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The global effect of extreme weather events on nutrient supply: a superposed epoch analysis

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Summary

Background To date, the effects of extreme weather events on nutrient supply within the population have not been quantified. In this study, we investigated micronutrient, macronutrient, and fibre supply changes during 175 extreme weather events within 87 countries in the year that a major extreme weather event occurred, with a targeted focus on low-income settings.

Methods We collected data from the International Disasters Database and the Global Expanded Nutrient Supply model for the period 1961–2010, and applied superposed epoch analysis to calculate the percentage change in nutrient supply during the year of an extreme weather event relative to its historical context. We composited globally and by subgroup (EU, landlocked developing countries, least developed countries, low-income food deficit countries, and net food-importing developing countries). Lastly, we reported nutrient supply changes in terms of recommended dietary allowance for children aged 1–3 years.

Findings Globally, all micronutrient supplies had a modest negative percentage change during the year of an extreme weather event; of these effects, those that reached an $\alpha=0\cdot05$ significance level included calcium, folate, thiamin, vitamin B6, and vitamin C, with nutrient supply changes ranging from –0·40 to –1·73% of the average supply. The effect of an extreme weather event was especially magnified among landlocked developing countries and low-income food deficit countries, with significant nutrient supply changes ranging from –1·61 to –7·57% of the average supply. Furthermore, the observed nutrient supply deficits in landlocked developing countries constituted a large percentage (ranging from 1·95 to 39·19%) of what a healthy child's sufficient average dietary intake should be.

Interpretation The global effects of extreme weather events on nutrient supply found in this study are modest in isolation; however, in the context of nutrient needs for healthy child development in low-income settings, the effects observed are substantial.

Funding Australian-American Fulbright Commission.

Introduction

Extreme weather events are defined as especially severe or unseasonal weather phenomena at the extremes of the historical distribution and rare for a particular place or time.[1] Agricultural production has been shown to decline during and after an extreme weather event,[2–7] and some case studies have specifically linked extreme weather events to nutritional outcomes, such as risk of child stunting due to drought-related crop loss in Uganda[8] and persistent reduced growth among flood-exposed children in Bangladesh.[9] Although many studies have referred to extreme weather events threatening food security, specifically in developing countries,[10–12] no study has yet quantified the global impact of extreme weather events on total nutrient supply. Yet it is imperative that we investigate this relationship now, as it is projected with high confidence that by the end of this century, we will have witnessed global increases in the frequency and magnitude of heatwaves, heavy precipitation, tropical cyclones, and droughts.[13–16]

Understanding historical nutrient supply fluctuations caused by extreme weather events will inform future estimates of nutritional impacts in the aftermath of such events. To this end, it is necessary to acknowledge the socioeconomic factors—such as human geography, economic development, and governance structure— that modulate a nation's response to extreme weather events.[17–22] Recovery is particularly difficult in low-income settings, where infrastructure maintenance and equitable food distribution are challenges even in fair weather. A vast majority of the world's 821 million undernourished people and 50·5 million children under 5 affected by wasting (low weight for height) reside in low-income countries, and they stand to lose the most from further nutrient supply fluctuations.[23]

This study builds on previous research by Lesk and colleagues,[24] where national cereal production losses resulting from extreme weather events were estimated using superposed epoch analysis. We used a modified superposed epoch analysis method to test whether extreme weather events have a significant impact on micronutrient, macronutrient, and fibre supplies in the year that an extreme weather event occurred (so-called year-of-event). Acknowledging the socioeconomic gradient of exposure,

Research in context

Evidence before this study

A bibliometric network analysis was done for the systematic query of literature in Web of Science. The following search terms were used in the title: *health* OR well-being OR wellbeing OR welfare OR *nutrition* OR *hospital* OR mortality OR morbidity. The following search terms were used in the topic: ("high-impact weather" OR "natural disaster" OR "natural hazard" OR drought OR flood OR heatwave OR "cold spell" OR hail OR cyclone OR frost OR storm OR (extreme* AND (weather OR climate OR precipitation OR temperature OR dry OR wet OR cold OR hot OR heat))) AND (human OR public OR population)". In the space of extreme weather events and nutrition, the most extensively studied topic was the effect of extreme weather events on cereal production. There is broad consensus that globally, droughts reduce cereal yield. Evidence for the effect of other extreme weather events (eg, floods, storms, extreme heat, extreme cold) was found largely in local case studies. Few studies have determined the nutritional consequences of these weather-related shocks, and those that have are limited in geographical scope.

Added value of this study

At best, food production analysis can only imply a link to food consumption. By shifting the focus onto nutrient supply, we attempted to measure the outcome (nutrition, proxied by nutrient supply) rather than the input (consumption, proxied by food production). To date, this is the first quantification of the nutrient supply reductions during extreme weather events, globally and within various low-income subgroups. By further framing the nutrient supply reductions in terms of child recommended dietary allowances, we also provided a practical, relevant, and important context for interpreting the results of this superposed epoch analysis.

Implications of all the available evidence

This study echoes previous literature which urges the international community to tackle the issue of malnutrition among vulnerable populations, especially because the nutritional landscape is poised to worsen with climate change. Our results show a significant reduction of micronutrients and macronutrients during an extreme weather event globally; this effect is further magnified within landlocked developing countries. These results point to a clear need to provide supplementation before, during, and in the immediate aftermath of an event. Children are a particularly susceptible subpopulation of interest, given how certain nutritional deficiencies can have irrecoverable consequences for health, growth, and development.

we adhered to the grouping conventions of the UN and the World Trade Organization for our subgroup analyses. Lastly, we contextualised our results by comparing the year-of-event nutrient supply changes with the universally accepted recommended dietary allowance (RDA) for children aged 1–3 years. The RDA is the average daily dietary intake that is sufficient to meet the nutrient requirements of nearly all healthy individuals in a group.[25] Regarding environmental hazards, children are an especially susceptible subpopulation because of the high nutritional needs of their developing physiology.[26,27] As the evidence base grows for the long-term implications of early life malnutrition on lifelong cognitive, social, and physical development,[28–31] it is not only fitting, but crucially important, that we also take a child's health perspective on the impacts of extreme weather events.

See **Online** for appendix

Methods

Data collection

For **GENuS** see https://dataverse.harvard.edu/dataverse/GENuS

For **EM-DAT** see https://www.emdat.be/database

We used the Global Expanded Nutrient Supply model (GENuS) and the International Disasters Database (EM-DAT) as the basis of our analysis. The GENuS model provides historical time series of 23 individual nutrient supplies at the national level for 152 countries from 1961–2011. The model's raw inputs—UN Food and Agriculture Organization (FAO) production and trade data—are used to calculate national supplies of edible food, which are then matched with nutrient density charts from regional food composition tables to estimate national nutrient supplies.[32] The EM-DAT database is the world's most comprehensive collection of natural and technological disasters from 1900 to the present day. Using EM-DAT, the following extreme weather events were extracted for the period 1964–2010: floods, droughts, extreme heat events, extreme cold events, and storms (see appendix p 16 for definitions). The extreme weather events were separated into single-year events or multi-year events. Extreme weather events were defined as multi-year if a country had the same type of extreme weather event for at least 2 years in a row. For this study, multi-year events did not have to be uninterrupted.

Any effects of extreme weather events on nutrition captured by this study must be substantial enough to overcome the limited spatial and temporal resolution of the GENuS and EM-DAT databases. In other words, because each event is identified by country and year, rather than by specific geographical coordinates and dates, we could only determine if one solitary event somewhere in the country at some point in the year ultimately affected the entire country's yearly nutrient supply. To overcome the challenges of poor data resolution in both time and space, we chose to isolate what we considered were the most severe extreme weather events. To be included in this study, an extreme weather event had to meet or exceed the 90th percentile of all recorded extreme weather events, across all countries with available data from 1964–2010 for at least one of the following conditions: total financial damage, in absolute terms or as a percentage of that country's gross domestic product (GDP) at the time of the extreme weather event; or total number of people affected, in absolute terms or as a percentage of that country's population at the time of the extreme weather event.

Extreme weather events that fulfilled the criteria for inclusion in this study were referred to as major extreme weather events (see appendix pp 3–4 for sensitivity analysis of threshold criteria). Population and GDP data were obtained from World Bank Open Data. Lastly, if a major extreme weather event coincided with at least one other major extreme weather event within 2 years of occurrence, then both extreme weather events were excluded to avoid conflating effects of multiple events (see appendix p 2 for complete exclusion flowchart). No ethical approval was necessary for this study; all data used are openly available online.

Data analysis

Superposed epoch analysis is a compositing approach that overlays multiple time series to identify a common signal in the data. It is preferred in cases where the response to particular events (eg, folate supply in response to extreme weather events) may be obfuscated by noise from other competing influences that operate at similar timescales (eg, seasonal variation of folate-rich produce). Superposed epoch analysis sorts data into categories dependent on a key synchronisation date, then compares the means of those categories. The superposed epoch analysis method as applied here functions under the assumption that if the number of time series composited is sufficiently large, a common underlying response to the event should theoretically emerge in the composite, while the noise caused by other variables in the data (eg, intranational policy changes or economic shocks) should be distributed evenly—positively and negatively—and therefore disappear after averaging.[33]

For **World Bank Open Data** see https://data.worldbank.org/

We applied the superposed epoch analysis method to nutrient supply data in the following manner. First, for all non-overlapping major extreme weather events, we produced 5-year windows by isolating the GENuS model's nutrient supply data from 2 years before the event, the year-of-event, and 2 years after the event. For multi-year events, one year-of-event value was generated by averaging the values for each year of the event. Next, for each of these 5-year time series, the percentage change relative to the non-extreme weather event year average was calculated as follows:

$$\text{Effect of extreme weather event as percentage change} = \left[\sum_{i=1}^{n} \frac{(x_{it} - \mu_{iz})}{\mu_{iz}}\right]_{nutrient} \times 100\%$$

where i is the unique extreme weather event, t is the year of the event, and z is the 5-year window excluding t.

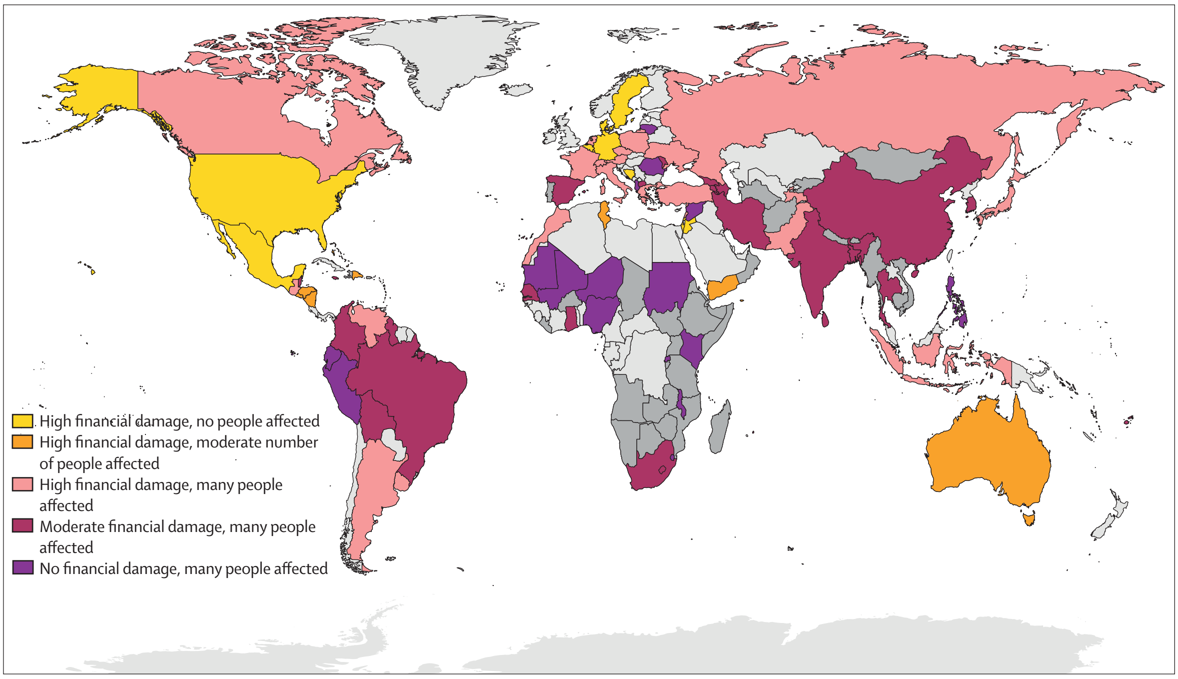

Figure 1: **Map of countries with major extreme weather events included in this study, 1964–2008**
Countries are represented in varying shades that indicate to what extent they satisfy both or either thresholds of financial damage and of people affected. 50 countries in dark grey were included in the preliminary analysis but excluded from the final analysis because of insufficient nutrient data. Countries in light grey were not included at all, because of dense overlapping time series of extreme weather events (see appendix p 2 for exclusion flowchart). Among the 87 countries included in this study, orange countries had extreme weather events with greater financial damage than people affected, and maroon countries had extreme weather events with more people affected than financial damage incurred. Yellow countries did not have any people affected by the extreme weather event and purple countries did not have any financial damage caused by an extreme weather event, as indicated by the International Disasters Database. Pink countries had extreme weather events with both high financial damage and many people affected.

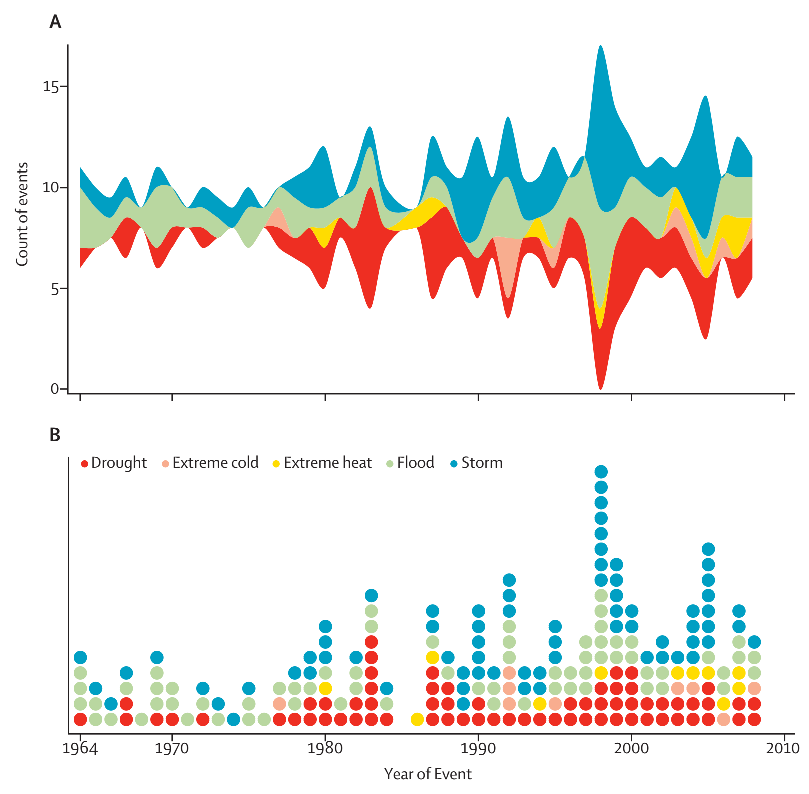

***Figure 2:* Stream-graph and dot-plot representations of all major extreme weather events from 1964–2008 included in this study**

The total number of observations here is 227 extreme weather events. 67 were caused by droughts, nine by extreme cold, 11 by extreme heat, 67 by floods, and 73 by storms. The years 1985–2008 are modestly over-represented, because of a combination of better data collection methods, increasing effects of climate change, and a growing population and global economy. We disaggregated multi-year events to show the incidence of extreme weather events more accurately. Note that although we collected International Disasters Database data through 2010, extreme weather events from 2009 and 2010 were excluded from the final analysis due to dense overlapping events (appendix p 2).

For the **FAOSTAT database** see http://www.fao.org/faostat

The non-extreme weather event year average is comprised of nutrient values from 2 years before and after the event and is used here as a rough proxy of what nutrient supply should look like in a non-disaster year in the country of interest. All percentage changes were then composited to produce a single time series analysis of the nutrients before, during, and after an extreme weather event. For these composites, 95% CIs were generated by bootstrapping the composite's individual components 1000 times and subsequently estimating the bias-corrected and accelerated CI; these 95% CIs correspond with a significance level of α=0·05. See appendix (pp 1–2) for a graphical illustration of the superposed epoch analysis process.[34]

To visualise the global extreme weather event dataset, a comparison group was generated by bootstrap to compare our global composited results to a business-as-usual group. The comparison group consisted of 1000 sets of fictitious extreme weather events (on average, around 150 extreme weather events per set), generated by randomly resampling years and countries of occurrence within the same event distribution as the global extreme weather event dataset (see appendix p 4 for distributions). If a randomly generated fictitious extreme weather event happened to be a real event, it was still included in the comparison group. Thus, the comparison group represents the overall true distribution of nutrient supply, not just the distribution of supply for years without extreme weather events. Neither the real extreme weather event time series nor the comparison time series were de-trended to take into account positive, technology-induced food production growth over time, which has persistently increased food supply and thus the accessible nutrient supply. Instead, nutrient supply fluctuations due to extreme weather events are visualised by noting the difference between experimental and comparison composites.

To test which low-income countries within our global dataset were most sensitive to extreme weather event effects, we did a subgroup analysis. Using the same superposed epoch analysis procedure, we tested for significant nutrient supply changes within four of the five low-income subgroups that the FAO recognises in its FAOSTAT database: landlocked developing countries, least developed countries, low-income food deficit countries, and net food-importing developing countries. We did not separately analyse the small island developing states subgroup because these nations collectively lacked sufficient data; the few observations we did have were included in the global analysis. Details of the inclusion criteria for group membership, as well as the primary authority that establishes and maintains each group are shown in the appendix (p 13). We included the EU in the subgroup analysis to provide a high-income comparison. See appendix (pp 14–16) for the detailed list of all extreme weather events analysed in this study. Note that not all countries included in this study were part of a subgroup, and some countries were members of multiple subgroups.

Finally, to interpret our results in a relevant public health context, we compared the absolute change of each nutrient supply during the year-of-event to that nutrient's RDA for children aged 1–3 years as follows:

$$\text{Effect of extreme weather event as percentage of RDA} = \left[\sum_{i=1}^{n} \frac{(x_{it}-\mu_{iz})}{RDA}\right]_{nutrient} \times 100\%$$

where i is the unique extreme weather event, t is the year of the event, and z is the 5-year window excluding t.

As before, the 95% CIs were generated by bootstrapping the composite's individual components 1000 times and subsequently estimating the bias-corrected and accelerated CI, which corresponds with an α=0·05 significance level.[34] All data processing, superposed epoch analysis, figures, and tables were

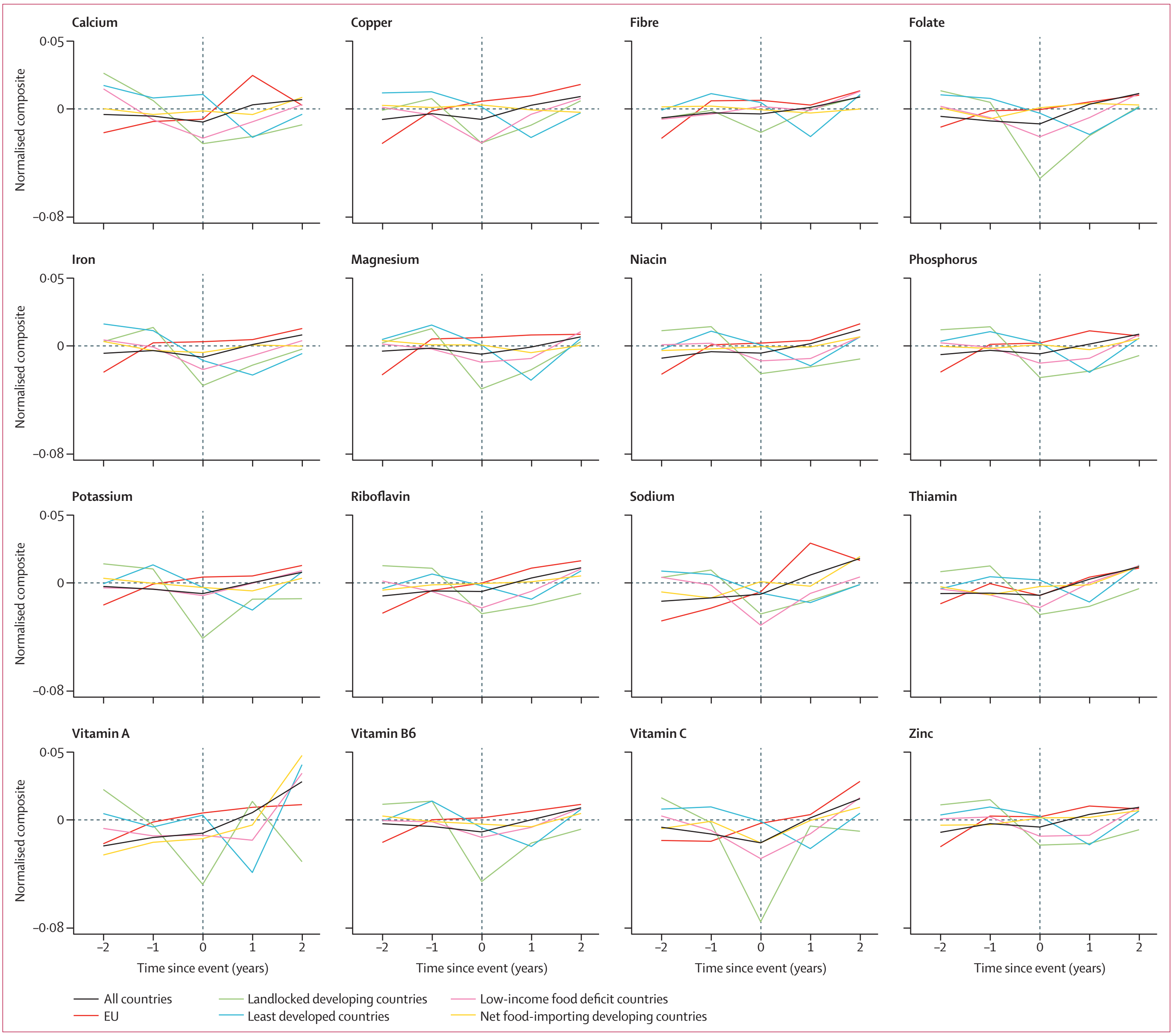

Figure 3: **Subgroup analysis of the percentage change in micronutrient and fibre supply for each 5-year window, composited and centred around the year-of-event**
The global dataset (all countries) has 175 extreme weather events. The EU subgroup has 29 extreme weather events, landlocked developing countries have 19, least developed countries have 15, low-income food deficit countries have 32, and net food-importing developing countries have 64 (see appendix p 4 for the potential sources of bias arising from varying sample sizes).

generated using R (version 1.1.383). The code is available upon request.

Role of the funding source

The Australian-American Fulbright Commission had no role in data collection, data analysis, data interpretation, writing of the manuscript, or the decision to submit for publication. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication.

Results

Using both absolute and relative thresholds for inclusion criteria, we included 87 countries from all socioeconomic backgrounds in the superposed epoch analysis of the global effect of extreme weather events on nutrient supply (figure 1) from 1964–2008. Extreme weather events in high-income countries (eg, Sweden, USA) tended to cause greater financial damage while affecting fewer people, whereas extreme weather events in low-income countries (eg, Sudan, Philippines, Peru)

	All countries	EU	Landlocked developing countries	Least developed countries	Low-income food deficit countries	Net food-importing developing countries
Calories	–0·40%* (–0·92 to –0·01)	–0·34% (–1·57 to 0·54)	–1·62%* (–5·79 to –0·16)	0·44% (–0·31 to 1·53)	–1·11% (–3·50 to 0·03)	0·22% (–0·33 to 0·73)
Carbohydrates	–0·34% (–0·76 to 0·08)	–0·18% (–1·01 to 0·87)	–1·61%* (–4·11 to –0·41)	0·2% (–0·46 to 1·18)	–0·89% (–2·51 to 0·18)	0·13% (–0·57 to 0·70)
Monounsaturated fatty acids	–0·84% (–2·00 to 0·03)	–0·97% (–2·82 to 0·62)	–1·9% (–13·06 to 2·11)	1·57% (–0·83 to 4·28)	–1·94% (–8·16 to 0·39)	0·2% (–1·02 to 1·57)
Polyunsaturated fatty acids	–0·68% (–1·57 to 0·33)	–0·58% (–2·02 to 0·95)	–0·3% (–4·36 to 2·87)	3·44% (0·24 to 8·93)	0·02% (–2·64 to 3·01)	0·07% (–1·40 to 2·12)
Protein	–0·48% (–1·03 to 0·07)	–0·24% (–1·64 to 1·31)	–1·95%* (–5·53 to –0·43)	0·13% (–0·92 to 1·12)	–1·48%* (–3·56 to –0·22)	0·32% (–0·57 to 1·07)
Saturated fatty acids	–0·34% (–1·35 to 0·40)	–0·02% (–2·34 to 2·17)	–1·1% (–8·25 to 2·16)	0·83% (–1·56 to 3·24)	–1·53% (–5·71 to 0·48)	0·84% (–0·18 to 1·96)

Data are % (95% CI). *Significant at the α=0·05 significance level.

Table 1: Percentage change in macronutrient supplies during the year-of-event relative to non-extreme weather event year averages

tended to cause less financial damage while affecting a greater number of people. A total of 227 extreme weather events were included in the study; 67 were caused by droughts, nine by extreme cold, 11 by extreme heat, 67 by floods, and 73 by storms (figure 2). However, when we aggregated multi-year events, the number of extreme weather events fell to 175, as this reflects multi-year extreme weather events collapsed into singular observations.

For the global dataset (ie, all countries included in this study), all micronutrient supplies exhibited modest negative percentage change during the year of an extreme weather event. These effects were significant (at the α=0.05 significance level) for calcium, copper, folate, iron, magnesium, niacin, phosphorus, potassium, riboflavin, thiamin, vitamin B6, vitamin C, and zinc; these significant effects ranged from –0.54% for niaicin to –1.73% for vitamin C (appendix p 6). The comparison group plot (appendix p 7) visualises these global percentage changes compared with the business-as-usual group, whereas figure 3 shows the percentage changes of the global dataset overlaid by the percentage changes of the five subgroups.

The extreme weather event effect was especially magnified among landlocked developing countries and low-income food deficit countries (appendix p 6). Landlocked developing countries had the greatest nutrient supply changes of the entire study with vitamin C at –7·57%, folate at –5·16%, and vitamin A at –4·80%. The nutrient supplies for the EU, least developed countries, and net food-importing developing countries did not show any significant percentage changes during the year-of-event (see appendix p 10 for the absolute changes in nutrient supply).

Compared with micronutrient supply, we did not find as large or comprehensive of a reduction in macronutrient supply during the year-of-event for any subgroup (table 1). The macronutrient comparison plot (appendix pp 7–8) shows a far more erratic picture. Macronutrients had highly variable values for all years of the 5-year windows, not just in the year-of-event. The most notable result from the macronutrient supply analysis is that landlocked developing countries and low-income food deficit countries had a significant –1·95% and –1·48% change in protein supply during the year-of-event.

We further compared effect sizes between the global dataset and the landlocked developing countries (figure 4). Vitamin C, folate, and vitamin A had the greatest magnitudes of percentage change in both sets. For all nutrients studied (except polyunsaturated fatty acids), landlocked developing countries had both larger percentage changes and wider CIs than those of the global dataset. The considerable difference in the magnitude of effect between the two sets is best visualised in figure 4, where both percentage changes (significant at the α=0·05 significance level) are overlaid. Notably, the smallest effect for landlocked developing countries (carbohydrates at –1·61%) is on par with the largest effects found within the global dataset.

Accordingly, landlocked developing countries appear to be a driving factor in the overall global effect (see appendix p 13 for the list of landlocked developing countries). Superposed epoch analysis of the global dataset excluding landlocked developing countries did not change the direction of the effects; however, the magnitude decreased, as well as the significance. Without landlocked developing countries included in the global dataset, only thiamin showed supply changes that were significant at the α=0·05 significance level (appendix p 9).

The absolute nutrient supply deficits of the global dataset and landlocked developing countries were then framed as percentages of the respective RDAs for children aged 1–3 years (see table 2 for the most substantial effects; see appendix p 11 for the complete table). The effect of extreme weather events on potassium supply in landlocked developing countries was nearly 40% of what a healthy

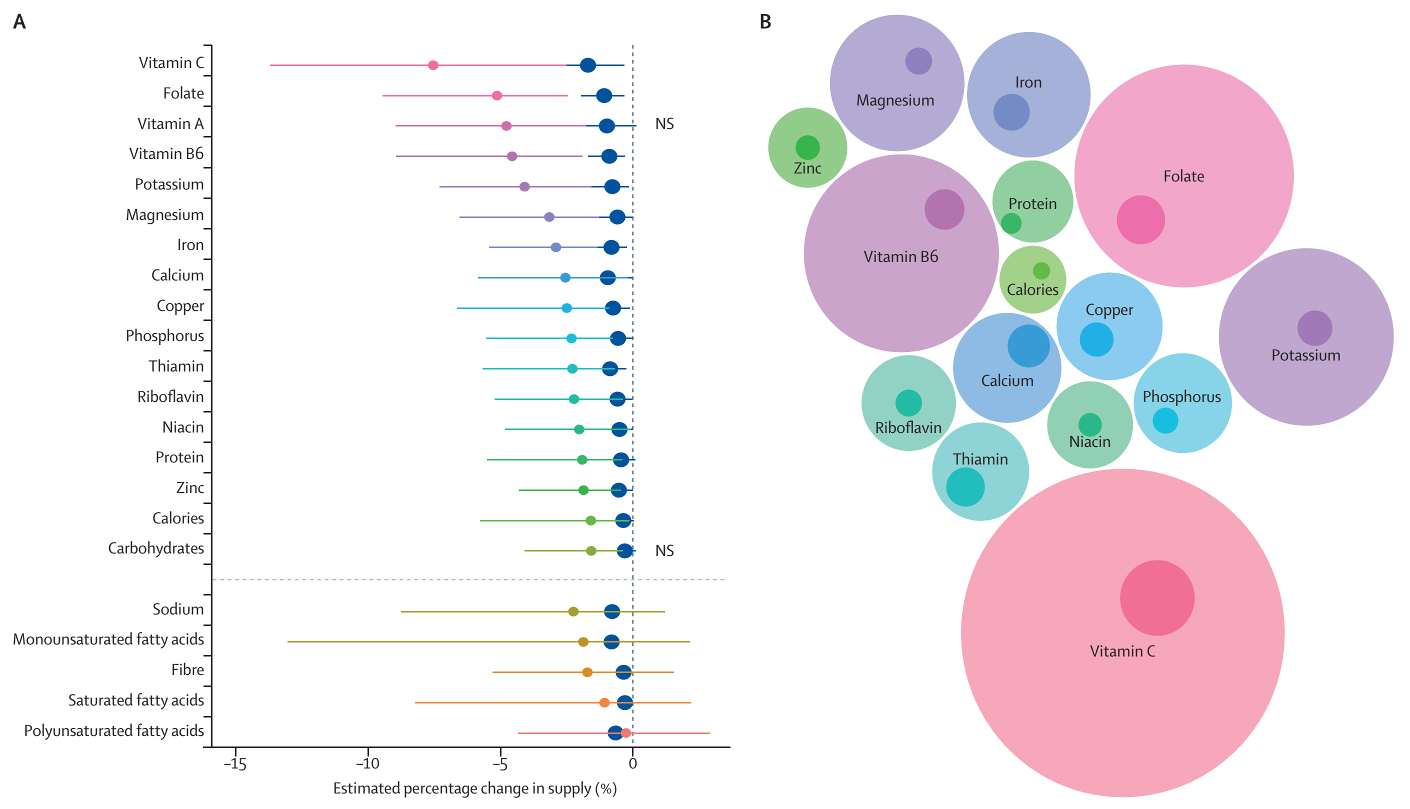

Figure 4: **Comparison of effect sizes between the global dataset and the landlocked developing countries**

(A) The percentage change of all nutrients in the year-of-event are plotted in rainbow colours for the landlocked developing countries, and in dark blue for the global dataset. The plot is organised vertically by decreasing magnitude of percentage changes in landlocked developing countries. CIs are drawn through the points. All nutrient supply changes above the dotted horizontal line reached significance at the α=0·05 significance level for landlocked developing countries, and also for the global dataset except where indicated. (B) Percentage changes for the landlocked developing countries and the global dataset are visualised; only the nutrients that had significant changes in both sets are shown here. For all circles, the radius is proportional to the size of the percentage change in nutrient supply. The larger circles represent the nutrient supply deficits for the landlocked developing countries, and the smaller circles represent the nutrient supply deficits for the global dataset. NS=not significant.

child's sufficient average dietary intake level of potassium should be. This makes up the largest effect of extreme weather events on nutrient supplies; however, potassium is also the only micronutrient studied here that does not have a clear RDA. Instead, the adequate intake indicator is used. Adequate intake is the recommended average daily intake of a nutrient based on observed or experimentally determined approximations of intakes that are assumed to be adequate for a group of healthy people. The effects of extreme weather events on vitamin C, protein, and vitamin B6 supplies are also substantial, making up 34·44%, 17·03%, and 15·24% of their respective RDAs. Appendix p 12 shows the percentage change of nutrient supply during year-of-event as a percentage of adequate intake for infants aged 0–12 months, and similar substantial effects are observed.

Discussion

All micronutrient supplies in this study exhibited negative percentage change during the year of a major extreme weather event. Macronutrient supplies showed more varied responses, probably because they are derived from a more diverse range of sources. Macronutrients come from nearly all food groups whereas micronutrients are derived primarily from fruits and vegetables, so the acquisition of macronutrients would be notably easier when food options are limited, such as in the immediate aftermath of an extreme weather event. Although outside the scope of the current study, future research should investigate the stability of fresh produce in response to extreme weather events, and how susceptible populations might substitute away from micronutrient-rich foods during extreme weather events in order to reach adequate caloric consumption.

In our study, landlocked developing countries and low-income food deficit countries were especially sensitive to extreme weather events, showing significant nutrient supply changes ranging from –1·28 to –7·57% of the average supply. These results were accompanied by wider CIs than those of the global results, which is an inevitable consequence of smaller and relatively volatile sample pools, as penalised by the bias-corrected and accelerated method. It is surprising that least developed countries and net food-importing developing countries did not

	Child RDA (mg/person per day)	All countries		Landlocked developing countries	
		In mg/person per day (95% CI)	As percentage of child RDA (95% CI)	In mg/person per day (95% CI)	As percentage of child RDA (95% CI)
Calcium	700	–4·87 (–13·64 to 3·67)	–0·7% (–1·95 to 0·52)	–13·67* (–35·4 to –3·24)	–1·95%* (–5·06 to –0·46)
Folate	150	–3·69* (–6·89 to –1·69)	–2·46%* (–4·59 to –1·13)	–13·92* (–25·91 to –6·11)	–9·28%* (–17·28 to –4·08)
Iron	7	–0·14* (–0·26 to –0·04)	–2·05%* (–3·76 to –0·57)	–0·48* (–0·94 to –0·24)	–6·90%* (–13·43 to –3·39)
Magnesium	80	–2·69* (–5·04 to –0·44)	–3·36%* (–6·30 to –0·55)	–10·9* (–19·98 to –5·27)	–13·63%* (–24·97 to –6·58)
Niacin	6	–0·09* (–0·18 to –0·01)	–1·53%* (–3·03 to –0·13)	–0·33* (–0·75 to –0·01)	–5·42%* (–12·52 to –0·20)
Phosphorus	460	–7·36 (–15·05 to 0·15)	–1·6% (–3·27 to 0·03)	–28·4* (–63·79 to –11·44)	–6·17%* (–13·87 to –2·49)
Potassium	300	–21·9* (–43·94 to –3·27)	–7·30%* (–14·65 to –1·09)	–117·56* (–220·03 to –47·02)	–39·19%* (–73·34 to –15·67)
Riboflavin	0·5	–0·005 (–0·01 to 0·003)	–0·99% (–2·74 to 0·67)	–0·03* (–0·06 to –0·004)	–5·31%* (–12·46 to –0·73)
Thiamin	0·5	–0·01* (–0·02 to –0·003)	–2·21%* (–4·02 to –0·61)	–0·03* (–0·07 to –0·01)	–6·11%* (–13·53 to –1·81)
Vitamin A	300	–5·88 (–13·65 to 0·69)	–1·96% (–4·55 to 0·23)	–25·12* (–56·1 to –9·75)	–8·37%* (–18·70 to –3·25)
Vitamin B6	0·5	–0·02* (–0·03 to –0·003)	–3·56%* (–6·80 to –0·69)	–0·08* (–0·14 to –0·03)	–15·24%* (–27·34 to –6·53)
Vitamin C	15	–1·21 (–2·9 to 0·94)	–8·08% (–19·33 to 6·24)	–5·17* (–10·58 to –0·12)	–34·44%* (–70·54 to –0·80)
Zinc	3	–0·06* (–0·12 to –0·005)	–2·12%* (–4·03 to –0·15)	–0·18* (–0·41 to –0·05)	–6·10%* (–13·62 to –1·64)
Calories	950	–10·24* (–23·69 to –0·41)	–1·08%* (–2·49 to –0·04)	–40·41* (–150·36 to –3·15)	–4·25%* (–15·83 to –0·33)
Carbohydrates	130	–1·46 (–3·28 to 0·32)	–1·12% (–2·52 to 0·25)	–6·23* (–15·22 to –1·82)	–4·79%* (–11·71 to –1·4)
Protein	7·7	–0·36 (–0·77 to 0·07)	–4·73% (–9·95 to 0·92)	–1·31* (–4·30 to –0·31)	–17·03%* (–55·79 to –4·06)

The table is organised by micronutrients first and then by macronutrients. All vitamins were measured in mg/person per day except vitamin A (μg retinol activity equivalents per person per day) and folate (μg/person per day). Fibre was measured in g/person per day. Calories were measured in kcal/person per day. There is no official RDA for potassium, so the adequate intake indicator is used instead. RDA=recommended dietary allowance. *Significant at the α=0·05 significance level.

Table 2: **Change in nutrient supply during the year-of-event as a percentage of RDA for children aged 1–3 years**

show significant nutrient supply changes during the year-of-event, although they did trend towards negative effects. This finding could be explained by better access to humanitarian response and food aid. Landlocked developing countries have no direct access to water ports, which has explicit implications for food security. Domestic food prices in these countries are up to three times more volatile than in their coastal counterparts.

Landlocked countries are often locked out of the global food market through high tariffs, bureaucratic border crossings, rent-seeking behaviour by authorities and transport sectors, and poor infrastructure.[35,36] The volume of international trade of a landlocked developing country is, on average, just 60% of the trade volume of a comparable coastal country.[37] Current domestic food production is not sufficient compensation, as landlocked developing countries typically have less arable land and less agricultural land under irrigation, leaving them particularly vulnerable to the effects of climate change and extreme weather events.[35] The frequency and type of extreme weather events that occurred in landlocked developing countries from 1964–2010 are visualised in the appendix (p 13).

The implications of our study are especially relevant for pregnant women and children under 5 years in resource-poor settings; it is estimated that chronic and acute child malnutrition, low birthweight, and suboptimal breast-feeding cause the deaths of 3·5 million mothers and young children every year.[38] Various micronutrients and macronutrients (ie, protein, fatty acids, iron, copper, zinc, B vitamins) are necessary for the neurodevelopmental processes that occur rapidly during pregnancy and infancy, such as neuron proliferation and myelination.[39] Maternal micronutrient deficiencies during lactation can also cause a reduction in the concentration of nutrients in breastmilk (especially thiamin, riboflavin, vitamin B6, and vitamin A), with subsequent infant depletion.[40,41] Repercussions of these nutritional deficiencies are long lasting; undernutrition during pregnancy and the first 2 years of life is a major determinant of stunting and poor development, with long-term consequences for adult health and work productivity.[29]

Although agricultural yields have been consistently increasing since the industrial revolution, the world has also witnessed an increase in the absolute number of people and the percentage of people in the world with insufficient dietary energy consumption in 2017.[23] Current estimates indicate that 250 million children under 5 years in low-income and middle-income countries are at risk of not reaching their developmental potential.[42] The effects of extreme weather events found in this study could significantly exacerbate current malnutrition burdens, as well as endanger those children who are on the cusp of adequate nutrition. Although there is a clear need to provide nutrient supplementation during and after an extreme weather event, it is also imperative that nations are better equipped to prepare for them. Anticipatory humanitarian aid must include comprehensive nutrient accessibility before an event, to help mitigate shocks on the nutrient supply. Strengthening domestic infrastructure of food supply and health care will also ensure that a nation is self-equipped to establish nutrient security in times of emergency.

The GENuS model has several limitations: (1) it does not directly measure consumption; (2) it is based on FAO data, some of which is interpolated rather than directly measured due to gaps in data collection;[43] (3) for some countries, there is absolutely no available data, thus rendering interpolation impossible; and (4) the per capita data used here does not discriminate between age, gender, or socioeconomic status. Certain subpopulations within a country might be more disadvantaged than others, and thus more exposed to the effects of food disruptions.[44,45] Another major limitation is that our analysis does not cover small island developing states as a subgroup—these are known to be highly vulnerable to extreme weather events and limited in their ability to import fresh foods in the case of an emergency.[46] One caveat with using EM-DAT is that the database is a compilation of field reports and post-disaster assessments, often carried out by a constellation of government ministries, non-governmental organisations, and international governance agencies. Although measurement units are standardised, the method of collecting and analysing data is not standardised. Lastly, while measuring supply fluctuations is important, measuring actual nutrient consumption would more closely align with health consequences. This could be an important area for future study.

Previous studies have established the negative effect of extreme weather events on food production, but few have made the final link between this food disruption and human nutrition. In this study, we aimed to bridge extreme weather events and nutrition through the quantification of micronutrient, macronutrient, and fibre supply fluctuations during the year of major extreme weather events. We found modest, but significant micronutrient and macronutrient supply declines in the year-of-event globally and among UN-designated low-income subgroups. We identified landlocked developing countries as an especially vulnerable subgroup, and further contextualised the magnitude of nutrient supply deficits with RDAs for children aged 1–3 years. Children in low-income settings not only face the greatest exposure to environmental risk, but also stand to bear the most severe long-term health consequences. As climate change increases the volatility of extreme weather events worldwide, it is imperative that the international community better prepares for and addresses the nutritional impacts of extreme weather events, especially within low-income settings.

Contributors

CSP designed the study, did the analysis, interpreted the results, and wrote the manuscript. LML, SSM, MD, and B-AB helped conceptualise aspects of the study, and EV was integral to coding the analysis in R. All authors commented on the manuscript draft and approved the final submission.

Declaration of interests

EV reports a PhD scholarship from the University of Melbourne during the conduct of the study. All other authors declare no competing interests.

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