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Nutrition-sensitive climate risk across food production systems

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Abstract

Global nutrition targets remain unmet, as over half of preschool-aged children and two-thirds of non-pregnant women of reproductive age worldwide suffer from micronutrient deficiencies. Climate change poses a growing threat to global food and nutrition security, but existing climate risk assessments often overlook the critical roles of both terrestrial and aquatic nutrient-rich foods that are vital for dietary diversity and micronutrient supply. In this study, we introduce an innovative framework that integrates data on future climate extremes, nutrient supply dependencies, and diet-related climate vulnerability. Our comprehensive analysis assesses nutrition-sensitive climate risk to five essential micronutrients across production systems. By mid-century (2041–2060), we estimate that 75% of calcium, 30% of folate, 39% of iron, 68% of vitamin A, and 79% of vitamin B12 produced in primary food products will face frequent climate extremes (at least every other year) globally. Nearly fifty countries are projected to face high domestic climate risk for two or more micronutrients during this period, with ten countries facing high risk across all five. We outline distinct climate risk profiles to offer data-driven entry points into strategies for bolstering the resilience of micronutrient supply chains and advancing progress toward global nutrient targets in the face of a changing climate.

1. Introduction

Malnutrition is a leading cause of global mortality and morbidity [1], negatively affecting cognitive development, educational outcomes, and gross domestic product [2]. Over half (372 million) of preschool-aged children and two-thirds (1.2 billion) of non-pregnant women of reproductive age worldwide are deficient in essential micronutrients like iron and vitamin A [3]. Despite their importance for achieving the 2030 Sustainable Development Goals (SDGs) [2], global nutrition targets to reduce stunting, wasting, and obesity in children and anemia in women are off track [4]. Climate change exacerbates these challenges, especially for poor populations in the Global South [5–7]. To date, climate risk assessments for food systems have largely focused on a few staple crops (e.g. maize, wheat, and rice) [8–10], neglecting nutrient-rich foods from land and water [11] that are vital for dietary diversity and quality, and micronutrient intake and status. Effective nutrition-sensitive climate policies—and climate-resilient nutrition policies—must consider the entire diet's role in nourishing people and its vulnerability to climate change.

Nutritious diets are diverse, including whole grains, legumes, nuts, fruits and vegetables, and moderate amounts of nutrient-rich aquatic and terrestrial animal-source foods [12]. These foods derive from various terrestrial and aquatic food production systems, susceptible to variable climate impacts [13, 14]. Climate change introduces multiple co-occurring drivers, including rising temperatures, drought, rainfall extremes, more intense storms, sea level rise, and ocean acidification. These drivers affect crop yields, livestock productivity, species distribution and phenology (especially fish), pest and pathogen pressure, supply chains, and labor capacity [5, 6]. Rising CO_2 levels can also reduce the nutrient density of crops [6]. Secondary impacts on economic development, food prices, conflict, and health (e.g. through water-borne diseases), further affect nutrient access and utilization. An integrative food systems approach [11, 14, 15] to assessing nutrient climate risk is therefore crucial to identify key areas of adaptation potential and build cross-sectoral climate resilience.

Several methods exist to estimate the exposure of food production systems to environmental hazards. Process-based models, such as plant-physiology models for terrestrial crops [10] and ecological models for fisheries [16], are the most sophisticated but are typically developed for individual production systems, limiting their scalability. Statistical models use relationships between observed food production and climate anomalies, but have also mostly been developed for staple foods [9, 17] as they require detailed production data. For many nutrient-rich foods, like fruits, vegetables, legumes, nuts, and farmed aquatic foods, neither process-based nor statistical models are available at global level.

Despite these limitations, some studies have attempted to link different food systems components in climate risk assessments, for instance staple crops and fishery models [14, 18] or in Integrative Assessment Models [19]. However, these analyses still miss the connection between climate impacts on different food production systems and their dietary contributions, as well as a grounding in an understanding of people's reliance on different food sources for essential nutrients [20], and their vulnerability to loss of those sources. To address this gap, we developed a framework to estimate 'nutrition-sensitive climate risk' at the national level. This framework combines disparate data sources [21–24] to assess countries' nutrient production exposure to climate extremes, their dependence on domestic production, and their diet-related climate vulnerability.

We focus on five essential micronutrients with severe morbidity impacts and high deficiency prevalence [3]: calcium (bone health), folate and iron (physical and cognitive development), vitamin A (vision and immune system), and vitamin B12 (red blood cells and nervous system). Our findings indicate that by mid-century (2041–2060), most countries will face medium or high nutrition-sensitive climate risk in at least one micronutrient, with ten countries facing high risk for all five. We identify eight distinct climate risk profiles to offer data-driven entry points into strategies that support climate-resilient nutrition outcomes.

2. Methods

In the IPCC framework, climate risk is the interaction between (a) environmental hazards from climate change, (b) exposure of people, infrastructure, and ecosystems to those hazards, and (c) vulnerability, or the propensity to be adversely impacted, which combines sensitivity and adaptive capacity [25]. To calculate domestic climate risk to diets, we developed national-level climate hazard scores, weighted by the contributions of six food groups to national nutrient supply. We defined exposure as the share of the total nutrient supply derived from domestic production, calculated from the self-sufficiency ratio (SSR) as defined below. Vulnerability was calculated using economic and nutritional indicators.

2.1. Nutrient supply

Our analysis focuses on five essential micronutrients—calcium, folate, iron, vitamin A, and vitamin B12—and dietary energy. Folate, iron, vitamin A and vitamin B12 were selected because they are among six 'sentinel micronutrients' that cause severe morbidity and for which deficiency is prevalent [3]. In addition, calcium was chosen because deficiency is widespread, particularly in low and middle-income countries [26].

The availability and dietary sources of the five micronutrients and dietary energy were derived from the Global Nutrient Database, which estimates the availability of 156 nutrients in 195 countries and territories [22], most recently available for 2017. To link nutrient supply data to climate hazards, we divided all food items into six food groups: (1) aquatic products; (2) fruits & vegetables; (3) legumes & nuts; (4) cereals & tubers; (5) livestock products (including dairy and eggs); and (6) other crops (mostly oil crops, sugar crops, and spices). This grouping aligns with commonly used dietary food groupings [27], although we separated aquatic products from other foods given their distinct production environment and nutritional benefits [28]. Additional details on nutrient supply data and limitations can be found in the supplemental materials.

2.2. Climate hazard

Due to the lack of process-based or statistical models for many food production systems, our climate hazard assessment focuses on the probability of future conditions deviating significantly from their historical range, compared to a baseline period [21]. This approach addresses the challenge of establishing science-based thresholds for all food products by recognizing the potential limitation of local food production systems outside their accustomed climate range [21, 29], serving as an indicator of the adaptation demands posed by climate extremes.

We assessed climate hazards by quantifying the likelihood of adverse climate conditions in 2041–2060 relative to historical baseline period (1961–1990) [21]. We used the historical and SSP3-7.0 (medium-high emissions) simulations from 30 models in the Coupled Model Intercomparison Project 6 (CMIP6) database [30], recognizing that the standard 'business-as-usual' scenario (SSP5-8.5) is currently considered statistically improbable [31]. For each of the six food groups, we developed spatial and seasonal masks (table 1) to calculate national-average anomaly time series relative to the baseline mean:

$$x_{t,f} = \frac{\sum_i w_{i,m,f} x_{t,i,m}}{\sum_i w_{i,m,f}}$$

$$\Delta x_f = x_{2041-2060,f} - x_{1961-1990,f}$$

where $x_{t,i,m}$ represents the climate variable for each year, grid cell, and month, and $w_{i,m,f}$ the area and seasonal weights for each food group.

Climate hazard is the probability of a growing season in which a climate variable—temperature[10], precipitation, or the combination thereof—exceeds a threshold α:

Finally, we derived a single climate hazard value for each nutrient and country by weighting the climate hazards for the six food groups by the relative contribution of each food group to the total supply of each nutrient [22]:

$$H_\mathrm{n} = \frac{\sum_\mathrm{f} H_\mathrm{f} \times S_\mathrm{f,n}}{\sum_\mathrm{f} S_\mathrm{f,n}}$$

where S is the supply of nutrient n from food group f.

2.3. Exposure to climate hazard

Although trade is an important driver of nutrient supply in many countries [36, 37], we focus in our risk calculations on the share of a country's nutrient supply that is exposed to climate hazards domestically. We calculated this using the SSR of each nutrient. The SSR indicates the extent to which a country's total use of a nutrient is supplied by domestic production:

$$\mathrm{SSR} = \frac{\text{production}}{\text{total use}}.$$

The term 'total use' encompasses all forms of utilization over and above direct food consumption, i.e. animal feed, waste, and all other forms of utilization[11]. To calculate an exposure score for each nutrient, we weighted the SSR for the six food groups by the relative contribution of each food group to the total supply of each nutrient:

$$E_\mathrm{n} = \frac{\sum_\mathrm{f} \mathrm{SSR_f} \times S_\mathrm{f,n}}{\sum_\mathrm{f} S_\mathrm{f,n}}.$$

Exposure to hazard is then the product of exposure and hazard:

$$EH_\mathrm{n} = E_\mathrm{n} \times H_\mathrm{n}.$$

For inclusion in the climate risk score calculations, exposure to hazard scores were first standardized and normalized.

2.4. Climate vulnerability

We calculated the vulnerability component of climate risk using key indicators to represent sensitivity and adaptive capacity to disruption of nutrient supply. Where possible we chose values for 2017, to align with nutrient supply data.

Nutrient vulnerability $NutV_\mathrm{n}$ is the average between the prevalence of inadequate nutrient intake (def_n; micronutrients [23]:—2011; dietary energy [38]:—2017) and dietary diversity div_n, as measured by the species evenness score across the six food groups [22, 39]—2017. Economic vulnerability $EconV$ is the average between the latest available percentage of the population with income below the national poverty line pov [24], latest available per capita Gross Domestic Product at Purchasing Power Parity gdp [24], and the 2017 cost of a healthy diet $cost$ [24]. The combined vulnerability score V_n is the average between $NutV_\mathrm{n}$ and $EconV_\mathrm{n}$.

$$NutV_\mathrm{n} = (def'_\mathrm{n} + div'_\mathrm{n})/2;$$
$$EconV = (pov' + GDP' + cost')/3$$

$$V_\mathrm{n} = (NutV'_\mathrm{n} + EconV')/2$$

where apostrophes indicate standardized and normalized values. For nutrient and economic vulnerability, an average score was still calculated if either of the indicators was missing; for the combined vulnerability score, no score was calculated if either of the input values was missing.

[10] 2 m air temperature for terrestrial crops and Livestock Products, and Sea Surface Temperature for Aquatic Products

[11] It should be noted that the underlying calculations for the nutrient content in production and total utilization have been undertaken separately for this publication and are not part of the GND [22].

Table 1. Overview of spatial masks and seasons used in calculating environmental hazards for each of six food groups. Note that the development of spatial masks for aquatic products was limited by data availability on subnational inland aquaculture, and fisheries production, as well as the spatial resolution of Global Climate Models.

Food group	Spatial mask	Seasonality [32]
Aquatic Products	*For countries with marine data* Exclusive Economic Zone [33] *For countries with no marine data* All terrestrial grid cells	Annual
Fruits & Vegetables	Harvested area [34]	For latitudes >23 N: April–September For latitudes <23 S: October–May For tropical latitudes: Annual
Legumes & Nuts	Harvested area [34]	For latitudes >23 N: April–September For latitudes <23 S: October–May For tropical latitudes: Annual
Cereals, Roots & Tubers	Harvested area [34]	For latitudes >23 N: April–September For latitudes <23 S: October–May For tropical latitudes: Annual
Livestock Products	Natural log of livestock production [35]	Annual
Other Crops	Harvested area [34]	For latitudes >23 N: April–September For latitudes <23 S: October–May For tropical latitudes: Annual

2.5. Domestic climate risk

Domestic nutrition-sensitive climate risk is the arithmetic mean between the exposure to hazard score and the vulnerability score:

$$R_{\mathrm{n}} = \left(EH'_{\mathrm{n}} + V'_{\mathrm{n}}\right)/2.$$

This method assigns equal weight (50%) to both vulnerability and exposure to hazard, creating a risk score that reflects the climate change risk to the domestically produced nutrient supply. This assessment does not account for risk through global markets, which is addressed in other studies [e.g. 40–42]. As a final step, we normalized and standardized the resulting risk scores, resulting in a nutrition-sensitive climate risk score ranging from 0 to 1. If data on either exposure to hazard or vulnerability was unavailable, the risk was not calculated.

2.6. Identifying climate risk profiles and interventions

To identify patterns in the specific nutrition-sensitive climate risk that countries face, we applied a K-means clustering analysis to the variables used in the climate risk calculations. We excluded countries that have more than half of these variables missing. Determination of the optimal number of clusters was facilitated through the use of statistical metrics such as the gap statistic and the Davies–Bouldin Index.

A list of key climate resilience and nutrition interventions for each of the climate risk profiles was developed through a broad search of peer-reviewed literature using a combination of keywords, including 'nutrition policy' 'food security policy' 'climate change,' and 'policy recommendations.' The search was limited to articles published in the English language from the year 2005 to present. We included articles that (a) are published in peer-reviewed journals, (b) identify action in either a case study, cross-sectoral, or multi-sectoral approach, and (c) provide concrete recommendations for policy action at one or multiple scales. The identified recommendations were then condensed to focus on those that tie directly to elements included in our analysis. Following several rounds of feedback and revision by our multidisciplinary team of co-authors, the list was narrowed and grouped into thematic categories. The relevance of each intervention for each climate risk profile was assessed based on the input variables to the cluster analysis.

3. Results

3.1. Climate extremes impacting food systems

Temperature extremes serve as a primary indicator of climate impacts because long historical records exist and projections are consistent between climate models. Temperature extremes are projected to become increasingly prevalent by the middle of the century (figure 1 (a), SI figure 1). They emerge most rapidly in tropical regions with low interannual climate variability, and in countries with large continental landmasses. In contrast, their emergence is slower in mid-latitudes and regions dominated by monsoon climates. The pace and magnitude of temperature increase differs substantially across the production areas of different food groups (SI figure 1). In countries with vast land areas (e.g. Brazil, India, the United States) different foods are produced in distinct regions, resulting in distinct climate trajectories. Notably, aquatic environments (SI figure 1 (f)) are governed by different dynamics than terrestrial ones. In some countries (e.g. Australia) marine temperature extremes emerge more rapidly than terrestrial ones, while in others (e.g. Peru, with a highly variable coastal upwelling system) they lag behind.

For terrestrial crops, extreme heat becomes particularly detrimental when coupled with dry conditions [43–45]. The spatial distribution of the probability of compounded hot and dry conditions (figure 1(b), SI figure 2) differs substantially from that of hot conditions alone (figure 1(a)) and is primarily driven by projected declines in national-average precipitation. Consistent with earlier work on fewer crops [21], we find that this interaction is particularly pronounced in the Mediterranean region, northern and southern Africa, Central and South America, and Australia. Globally, terrestrial crop systems are projected to face compound hot and dry conditions approximately once every three years by the end of the century (figures 1(c)–(f), SI figure 2), the impacts of which will vary depending on the crop type and system (e.g. irrigated vs. rainfed). In the remainder of this paper, we base calculations of climate risk on probabilities of compound hot and dry conditions for terrestrial crops (SI figure 2), and hot conditions alone for aquatic products and livestock products (SI figure 1).

3.2. Nutrient supply and deficiency

Climate risk assessments that exclusively focus on staple crops such as maize, wheat, and rice place a premium on dietary energy compared to micronutrients (figure 2). Whereas Cereals & Tubers and foods in the 'Other Crops' food group (largely oil crops and sugar) provide most of global energy supply, livestock products and fruits & vegetables provide the bulk of global calcium and vitamin A. Folate and iron derive from a larger diversity of foods, which also include legumes & nuts and smaller quantities of aquatic foods. Vitamin B-12 derives exclusively from animal-source foods, either aquatic or terrestrial.

Even without the impacts of climate change, food systems in large parts of the world fail to deliver access to diets that meet minimum nutrient requirements. Of the 167 countries with data on micronutrient deficiencies [23], 20% or more of the population is deficient in at least one or the micronutrients evaluated here in 141 countries and in all five micronutrients in 22 countries (SI figure 11). South and Southeast Asia and sub-Saharan Africa have higher-than-average nutrient deficiencies, with substantial shortfalls in calcium, iron, and Vitamin A supply (figure 2). These places have comparatively lower supplies of nutrients from non-staple foods, especially livestock products and fruits & vegetables.

Large regional differences also exist in the relative contributions of different food groups to nutrient supply. For example, livestock products provide a larger share of the nutrient supply of North America, Europe, and Oceania—in conjunction with lower deficiencies in calcium and vitamin B-12—whereas Fruits & Vegetables play a larger role in East Asian diets—in conjunction with lower deficiencies in folate. It is worth noting that regional averages mask important sub-regional variation (SI figures 4–9). Aquatic Products, for example, contribute relatively little to regionally averaged nutrient supply for four of the five micronutrients considered here, but make high contributions in specific countries [46], for instance nearly 15% of iron in the Maldives, and more than a fifth of calcium and vitamin A in Cambodia.

3.3. Nutrition-sensitive climate risk

Combining climate hazard estimates for different food groups (figure 1) with insights into their contributions to nutrient supply (figure 2) we calculate integrated climate hazards confronting domestic production of each nutrient (figure 3). Despite the relatively simple hazard indicators utilized in this study,

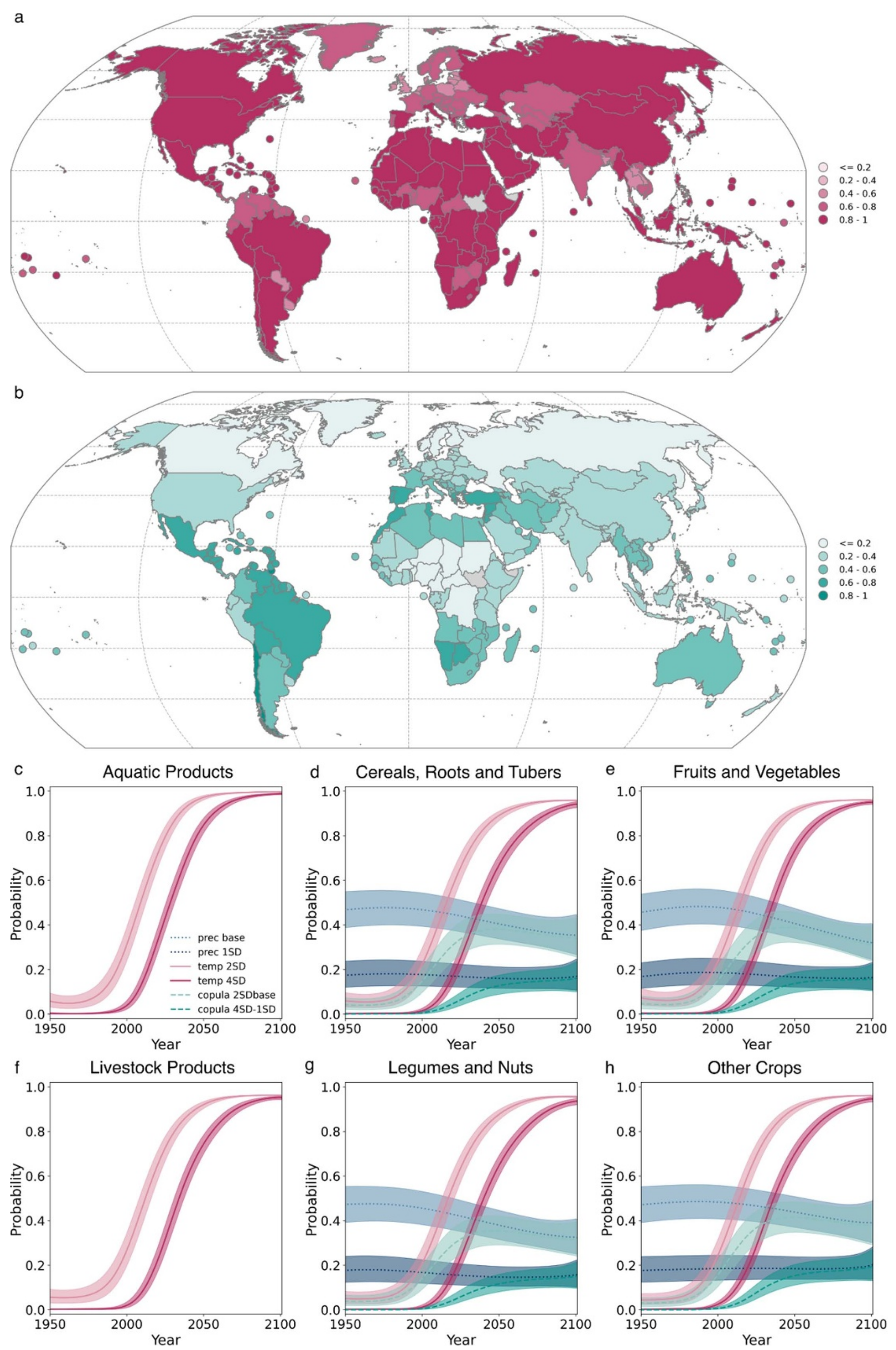

Figure 1. Probability of climate extremes by various metrics. Probability of climate extremes during the 2041–2060 period, (a) probability of encountering extremely hot conditions (temperature exceeding the historical mean by 4SD) and (b) probability of encountering compound hot and dry conditions (temperature exceeding the historical mean by 2SD with precipitation below the historical mean); and (c)–(h) global mean averages of climate extremes, categorized using different thresholds (precipitation below the historical mean and more than 1SD below the historical mean, blue; temperature exceeding the historical mean by 2SD and 4SD, red; and compound hot and dry conditions with temperature exceeding the historical mean by 2SD and precipitation below the historical mean, and with temperature exceeding the historical mean by 4SD and precipitation more than 1SD below the historical mean, green) for (c) aquatic products, (d) cereals, roots, & tubers, (e) fruits & vegetables, (f) livestock products, (g) legumes & nuts, and (h) other crops. dark lines signify the multi-model ensemble mean, while shading corresponds to the multi-model mean of 95% confidence intervals. Global averages are weighted by each country's share of global production [38]. It should be noted that precipitation-based indicators were not calculated for Livestock and aquatic products. Countries shown in gray have no data available.

we find substantial variation in integrated hazard scores across different nutrients. Hazard scores are generally highest for vitamin B-12 and calcium, which have large contributions from the animal-source foods that in our model are connected only to temperature extremes. Several regions face high hazards across all micronutrients, notably the Mediterranean region and Central America. Other regions, such as

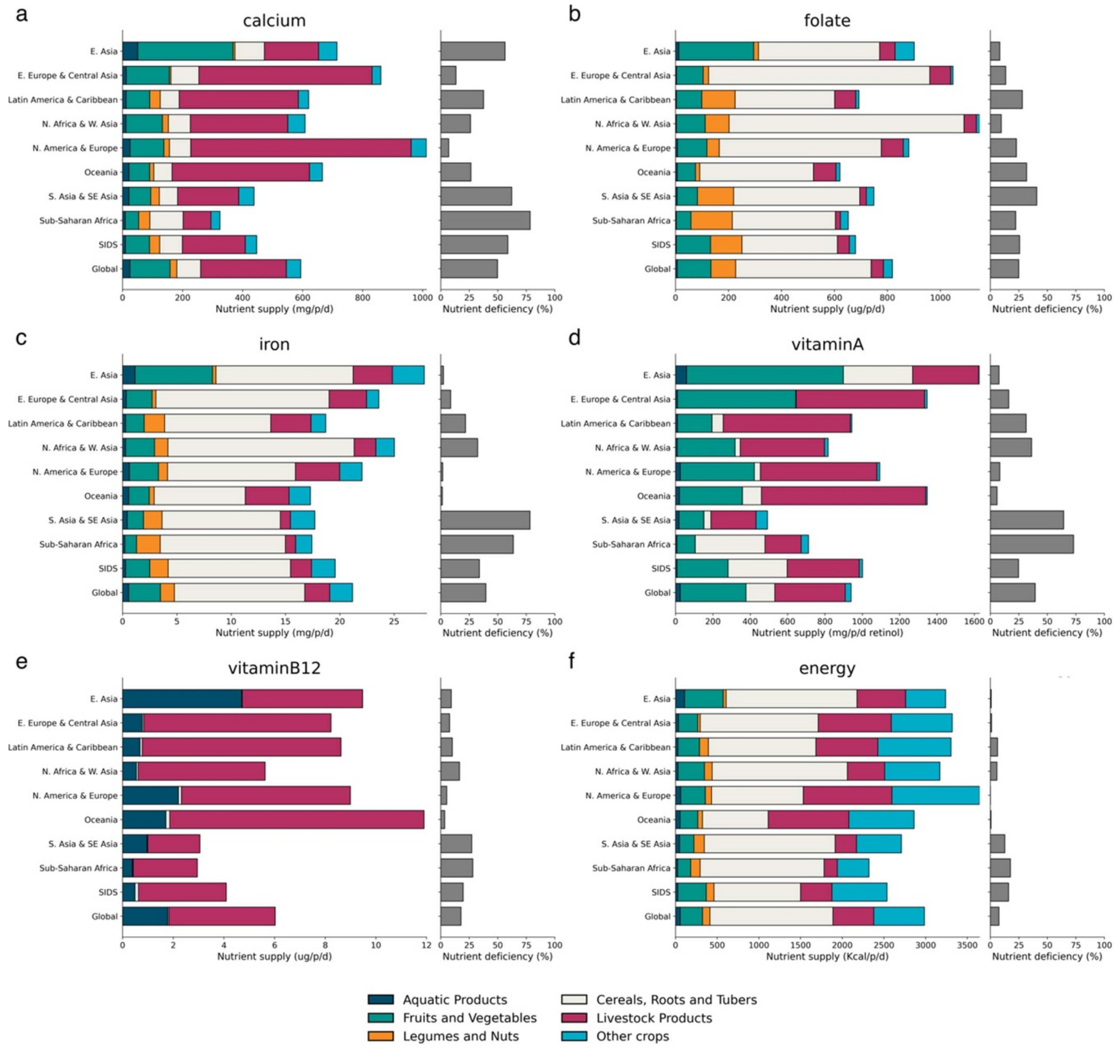

Figure 2. Contributions of food groups to average nutrient supply and population-average nutrient deficiency in different regions of the world. Energy and nutrient supply provided by each of six different food groups—aquatic products (dark blue); fruits & vegetables (green); legumes & nuts (orange); cereals, roots & tubers (white); livestock products (red); and other crops (light blue)—based on 2017 national-average per capita nutrient supply estimates [22] (left); and the percentage of the population estimated to be deficient in nutrients [23] and dietary energy [38] (right). Regional and global averages are weighted by population estimates from FAOSTAT [38].

sub-Saharan Africa and South America, face especially high climate hazards in one or two specific nutrients. Globally, 75% of calcium, 30% of folate, 39% of iron, 68% of vitamin A, 79% of vitamin B12, and 54% of energy production is projected to face climate extremes at least every other year by the middle of the century.

To assess nutrient-specific climate vulnerability we examine a combination of dietary and economic indicators (figures 4(a) and (b); see Methods). We assume populations to be vulnerable to a (temporary) loss in nutrient supply if they are already consuming the nutrient below recommended levels (figure 2; SI figure 10), if they are highly dependent on a single food source for their nutrient supply (that is, low nutrient supply diversity; SI figure 12), or if they face high economic barriers to accessing healthy diets (SI figure 13). We find nutrient supply diversity to be lowest in large parts of Africa, and Central and South Asia. Economic and nutrient indicators of vulnerability generally are highly correlated, except for calcium which in high-income (Western) countries is almost exclusively derived from a single food source (dairy), exhibiting low supply diversity (SI figure 12). In aggregate, countries in sub-Saharan Africa are most in need of investments to reduce vulnerability to climate shocks (figure 4(a)): out of the 23 countries that make up the top ten most vulnerable countries for each of the micronutrients, eighteen are located in this region.

The growing role of international trade in nutrient supply [36, 37] complicates assessment of climate risk: countries can both be impacted through domestic climate hazards or through changes in international markets [29, 40, 47]. To estimate domestic nutrient climate risk, we define exposure as the share of the total nutrient supply derived from domestic production (figure 4(c), SI figure 14; see

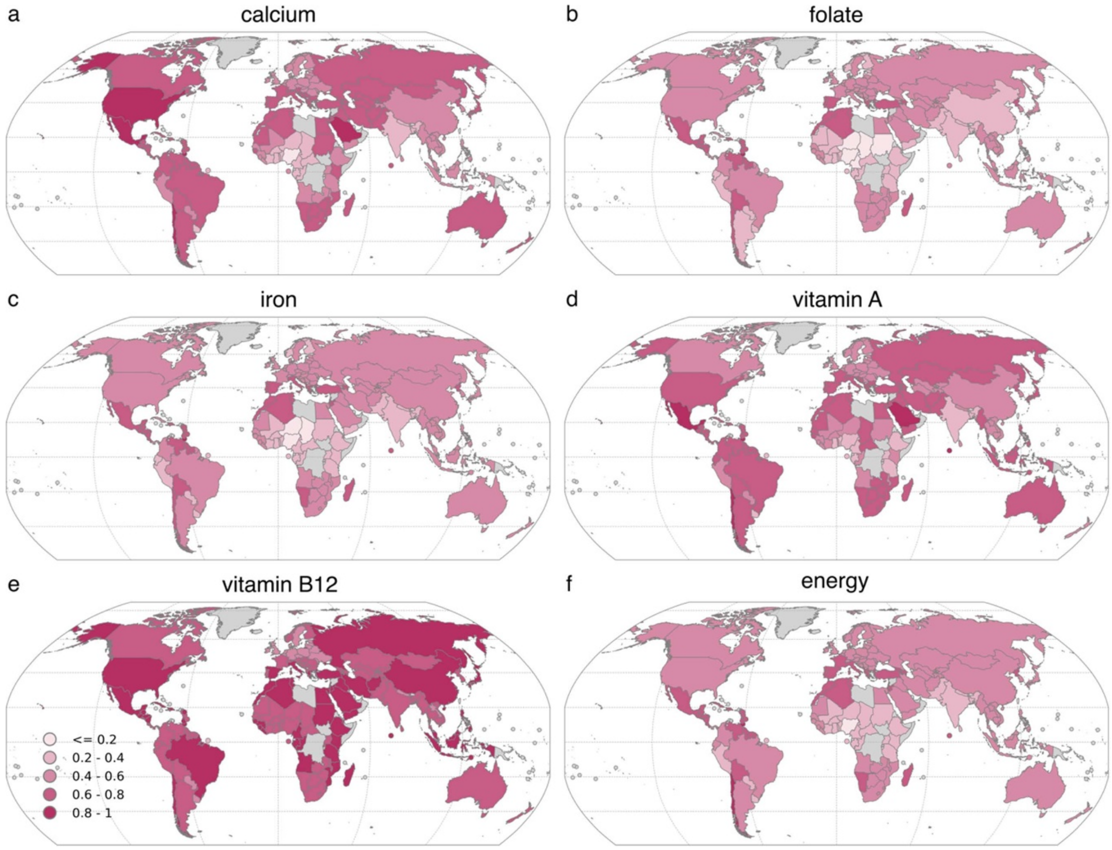

Figure 3. Food group weighted probability of climate extremes facing domestic production of five micronutrients and energy supply. Probability in 2041–2060 of climate extremes facing (a) calcium, (b) folate, (c) iron, (d) vitamin A, (e) vitamin B12, and (f) energy production, weighted by food group contribution to the supply of each nutrient (figure 2), based on hot and dry conditions (temperature $>2\sigma$ above historical mean and precipitation below historical mean) for terrestrial crops and extremely hot conditions (temperature $>4\sigma$ above historical mean) for aquatic products and livestock products. Countries shown in gray have no data available.

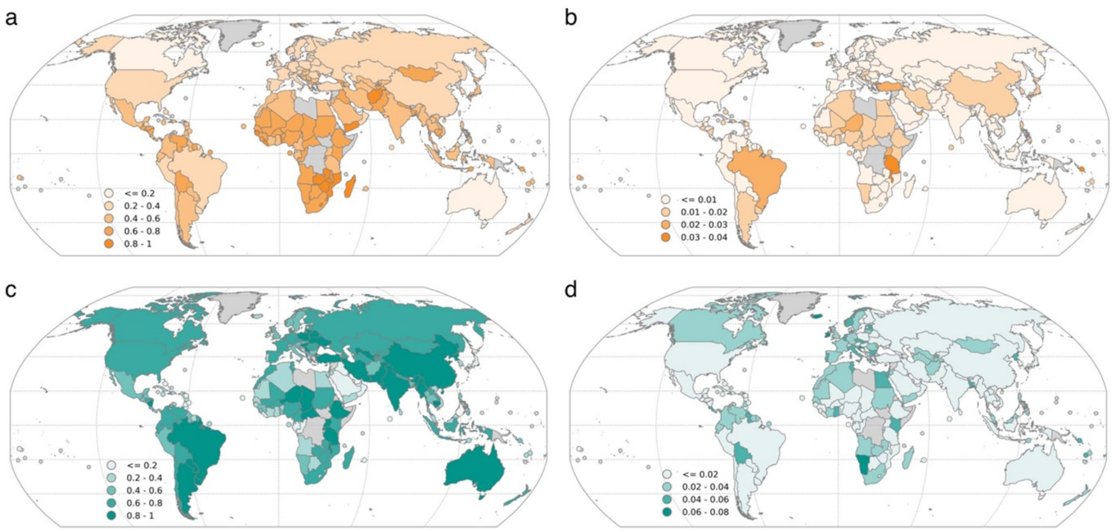

Figure 4. Mean and variance of vulnerability to loss of nutrition and exposure to domestic climate hazards across micronutrients. Mean (a) and variance (b) of vulnerability to loss of nutrition based on nutrient deficiency, diversity of nutrient supply, and economic vulnerability (GDP, poverty, and cost of a healthy diet); and mean (c) and variance (d) of exposure to domestic climate hazards, based on the share of nutrient supply that is produced domestically (see materials and methods). Vulnerability and exposure indicators were standardized and normalized before calculating scores for each nutrient. Mean and variance were calculated across all five micronutrients (calcium, folate, iron, vitamin A, vitamin B-12). Countries shown in gray have no data available.

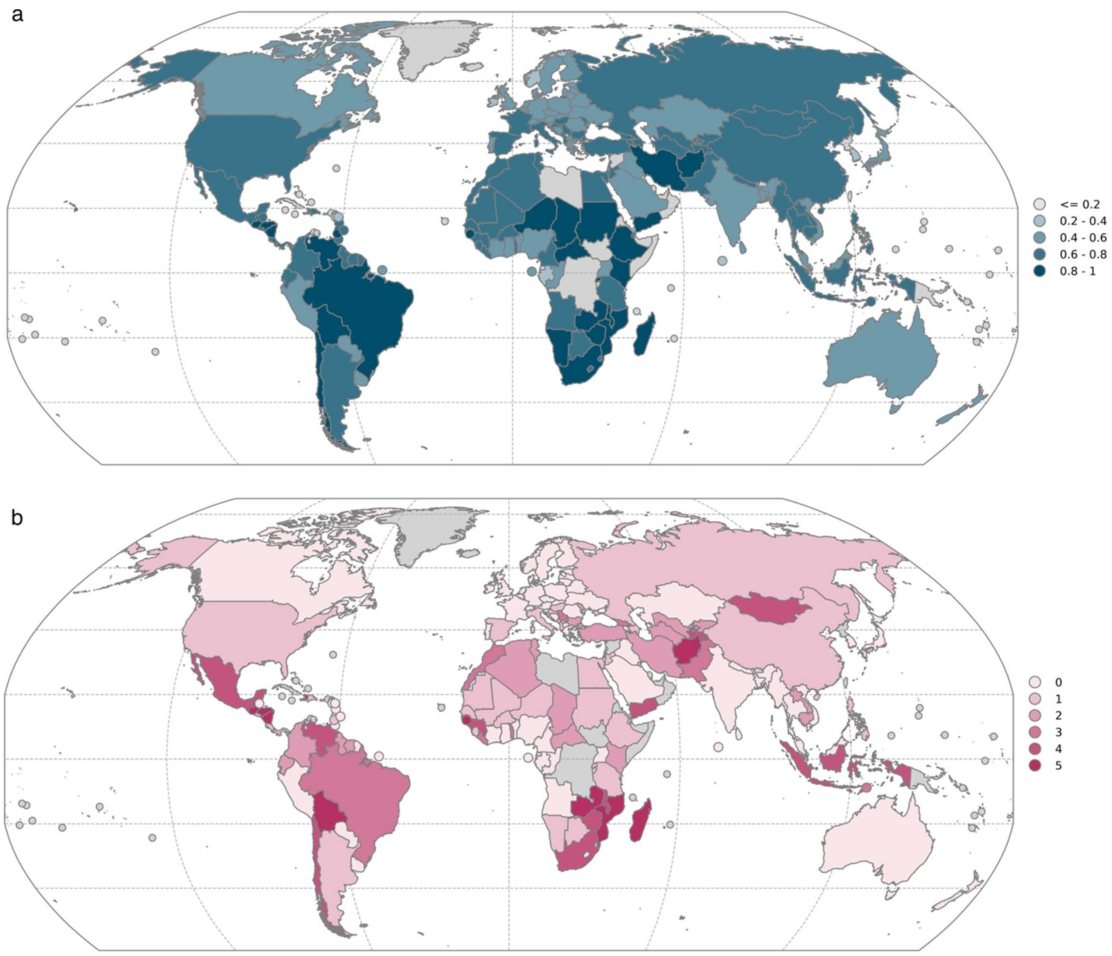

Figure 5. Climate risk to domestic supply of micronutrients. Maximum climate risk score across all micronutrients (a) and number of micronutrients with climate risk scores exceeding the 75th percentile of climate risk scores for each micronutrient (b). Climate risk scores were calculated based on standardized and normalized scores for climate hazard (figure 3), vulnerability (figures 4(a) and (b)), and exposure (figures 4(c) and (d)). Countries shown in gray have no data available.

methods). By this definition, the countries with the highest average exposure are Argentina, Uganda, and Brazil, whereas Saint Kitts and Nevis, Saint Lucia, and the United Arab Emirates are most import-dependent. Combining then climate hazard, vulnerability, and exposure into a holistic domestic nutrient climate risk score (figure 5, SI figure 15), we estimate that 82 countries—containing more than half of the current global population (57%)—face high climate risk (exceeding the 75th percentile) to the domestic supply of at least one micronutrient (figure 5(a)). 48 of these countries face high climate risk for two or more micronutrients (figure 5 (b)), containing 1.7 billion people, or 22% of today's world's population. Ten countries—Afghanistan, Bolivia, Guatemala, Guinea–Bissau, Haiti, Honduras, Madagascar, Mozambique, Nicaragua, and Zambia—face high climate risk to domestic supply in all five micronutrients. It is worth noting however that these results present a relative ranking of climate risk: low values do not indicate the absence of risk.

In addition to domestic climate risk, importing countries can also be exposed to climate hazards through international markets [36, 37, 40, 41]. Given the dynamic and evolving nature of international trade networks [48], a true estimate of the climate risk associated with imports would require a model that can account for substitution based on supply, demand, prices, and policies, which is beyond the scope of this paper. However, based on our analysis we are still able to identify countries that are both highly exposed to global markets and highly vulnerable to loss of nutrition (SI table 1), creating risk from trade-related climate impacts. This primarily concerns arid countries in North Africa and the Middle East, small island states, and smaller countries in Africa. These countries will be highly affected by climate shocks to production in major exporting countries [29]. By the middle of the century, micronutrient production in the top 10 producing countries faces adverse climate conditions on average every other year (ranging from 42% for folate to

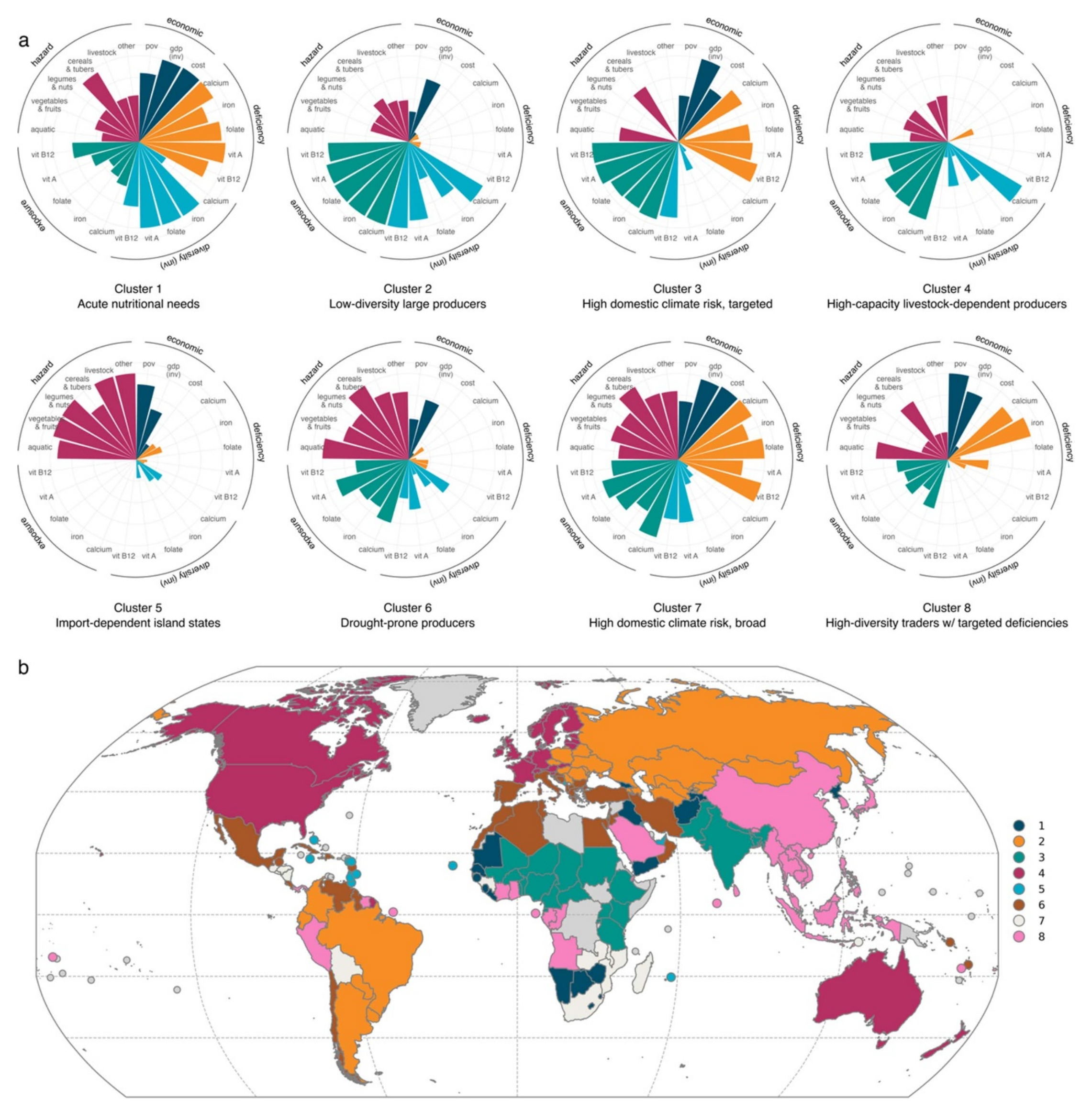

Figure 6. Nutrition-sensitive climate risk profiles based on clustering analysis of input parameters. (a) Polar plots showing median values of the input variables to the K-means clustering: economic vulnerability (cost of healthy diet, GDP, poverty; dark blue); nutrient deficiency for each micronutrient (orange); supply diversity for each micronutrient (light blue); share of supply from domestic production for each micronutrient (dark green); and probability of climate extreme facing each micronutrient (dark red). Values for GDP and supply diversity were inverted to display higher values as corresponding to higher vulnerability. Values for each variable were standardized across the profiles, so that a value of 1 indicates the highest across profiles, and 0 indicates the lowest across profiles. (b) Climate risk cluster assignment for each country. Countries shown in light gray have no data available.

59% for vitamin B12), suggesting that investments are urgently needed to both strengthen domestic production systems in importing countries and increase the resilience of global markets (see Discussion).

3.4. Patterns of nutrition-sensitive climate risk

The components of nutrition-sensitive climate risk presented here can help inform context-specific strategies for supporting climate-resilient healthy diets. Based on a clustering analysis, we identify eight archetypal climate risk profiles (figure 6; table 2) for which different policy and investment objectives could be prioritized to achieve national goals on nutrition under climate change. The distribution of input variables for each of the identified clusters is shown in SI figure 18, with a complete list of countries in SI table 1.

We identify three clusters with high vulnerability (figure 4(a)): one with high levels of exposure to climate hazards in all nutrients (‘High domestic climate risk, broad’), one with high levels of climate hazards in select food groups (‘High domestic risk, targeted’), and one where present-day nutritional needs are particularly high (‘Acute nutritional needs’). Amongst large producers, we identify one cluster with low nutrient supply diversity in all nutrients (‘Low-diversity large producers’), one cluster with low nutrient supply diversity in calcium

Table 2. Dominant characteristics of each of the eight risk profile clusters.

Cluster	Examples	Description
(1) 'Acute nutritional needs'	Afghanistan, Guinea–Bissau, Lesotho, Yemen	Generally vulnerable in all dimensions identified here: low GDP per capita, high poverty, high rates of deficiency in all micronutrients, low dietary diversity. Average levels of projected climate hazards and exposure.
(2) 'Low-diversity large producers'	Argentina, Brazil, Ukraine, Russia	Large domestic producers with generally low economic vulnerability and low rates of nutrient deficiencies but also low diversity of nutrient supply. Average levels of projected climate hazards.
(3) 'High domestic climate risk, targeted'	Chad, India, Nigeria, Tanzania	Highly vulnerable to climate impacts to nutrition through high rates of nutrient deficiencies, low GDP per capita, and high poverty. Large producers of all nutrients, facing high levels of projected climate hazards in specific food groups.
(4) 'High-capacity livestock-dependent producers'	Australia, France, Sweden, USA	Highly adaptive countries (low poverty, high GDP per capita, low cost of healthy diet, high nutrient supply diversity) with low rates of nutrient deficiency, facing medium levels of exposure to climate hazards. Supply diversity is low for calcium due to high dependence on livestock.
(5) 'Import-dependent island states'	Barbados, Cabo Verde, Jamaica, Mauritius	Generally low rates of nutrient deficiencies and high nutrient supply diversity, but highly reliant on imports with high cost of a healthy diet. Projected climate hazards are high for all food groups.
(6) 'Drought-prone producers'	Egypt, Mexico, Oman, Spain	Big producers that are particularly prone to joint heat and drought extremes but that have relatively low sensitivity to loss of nutrition and medium to high adaptive capacity.
(7) 'High domestic climate risk, broad'	Guatemala, Madagascar, Malawi, Timor Leste	Highly vulnerable to climate impacts to nutrition through high rates of nutrient deficiencies, low GDP per capita, and high poverty. Large producers of all nutrients, facing high levels of projected climate hazards across all food groups.
(8) 'High-diversity traders with targeted deficiencies'	Indonesia, Thailand, South Korea, Suriname	Medium levels of trade dependency with high nutrient supply diversity and high cost of healthy diets. Typically nutrient deficient in just one or two micronutrients. High climate hazards are concentrated in specific food groups.

specifically ('High-capacity livestock-dependent producers'), and one cluster that is especially prone to combined heat and drought extremes ('Drought-prone producers'). Finally, we identify two clusters of import-dependent countries with high costs of healthy diets, one facing high climate hazards in all food groups ('Import-dependent island states') and one facing high hazards and nutrient deficiencies in one or two nutrients ('High-diversity traders with targeted deficiencies').

4. Discussion

Diverse, high-quality diets are critical for the supply of essential micronutrients, yet to date, climate risk calculations have focused mainly on a handful of staple terrestrial crops that primarily provide dietary energy instead of nutrient-rich terrestrial and aquatic foods. Here we developed a framework for estimating nutrition-sensitive climate risk across terrestrial and aquatic food production systems. We find that more than half of today's global population faces high domestic climate risk to at least one micronutrient by the middle of the century, suggesting that the need to develop climate-resilient nutrition strategies is widespread. In addition, nearly fifty countries face high domestic climate risk in multiple micronutrients, and ten countries in all of the micronutrients considered here, indicating that climate change will pose a substantial threat to achieving the nutrition and health targets of the 2030 SDGs. Climate hazards within a given country differ across nutrients, highlighting the need to develop nutrient- and food group-specific risk assessment tools and interventions. In light of the multiple sources of climate risk, adaptation and resilience measures are needed across food system dimensions and domains, including production systems, public health, trade, R&D, and finance.

4.1. Strategies for climate-resilient healthy diets

Based on our climate risk assessment, we identified key climate resilience and nutrition interventions from the literature and assessed where they may be most relevant for each of the climate risk profiles (table 3). Climate interventions focused on food production and domestic supply chains—ranging from diversifying production and adopting climate-adaptive practices to strengthening infrastructure—may be most salient for countries with high levels of domestic production facing high climate hazards ('High domestic climate risk, broad', 'High domestic climate risk, targeted', 'Low-diversity large producers', 'High-capacity livestock-dependent producers') [5, 49–54]. Additionally, nutritionally vulnerable countries may consider investing specifically in low-trophic, nutritious aquaculture. Aquaculture of particular species offers the potential to contribute to nutrition, climate adaptation, and sustainability goals, but requires intentional investment to support those outcomes [55–57].

Interventions outside food supply chains can also enhance food and nutrition security outcomes under climate change. For example, both social safety nets and nutrition education programs can be expanded to focus on nutritious and climate-resilient foods—especially for those facing high nutrient deficiencies and high climate hazards ('High domestic climate risk, broad', 'High domestic climate risk, targeted', 'Acute nutritional needs', 'Import-dependent island states') [50, 51, 54, 58, 59]. Countries that have not done so already, could adopt and update dietary guidelines and food environment policies to support diversity, climate-resilience, and sustainability outcomes, as currently underway in the Nordic countries [50, 60, 61]. Meanwhile expanding access to financial services, tools, insurance, and loans—while important in all countries with high numbers of small-scale food actors—may be particularly important in places with high rates of domestic production and high climate hazards ('Drought-prone producers', 'High domestic climate risk, broad') [50, 51]. Lastly, investing in R&D targeting climate-resilient food innovation should be *a priori*ty in countries with strong financial resources (especially 'High-capacity livestock-dependent producers') [5].

Given that trade can both expose countries to and shield them from production and market shocks [36, 37, 40], climate-resilience of nutrient supply is a transboundary issue. Bilateral and multilateral trade agreements will need to be renegotiated in a climate just framework that recognizes the universal Right to Food [49, 62]. Countries can put in place policies to diversify their imports—both in terms of food groups and trade partners ('Import-dependent island states', 'High-diversity traders with targeted deficiencies')—or to (re)build stockpiles of diverse food sources to buffer against shocks in food prices and availability ('High domestic climate risk, broad', 'High domestic climate risk, targeted', 'Acute nutritional needs') [66]. Finally, all countries can develop and strengthen forward-looking national commitments on climate change and nutrition, for example through their National Pathways, Nationally Determined Contributions, and National Adaptation Plans [51, 54, 65].

4.2. Data and model limitations

Our framework provides an initial, national-level assessment of nutrition-climate interactions, but results need to be interpreted with a few data and modeling gaps in mind. Our extremes-based approach did not incorporate information about the sensitivity of different foods and food production systems to different climate conditions, and has proven to be sensitive to the choice and superposition of climate variables (compare e.g. figure 3 to SI figure 3, and figure 5 to SI figure 17). In particular, using only temperature-based indicators for aquatic and livestock products may have led to an overestimation of their relative climate hazards. However, there is currently insufficient data to estimate climate sensitivity for all foods relevant for nutrient supply, especially to compound exposure. As of now, process-based crop models only exist for major crops like maize, soybeans, wheat, barley, and millet [67], while the impacts on livestock, inland fisheries, and aquaculture remain poorly quantified [68].

In addition, key processes, like the impacts of elevated CO_2 levels on yields and nutrient composition [69], secondary impacts through feeds [70], impacts on labor [71], or post-production impacts [5], were not included. Elevated CO_2 levels can both stimulate photosynthesis and water use efficiency [72] and reduce the concentration of important nutrients such as protein, iron, and zinc [69] leading to competing impacts on nutrient supply that depend on the crop or variety and environmental factors [68], precluding inclusion of these effects within our model. While

Table 3. Climate adaptation and resilience priorities for each climate risk profile. Recommendations were sourced from the literature and organized and assigned based on expert knowledge of our multidisciplinary team of co-authors.

Recommendation	Examples	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
	Food production and supply chain								
Align policy incentives and subsidies with a diversified and nutritious food production system [5, 49, 54]	(1) Tax incentives for farms that diversify their crops and/or implement climate-resilient food production practices. (2) Removal and/or reallocation of crop subsidies designed to amplify production of just one or a few crops. (3) Promote use of traditional and Indigenous knowledge and approaches that value foods that are culturally important and nutrient-rich.	+	+++	+++	+++	++	++	+++	+
Facilitate the adoption of climate-adaptive production practices [5, 50, 51]	(1) Extension services for farmers on heat- and drought-resilient crops and farming techniques. (2) Workshops on climate-resilient fishery management. (3) Implementation of early warning systems for climate impacts. (4) Adjustment of farm work schedules, clothing, and hydration plans for farm workers in extreme heat.	+	+++	++	++	++	++	+++	+
Invest in nutritious, low trophic aquaculture [55, 57]	(1) Public-private partnerships for low-trophic aquaculture initiatives. (2) Grants and extension services for research and development of low-trophic aquaculture, such as seaweed and filter feeders. (3) Grants to sustainably develop aquaculture systems that focus on cultivating a diverse array of nutrient-dense aquatic foods.	++	+	+++	+	+++	++	+++	+++
Strengthen food supply chain infrastructure to accommodate for climate hazards and allow for the distribution of diverse food products [5, 50, 52, 53]	(1) Expansion of cold-chain storage facilities. (2) Construction or expansion of road infrastructure. (3) Increased funding for innovations in food transportation packaging. (4) Establishment of local hubs for collecting and distributing foods.	+++	+	+++	+	+	++	+++	++

(Continued.)

Table 3. (Continued.)

Recommendation	Examples	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
	Public health and education								
Target social preferences for nutritious, resilient foods through nutrition education programs, especially for youth and women [50, 58]	(1) School programs and community workshops on the benefits of diverse diets. (2) Media awareness campaigns on diverse and nutritious diets, particularly targeting women and youth.	+++	++	+++	+	++	++	++	+
Expand social safety nets focusing on nutritious and climate resilient foods [50, 51, 54, 59]	(1) Nutritious school feeding programs incorporating local and climate-resilient foods. (2) Development or expansion of nutrition assistance programs. (3) Food vouchers and cash transfers with guidelines on spending for nutritious foods. (4) Early-warning systems for climate-driven food insecurity.	+++	+	+++	+	+++	++	+++	++
Revise national dietary guidelines and policies shaping food environments to incorporate food diversity, climate resilience, nutrition, and sustainability considerations [50, 60, 61]	(1) National dietary guidelines incorporating diverse and resilient food sources, with a particular focus on traditional and indigenous foods. (2) Encourage procurement policies in public institutions that favor a variety of diverse, nutritious foods that are produced in a climate-resilient manner. (3) Develop and implement marketing campaigns that highlight the benefits of consuming a diverse range of nutritious foods. (4) Partnerships between government agencies, public institutions, and food retailers that promote the increased accessibility of diverse and nutritious foods.	+++	+++	+++	+++	+++	+++	+++	+++

(Continued.)

Table 3. (Continued.)

Recommendation	Examples	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
	Trade								
Align national trade policies with food and nutrition priorities [5]	(1) Alignment of tariffs with the import and export of nutritious foods. (2) Implementation of trade policies that incentivize the export of nutritious foods specifically to areas identified as food deserts, such as the provision of subsidies to suppliers who prioritize delivering nutritious foods to areas with limited access to diverse foods. (3) Alignment of access agreements for fishery resources with national food and nutrition objectives. (4) Enhancement of Sanitary and Phytosanitary (SPS) measures to ensure the safety, quality, and continuous availability of nutrient-rich foods in climate vulnerable regions, including the development of standards that are robust across changing climate conditions.	+++	++	+++	++	+	+	+++	++
Incorporate climate considerations, including both distribution of risk and building resilience, into international trade agreements [49, 62]	(1) Prioritize trade with countries that support diversified and nutritious food production systems. (2) Establishment of trade agreements that encourage partnerships with multiple countries producing a variety of food products, ensuring a consistent and varied food supply even under climate events.	++	+++	+++	+	+++	+	++	+++
	Finance								
Expand access to financial support tools for food producers [50, 51]	(1) Loans for farmers implementing climate-adaptive practices. (2) Crop insurance covering climate-related losses. (3) Grants for fishers using sustainable practices. (4) Extension programs for food producers on accessing financial services.	+	++	++	++	++	+++	+++	+

(Continued.)

Table 3. (Continued.)

Recommendation	Examples	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Cluster 8
Expand international development assistance programs to include tailored support for the production and distribution of nutritious and climate-resilient foods [63, 64]	(1) Co-developed programs for agricultural technology transfer focused on nutritious food production. (2) Funding for infrastructure improvements to increase efficiency in the transport of nutritious foods. (3) Support for the adoption of climate-adaptive technologies, such as solar powered refrigeration systems.	+	++	+	+++	+++	++	+	++
Research & Development									
Allocate funding towards research and innovation for resilience and nutrition research [5]	(1) Provide research grants on innovation for sustainable food production and storage technologies (2) Research on heat- and drought-resistant crop varieties. (3) Invest in model and scenario development for nutritious food products under climate change.	+	++	+	+++	++	++	+	+
National and sub-national food and climate policies									
Incorporate climate resilience and nutrition into national climate commitments [50, 51, 65]	(1) National Adaptation Plans (NAPs) and Nationally Determined Contributions (NDCs) detail strategies for establishing nutritious and resilient food systems under climate change predictions, emphasizing both mitigation and adaptation approaches. (2) National forums to discuss progress on the intersection of climate and nutrition. (3) Development of government bodies focused specifically on food systems, such as a ministry or special council on food systems, to ensure coordination across various sectors.	+++	+++	+++	+++	+++	+++	+++	+++
Build and/or maintain a diverse, nutritious national food stockpile containing a variety of climate-resilient food commodities [66]	(1) Ensure that stockpiles contain a mix of diversified foods. (2) Development of partnerships with producers practicing resilient and diversified food production techniques for regular stockpile replenishment.	+++	+	+++	+	++	++	+++	++

it may not be feasible to develop process-based models for every crop, livestock, and aquatic food system, our analysis of food group contributions to nutrient supply (figure 2) could help identify 'keystone' production systems for priority model development. Alternatively, integrative indicator approaches such as fuzzy logic modeling [73, 74] could be used to cross-evaluate food group-specific variables, especially when grounded in regional understanding of climate change and sensitivity.

For several countries—notably in Central and East Africa and many small island states—one or more of the indicators used in our nutrition-sensitive climate risk framework were missing, precluding a holistic climate risk assessment. Failing to address these data gaps can perpetuate inequities, as resilience investments are likely to go to places and systems assessed in the research and policy literature [75]. A further update on analysis and recommendations could also address how variability between food groups compares to variability within food groups. For example, the Aquatic Products group contains a large diversity of species that vary widely in both nutrient composition [28] and climate sensitivity [74]. Similarly, future work applying this framework at national or regional levels could include subnational indicators of nutrient availability, climate hazards, and climate vulnerability [e.g. 46,71,76] to further identify climate risk hotspots. Finally, further research and evaluation are needed to test options and effectiveness for the recommendations presented in table 3, including how they could generate co-benefits with other SDGs, including targets for biodiversity and emission reductions [77]. In particular, micronutrient deficiencies coexist with other food-related health outcomes such as diabetes and cardiovascular disease [1]. Our results on food group climate hazards (SI figures 1–2) could inform further analysis on climate impact pathways for diet-related non-communicable diseases [78, 79].

5. Conclusion

As rising rates of malnutrition and an unfolding climate crisis converge in the 21st century, we need new frameworks for assessing and acting on dietary climate risk that move beyond a focus on single crops or food groups and dietary energy. Here we developed an integrative nutrient-sensitive climate risk framework that spans the whole of diets and covers five key micronutrients. Our analysis revealed eight climate risk profiles that can be used to guide resilience interventions that are specific to nutritional needs, food system context, and projected climate impacts. Most urgent are actions and investments for countries that presently have high rates of micronutrient deficiencies and high economic barriers to accessing healthy diets, with resilience strategies diverging based on whether they are large domestic producers or vulnerable to shocks in international markets. Our analysis also highlighted the shortcomings of existing datasets and analytical tools to evaluate dietary climate risk. Adaptation timelines are short, meaning that research and action deployment in this area will need to go hand in hand to prevent climate change from further exacerbating the failings of our current food systems.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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