, 2009), or reduce crop yields and/or livestock production (Block et al., 2022; Skoufias and Vinha, 2012). By definition, natural disasters are disastrous and often lead to loss of life as well as long-term nutritional and cognitive "scarring". Their disruptive economic influence makes them more difficult to survey in many instances, but at least attracts attention in terms of relief efforts and disaster preparedness. Less well understood, it could be argued, are the more subtle and perhaps hidden nutritional impacts of climate change and extreme weather events. Is more frequent exposure to heat or changing rainfall patterns slowing progress against nutrition, and if so through which pathways? In our view these seems a crucial policy question, because: (a) policymakers may not be aware of these more subtle impacts of climate change and extreme weather events; and (b) responding to these challenges requires more understanding about those impact mechanisms.

Do extreme weather events have the same impact on children in one part of the world as they do in other parts of the world? While many of the concerns described above pertain to internal validity – i.e. are coefficients estimated without bias and with sufficient precision? – external validity is undoubtedly a concern for the literature as a whole. Whether the impact of weather shocks on nutrition are highly context-specific or more generalizable surely depends on the type of climate shock. For heat stress as well as cold weather stresses, physiological and socioeconomic acclimatization may play a role, but it at least seems plausible that extreme temperature stresses at least have broadly similar impacts across similar climates (i.e., acclimatization only has a partial dampening effect). However, the impacts of other types of extreme weather events (e.g., floods, weather-induced crop failures) are likely to be highly heterogeneous because the mechanisms will systematically vary across livelihoods, geographical conditions and household and community economic conditions. For example, rural populations in low-income countries are highly dependent on staple food production for their livelihood and could be very vulnerable to crop and livestock production failures, but rural populations in many middle-income countries often have highly diversified livelihoods and may be quite resilient. And as noted above, the impacts of extreme weather on wasting are likely to be highly context specific, since wasting is highly concentrated in South Asia and the more arid regions of Africa, but also has different etiologies in each of these regions.

How likely is it that studies that reveal significant and large associations between extreme weather and undernutrition are more likely to be published than studies with insignificant associations, producing "publication bias"? Publication bias is a general problem in science but perhaps even more so in observational or quasi-experimental climate-nutrition studies where researchers do not typically register and commit to a particular pre-analysis plan. Hence, it is perhaps surprising that previous reviews have paid scant attention to it in this context. Above, we have highlighted many reasons why an analyst may not detect a significant association between an extreme weather event and child undernutrition even when a true causal relationship might exist. Yet there may also be situations in which extreme weather does not impact child nutrition, as in the example above in which livelihoods are substantially diversified out of agriculture. In the politically charged context of the scientific community often battling with climate change denial, many researchers, reviewers, and editors may refrain from trying to publish papers reporting null results.

How confident can we be in systematic reviews and meta-analyses of this literature? Systematic reviews are a popular approach in many disciplines, and they could certainly have value as climate-nutrition literature continues to expand. Yet for them to be useful in this context they need to be more discerning in rating the quality of existing studies, according to the potential pitfalls highlighted above. Meta-analyses to uncover average impacts and heterogenous impacts may also be desirable in the longer term, but also would require more stringent assessment of quality and more homogeneity in the measurement of shocks. As our mapping of the climate-nutrition literature revealed, there is tremendous heterogeneity in the specific types of weather event indicators used. Meta-analysis results can also lead to incorrect inferences if there is serious publication bias in the literature. In our view, what is additionally needed are large scale studies using high-quality statistical models to compare results for different climate indicators across multiple LMIC regions.

4. Developing guidelines for climate-related regression analyses for nutrition (CLIMRAN)

In this section we use the discussion above to construct a proposed set of guidelines for climate-related regression analyses for nutrition, for which we use the acronym CLIMRAN hereafter (Table 3). These guidelines are in the spirit of guidelines developed for other types of studies, such as the PRISMA guidelines for systematic reviews and meta-analyses (Page et al., 2021), with specific recommended elements for reporting for each article section. The guidelines are intended for statistical analyses of historical data that try to estimate associations between extreme weather events and nutrition indicators, or impacts of the extreme weather on nutrition via quasi-experimental statistical techniques. We do not propose that all of the reported elements are applicable to all studies; for example, some recommended elements are only applicable to analyses of child anthropometric indicators (HAZ, WHZ) but would not be applicable to analyses of dietary indicators, and vice versa.

For the introduction section of a climate-nutrition article, we recommend describing the rationale for the study in relation to previous research, and briefly identifying dependent and independent variables and the hypothesized mechanisms or impact pathways linking extreme weather events to the nutrition indicators of interest.

For the methods and data section, we first recommend describing the data sources for key variables, but also the rationale for the chosen data sources. Next, very clear definitions are required, especially operational definitions of the weather phenomena, including issues such as how an extreme event is defined in relation to norms, the duration of the event (e.g. what period of low or delayed rainfall constitutes a drought, or monsoon failure), or where flexible non-linear specifications are used to define weather extremes (e.g. temperature bins), and the reference period for defining measures of extreme deviations. For self-reported shocks, validation against exogenous weather data is recommended because of potential subjectivity in responses. It is also critically important to describe the spatial unit of the extreme weather indicator being used (e.g. the size of the grids or pixels in GIS data). If indicators of food security or dietary quality are being used, then reporting the recall period is necessary. Finally, in either the data/methods section or the discussion section, it is critically important to discuss issues of measurement error in both dependent variables (such as HAZ or WHZ indicators) and the weather data (e.g. in relation to underlying quality of the meteorological data).

In terms of the regression model, we noted in the previous section that very few studies in this literature discuss explicitly whether they are powered to detect impacts. We also noted the importance of understanding the dynamics of HAZ and WHZ, but dynamics and structuring of lagged effects are equally important for weather indicators. Other key estimation issues pertain to minimizing the influence of confounding factors, and studies should prioritize reporting on the use of spatial fixed effects with the objective being the removal of spatial variation in weather/climate and instead focusing on time-varying shocks. The estimation strategy should also discuss controlling for other confounding factors at individual, household and community levels, as well as other climate and time-varying geographical factors. Regression models in this literature will likely almost always need to control for spatial correlation in the model's error terms, and potentially also temporal autocorrelation.

The remaining reporting elements in estimation strategies refer to sub-sample analysis or interaction terms with gender and age (at a minimum), testing of hypothesized pathways and factors that could magnify or attenuate impacts (e.g., resilience factors) as well as robustness checks of potential biases, such as potential endogeneity, selection biases related to survey timing, misclassification due to migration.

The results section explicitly discusses and interprets the magnitude of key coefficients, but also discusses and reports the precision of key coefficient estimates. One under-utilized means of interpreting magnitudes is through conducting predictions of the impacts of weather shocks or climate change based on estimated parameters. Robustness checks and tests of key modeling assumptions should be reported, along with extensive parameter heterogeneity tests. The discussion section should obviously flag study limitations, ideally discussing both internal and external validity issues, and compare the study's findings to previous results in the literature.

Table 3. Suggested guidelines for assessing quality control and completeness of reporting in Climate-related Regression Analyses for Nutrition (CLIMRAN guidelines)

		Elements recommended for reporting
1. Introduction		
Rationale & Objectives	1.1	Describe the rationale for the study in relation to previous research
	1.2	Identifies dependent and independent variables
	1.3	Hypothesizes mechanisms linking extreme weather to nutrition outcomes
2. Data		
Data Source Selection	2.1	Describes data sources, including sample design and representativeness
	2.2	For case-control studies, describes control population
	2.3	Describes selection criteria for chosen data sources
Definitions Of Key Indicators	2.4	Uses continuous nutrition outcome indicators (e.g. HAZ, WHZ) as well as dichotomous indicators (e.g. stunting, wasting)
	2.5	Describe spatial and temporal unit of analysis for weather event data
	2.6	Provides detailed operational definition of weather phenomenon, including any non-linear transformations
	2.7	Discusses potential measurement errors in nutrition data and weather data
3. Statistical analysis		
Estimation Strategy	3.1	Discusses statistical power to detect impacts
	3.2	Discusses dynamics and lags appropriate to the indicators used
	3.3	Describes how estimation strategy controls for spatial fixed effects
	3.4	Describes how estimation strategy controls for other potential confounders at individual, household and community level, as well as other extreme weather events
	3.5	Describes treatment of spatial or temporal autocorrelation (e.g. Conley 1999)
	3.6	Describe sub-samples of analysis, particularly age and gender
	3.7	Describe testing of hypothesized impact pathway(s)
	3.8	Describe testing of hypothesized factors that magnify or attenuate impacts
	3.9	Describes tests to assess violation of assumed exogeneity of extreme weather events
	3.10	Describes any selection or misclassification biases (e.g., survey timing, migration)
4. Results		
Main Results	4.1	Discusses and interprets magnitude of key coefficients, implied impact sizes, and precision of coefficient estimates (standard errors, confidence intervals)
Robustness Checks	4.2	Reports tests for alternative specifications, sub-samples, statistical estimators
	4.3	Reports tests of exogeneity assumptions (e.g. placebo tests)
Parameter heterogeneity tests	4.4	Reports heterogeneity tests of differential effects across spatial units, survey rounds, age, gender and potential resiliency factors
	4.5	Reports results on potential mechanisms or impact pathways
5. Discussion		
Study Framing	5.1	Describes study limitations
	5.2	Compares and contrasts results to other findings in the relevant literature

Source: Authors' construction.

5. An exemplar case study: "Heat exposure and child nutrition: Evidence from West Africa" by Blom, Ortiz-Bobea and Hoddinott (2022)

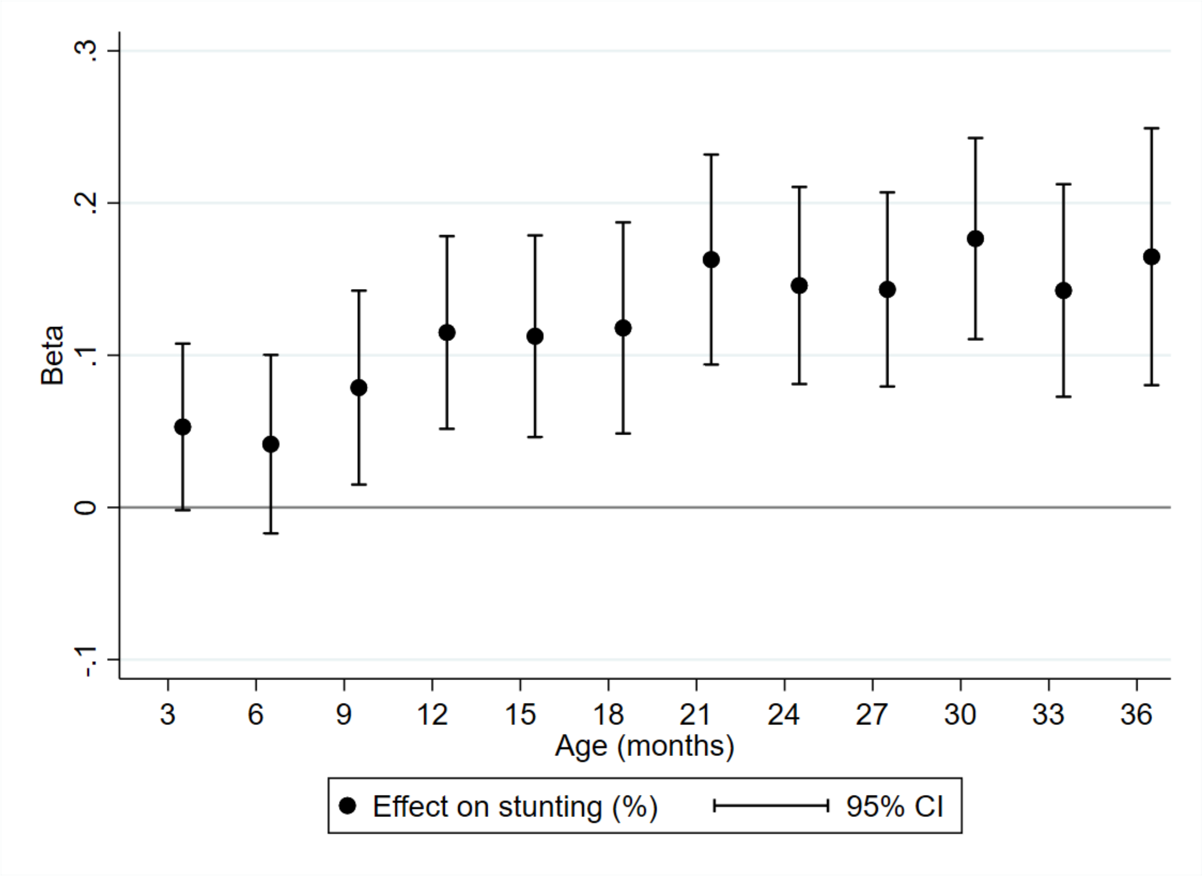
Blom et al. (2022) study the impact of heat exposure in early childhood on HAZ and stunting and WHZ wasting. In this section we first describe the study and then cross-check the features of their analysis against a checklist developed from the critique offered in the previous section.

Blom et al. analyze multiple DHS rounds from five West African countries, with a sample of over 32,000 children. For HAZ/stunting regression models, the authors rely solely on temporal variation to identify causal effects by employing fixed effects at the geocoded cell-level (the smallest unit in the weather dataset) to eliminate all spatial variation in weather/climate. They then interact the cell identifier with month and year of each child's interview so that the temporal variation stems entirely from differences in dates of birth; i.e. for HAZ/stunting, they compare children who live in the same location and are interviewed at the same time, but have different ages.

The heat exposure indicator they analyze is based on geocoded temperature data grouped into 5-degree Celsius bins that measure the mean number of hours per month in each temperature bin over the child's lifetime: 25-30 degrees, 30-35 degrees and >35 degrees, with effect sizes measured relative to the omitted <25 degrees. For WHZ/wasting, they measure exposure in the 90 days prior to the day-of-interview. In addition for location fixed effects, their regressions control for child age in months to model the typical patterns of linear growth and weight/gain loss depicted in Figure 6, month of birth (birth seasonality) and year of birth (general nutrition trends), as well as other weather indicators (precipitation) and household determinants of nutrition from the DHS. The regression models are least squares but use spatial autocorrelation consistent standard errors (Conley 1999). With the use of the most granular possible fixed effects, this type of model is similar to a difference-in-difference model.

Figure 7 - drawn from their study - shows arguably their most important finding, that heat exposure increasingly affects children's stunting risks from 6 months of age onwards. In fact, on closer reading, the impacts reported in the figure reflect the combined effects of: (1) *in utero* exposure to hours where temperature is in excess of 35 degrees, which increases the risk of stunting by 7.7 SDs (significant at the 5% level); and (2) post-natal exposure to temperatures greater than 35 degrees, which increases stunting risks by 5.9 percentage points on average but with variation by age. By 21 months, 100 hours of mean monthly lifetime exposure to temperature in excess of 35 degrees increases the risk of stunting by around 16 percentage points; a huge impact. For acute malnutrition (not shown), they find evidence that more hours a child has spent in the 30–35-degree range significantly increases the risk of malnutrition, especially in the 6–24-month window, but the coefficient on >35 degrees is not statistically significant.

Figure 7. Age-specific effects of 100 hours of mean monthly lifetime exposure to >35 °C on stunting (relative to <25 °C), including in utero and postnatal heat exposure effects

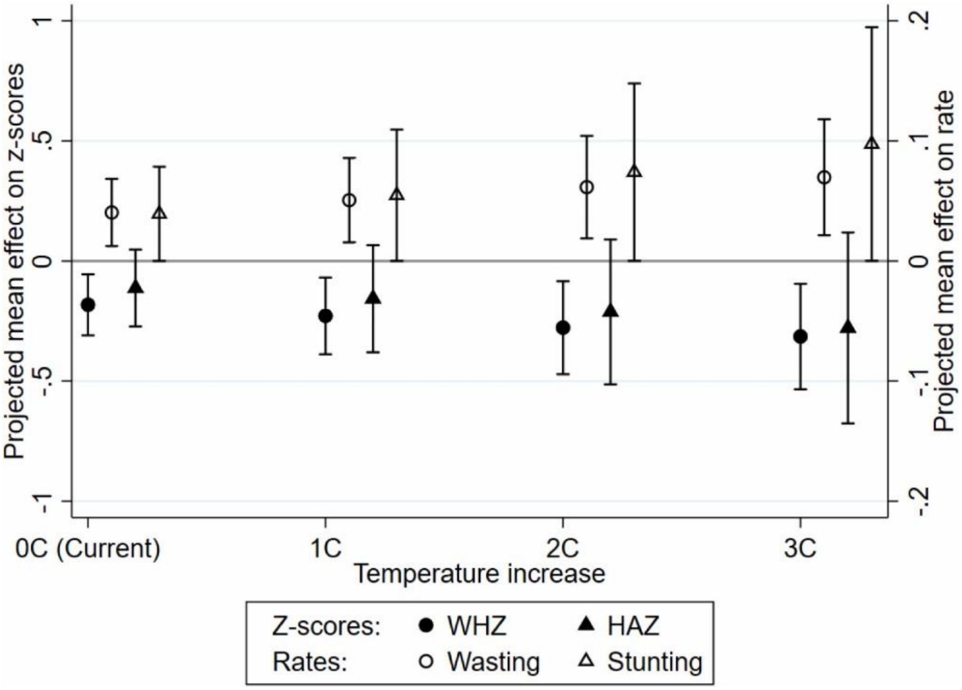


Source: Blom et al. (2022).

Like many studies in this literature, the data Blom et al use does not allow them to say a great deal about mechanisms, because data on disease pathways, dietary pathways and other economic pathways is quite limited. With the confines of DHS data, they find no evidence that heat exposure increases risks of caregiver reports of fever or diarrhea among children, but heat does reduce children's consumption of animal-sourced foods, which are widely established as being conducive for linear growth.

A significant contribution of this study is that the authors project the impacts of further climate change on child undernutrition prevalence. To our knowledge, very few such papers engage in projections that utilize their statistical coefficients, and it would certainly be difficult to do so confidently with precipitation indicators. Blom et al. first link secular climate change predictions to changes in their explanatory "heat exposure" variables used in their model, and then use their regression coefficients to predict increases in malnutrition under different degrees of climate warming. They find that if temperatures rise 2°C, the mean effect of mean monthly heat exposure on the stunting rate will almost double from 4.0 percentage point increase to a 7.4 percentage point increase while the mean effect on wasting will rise from 4.1 percentage points to 6.2 percentage points (Figure 8).

Figure 8. Estimated mean effects of lifetime exposure above 35 °C on HAZ and the stunting rate and of exposure to 30–35 °C heat on WHZ and the wasting rate under various warming scenarios.



Source: Blom et al. (2022).

Table 4 provides a proposed checklist for implementing quality assurance in climate-nutrition studies, drawing upon the critique in Section 3, and applies it to Blom et al. (2022). This study scores highly on the proposed checklist, implementing most of the recommended practices with only a few exceptions, which are as follows.

First, the study only implicitly discusses the issue of statistical power, though it does make note of the large sample and the variation in climate and weather variation across its sample, such as the hotter conditions in Burkina Faso compared to the other four countries studied. Yet it does not explicitly report the number of clusters or report measures of variation in exposure to extreme heat.

Second, the regressions do not report any interaction effects between heat exposure and gender, despite many other studies in this broader literature finding significant gender interaction effects.

Third, although the study discusses measurement error in nutrition outcomes and child age, it does discuss measurement error in extreme weather data in any detail.

Fourth, although the study does its best to look at potential mechanisms of impact (with the constraints of DHS variables), it only briefly examines socioeconomic status (wealth) as a potential nutritional buffer, as well as sanitation. The study could have more extensively considered other sources of resilience to extreme heat, like access to electricity, improved water or medical facilities. And unfortunately, the DHS data used by Blom et al. does not have information on potentially important agricultural mechanisms or agricultural coping mechanisms (e.g. livestock sales, crop choice).

Table 4. Applying the CLIMRAN guidelines to Blom et al.'s (2022) study on heat exposure and child nutrition in West Africa

Elements recommended for reporting	**Applied by Blom et al.?**
Describes the rationale for the study?	**YES**
Identifies dependent and independent variables?	**YES**
Hypothesizes mechanisms/impact pathways?	**YES**
Describes sources, sample design, representativeness?	**YES**
For case-control studies, describes control population?	*Not applicable*
Describes selection criteria for chosen data sources?	**YES**
Uses continuous nutrition outcome indicators?	**YES**
Describe spatial and temporal unit for weather data?	**YES**
Provides detailed definition of weather phenomenon?	**YES**
Discusses potential measurement errors?	**PARTIALLY.** More discussion of weather data needed
Discusses statistical power to detect impacts?	**PARTIALLY.** Notes large sample size and weather variation across regions, but doesn't report number of clusters
Discusses dynamics and lags in indicators used?	**YES.** Life-long heat exposure for HAZ, recent heat exposure for WHZ
Describes estimation controls for spatial fixed effects?	**YES.** Notes fixed effect is same unit as weather data
Describes other controls confounders?	**YES.** Controls for rainfall and range of DHS indicators
Describes treatment of spatial/temporal autocorrelation?	**YES.** Uses Conley standard errors
Describe sub-samples of analysis? Age and gender?	**PARTIALLY.** Flexible control for age, but no tests by gender
Describe tests of hypothesized impact pathway(s)?	**PARTIALLY.** Looks at ASFs, disease, sanitation. No DHS data on agricultural mechanisms.
Describe tests of hypothesized factors that magnify/attenuate impacts?	**PARTIALLY.** Examines household wealth ("income"), sanitation. However, there are no DHS data on agricultural mitigation or coping mechanisms
Describes tests to assess violation of exogeneity?	**YES.** Conducts a placebo test, randomizing weather data
Describes any selection or misclassification biases?	**PARTIALLY.** Restricts sample to resident children. Does not discuss survey timing issues.
Discusses and interprets magnitude of key coefficients?	**YES.** Clear interpretation and discussion of precision
Reports tests for alternative methods?	**YES.** Sub-samples reported & sensitivity to specification
Reports tests of exogeneity assumptions?	**YES.** Conducts a placebo test, randomizing weather data
Reports heterogeneity tests of differential effects across spatial units, surveys, age, gender, resilience factors?	**PARTIALLY.** Tests across countries, age, wealth, but not gender
Describes study limitations?	**YES.** Focuses on challenges of identifying mechanisms
Compares and contrasts results to other findings?	**NO.** No explicit comparisons to other studies

Source: Authors' construction.

Fifth, the study's discussion section stops short of providing comparisons or contrasts to other studies in the literature, though it does point to useful areas for future research.

These limitations aside, the study uses a strong quasi-experimental regression model, considers and controls for confounding factors well, and has an excellent discussion on the interpretation of coefficients (not just significance levels) and a novel projection of potential impacts of temperature increases on the prevalence of undernutrition among young children. It also acknowledges many limitations of the data and possible sources of bias. We therefore view it as an exemplar – a "recommended reading" – in this literature.

5. Discussion

In this study we critically reviewed the growing literature on climate and nutrition, with a view to mapping the existing studies, outlining the potential pitfalls of existing empirical approaches, and developing a checklist against which studies can be compared for quality.

What conclusions can we draw from this literature, and with what confidence?

Perhaps the most salient conclusion from the mapping of existing studies is the sheer diversity of data and methods used. In terms of dependent variables, many studies focus on standard child anthropometric outcomes, but there is a great deal of diversity in the types of weather indicators, even within broad categories such as "heat", "drought", "precipitation". We also found diversity in empirical methods used, which is perhaps unsurprising in a multi-disciplinary literature. However, this diversity in metrics and methods makes it difficult to draw conclusions with confidence when some quasi-experimental studies approximate difference-in-difference estimators and control well for other potential confounding factors, whilst others do not. Existing studies and reviews rightly emphasize the critically important problem of existing surveys providing scant room to identify specific mechanisms linking extreme weather to nutrition, but we raise additional concerns about the literature as a whole, particularly insufficient attention to measurement error and statistical power, external validity and heterogeneity of these linkages, and publication bias. Moreover, while identifying mechanisms is important, it is also important to understand sources of nutritional vulnerability and resilience.

To move forward, we proposed a checklist of recommended practices for analysts, reviewers and editors to use in assessing the most common type of large-scale empirical studies on climate, weather and nutrition. These practices include specific empirical methods (often already widely used), more consideration to statistical power and measurement error, and acknowledgement of the potential limitations of existing approaches. However, it also clear that new types of data and new types of inter-disciplinary studies are needed, particularly for improving understanding of mechanisms like physical heat stress in pregnancy and early childhood, as well as testing potential interventions to protect vulnerable populations from weather extremes. Existing survey initiatives, particularly the DHS, have been tremendously useful in this literature, but we propose that higher frequency multi-thematic surveys are needed for studying the linkages between weather and an array of nutrition, health and socioeconomic indicators. This could include panel surveys but also repeated cross-sectional surveys, perhaps stratified across agro-climatic zones. Such surveys share traits with nutrition surveillance systems but need to cover a richer array of data and be designed by multi-disciplinary research teams (Headey and Barrett, 2015).

This review was also chiefly limited to anthropometric outcomes in children, but more work is needed on the impacts of extreme weather on: (1) alternative nutrition metrics, such as micronutrient adequacy and deficiencies, and dietary quality indicators; (2) nutritional outcomes of other vulnerable populations, especially pregnant women; (3) other indicators of public health relevance, such as common morbidities in early childhood as well as mortality (Gasparrini et al., 2015); and (4) cognitive and educational outcomes of children.

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Appendix A. Further details on the screening process

The initial search yielded a total of 992 unique entries. Of these, 990 (99% of original) English language publications were retained. Subsequently we excluded surveys, interviews, editorials, guidelines, protocols, editorials (including letters, notes, and comments), event-specific outputs (documents from congresses, conferences, or proceedings), and any retracted publications or errata. These criteria yielded 788 original publications (79% of the original sample), which were further narrowed down to 238 publications, including 10 reviews excluded from the main analysis but retained as supporting studies for cross-referencing of included publications.

At first stage, title and abstracts of all 788 publications were screened to identify whether each study addressed climate-impacted nutrition outcomes in humans. 361 studies (46%) were excluded for relevance. Next, articles on related topics which do not directly address nutrition or food consumption, e.g. income and yield impacts, were excluded (n=26) Additionally, investigations around knowledge, attitudes, and practices around diets and nutrition were excluded unless quantitative measures of nutrition were also investigated (n=73). Publications on non-environmental hazards, e.g. Covid-19, catastrophic health expenditures, and earthquakes, were also excluded (n=70). Finally, studies utilizing only primary data, such as self-reported shocks, were excluded due to limited comparability across regions (n = 20). At the end of first stage, 530 publications (53%) were classified for exclusion. Excluded publications generally belonged to food technology, hydrology, energy, medicine, and agricultural economics disciplines. Included publications (n = 238, 30%) generally consisted of articles in nutrition, economics, and public health disciplines.

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