



Towards food supply chain resilience to environmental shocks

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Environmental variability and shock events can be propagated or attenuated along food supply chains by various economic, political and infrastructural factors. Understanding these processes is central to reducing risks associated with periodic food shortages, price spikes and reductions in food quality. Here we perform a scoping review of the literature to examine entry points for environmental variability along the food supply chain, the evidence of propagation or attenuation of this variability, and the food items and types of shock that have been studied. We find that research on food supply shocks has primarily focused on maize, rice and wheat, on agricultural production and on extreme rainfall and temperatures—indicating the need to expand research into the full food basket, diverse sources of environmental variability and the links connecting food production to consumption and nutrition. Insights from this new knowledge can inform key responses—at the level of an individual (for example, substituting foods), a company (for example, switching sources) or a government (for example, strategic reserves)—for coping with disruptions.

Food production, storage, processing, distribution, retail and consumption are all exposed to wide-ranging forms of environmental change, including slow-moving changes in average conditions (for example, climate, nutrient and water cycling), smaller-magnitude variations around those means and larger, anomalous disruptions^{1,2}. Environmental variability and disruptions are manifested not only as floods, droughts and extreme heat (that is, climate variability) but also as natural hazards, pests, disease, algal blooms, coral bleaching and aflatoxins^{3–5}.

Environmental variability includes fluctuations within the historical range but increasingly consists of extreme—and at times unprecedented—events driven by climate change and other forms of human-environmental change. While expected changes in climatic and environmental conditions over the coming decades will certainly have important implications for future food security, nutrition, and human and planetary health^{1,2,4,6,7}, environmental variability and extreme events are already leading to harvest losses and distribution disruptions each year⁸. In many cases, these short-term impacts (that is, those occurring within the span of a production/growing season) have been shown to be stronger than those caused by slow-moving changes in climate and the environment⁷. Such developments point to a growing need to protect the stability of not only food production but also other steps in food supply chains in the face of rising environmental variability and risk⁹.

Environmental variability can affect food supply chains at local to global scales. In regions with limited global market access and where food production and consumption are tightly coupled (that is, short supply chains common in subsistence-based food systems), environmental variability can more readily translate into local shortages of specific foods¹⁰, creating food insecurity depending on available substitutes, the impacts on livelihoods¹¹, and how household diets and nutrient intake are modified¹². Increasingly, the impacts of environmental variability are not limited to local producers but spread through longer supply chains. A prominent example was seen in 2008, when a drought in key grain-producing regions, combined

with rising biofuel demand, high oil prices, decreasing grain stocks and the depreciation of the US dollar, led to a spike in global grain prices¹³. That set off a series of rice export bans, furthering shortages and ultimately driving more than 130 million people into poverty and an additional 75 million people into malnourishment¹³. Although only partially an environmental shock, this global-scale disruption illuminated the potential for shocks to cascade through the food trade network and to impact geographically distant places and people.

As food supply chains grow increasingly globalized, it is important to understand the potential novel risks of how environmental variability is propagated or attenuated within food systems. Ongoing globalization and the rise of multinational food corporations have enhanced the efficiency and complexity with which producers and consumers are linked. Research is only beginning to understand how these dynamics influence the propagation of the effects of environmental variability through global and local food supply chains, how large-scale events (for example, blockades, recessions and pandemics)^{14–16} may compound these effects, and what they ultimately mean for the stability and affordability of nutritious diets. Identifying the key processes and actors in food supply chains—and understanding their interactions with, and exposure to, environmental variability and the economy—is central to reducing food and nutrition security risks associated with periodic food shortages and to improving resilience within food systems.

Here we perform a scoping review (Extended data Fig. 1) to synthesize existing knowledge on the impacts of environmental variability on food supply chains and the transfer of such impacts along local and global food supply chains. We first highlight the entry points for environmental variability along each step in the supply chain, drawing on examples from the scoping review. Then, we present the quantitative review results related to which food items, supply chain steps and types of environmental variability have been the focus of research to date. Finally, we summarize the qualitative review results on the response option space for actors along the supply chain.

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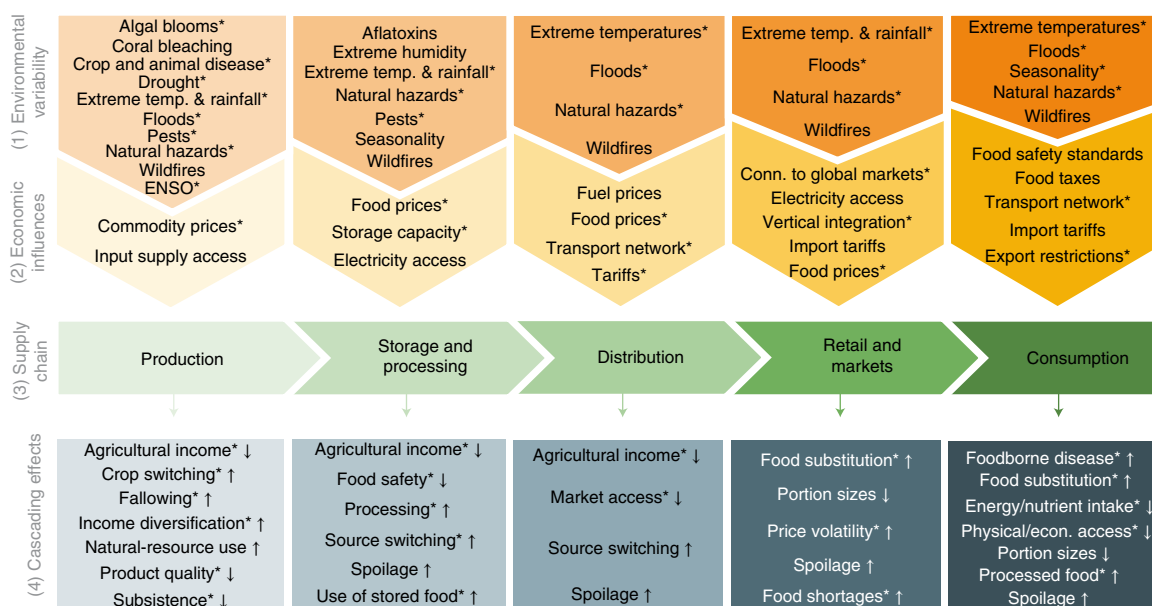


Fig. 1 | Entry points for environmental variability in food supply chains. 1) Environmental variability can enter at each step of the food supply chain. 2) Economic conditions and infrastructure quality can dampen or enhance these environmental factors. A variety of geopolitical and other economic factors influencing the interactions of environmental variability and food supply chains are also discussed in the text. 3) The impacts of this variability on food quantity and quality can also be passed between steps in the food supply chain. 4) The cascading effects represent the main outcomes that could occur without intervention from supply chain actors, and the direction of the arrow next to each effect indicates whether there would be an expected increase or decrease. Depending on the specific context, only certain cascading effects may emerge in response to environmental variability. The asterisks indicate a type of environmental variability, economic influence or cascading effect that was identified within the scoping review. Temp., temperature; conn., connectivity; econ., economic.

On the basis of our findings, we contend that a new wave of food systems research focused on the full food basket, diverse forms of environmental variability and local-to-global interactions across the supply chain is required to understand the diverse impacts of environmental variability on the spectrum of food systems. This new knowledge can inform a range of policy options and business decisions across the supply chain that provide flexibility in responding to variability in food supplies and that enhance the resilience and adaptability of food systems to known and novel shocks.

Results

Entry points for environmental variability. Environmental variability can affect the quantity, quality and timing of food as it travels through the supply chain (Fig. 1). Most entry points for environmental variability to impact food supply chains occur at production. Exposure to variability and shocks is particularly pronounced for rainfed agriculture and smallholders (that is, households with <5 ha), who account for the majority of the world's food production (57% (ref. 17) and 55% (ref. 18), respectively) and rely largely on locally available natural resources. A large body of literature documents the impacts of floods, droughts, natural disasters and other extreme events on food production^{19–21}. In some instances (for example, disease and pests), individual food items may be impacted, while other phenomena (for example, large-scale drought and algal blooms) may induce declines across entire portions or regions of the food production basket. Environmental variability also presents challenges related to the quality and safety of food items, possibly leading to changes in the nutrient content of some species as well as increased food safety risks. Increasing variations in rainfall have been linked to greater variability in the protein content of wheat²² while higher temperatures have been associated with changes in the fatty acid content of some fish^{4,23} and declining milk quality in dairy cows²⁴. Temperature, humidity and precipitation variability,

along with increased pests, are associated with increased aflatoxin levels during production, while algal blooms can produce toxins that enhance the risk of shellfish poisoning^{25,26}. Environmental variability also affects the transmission of animal diseases (which can necessitate mass animal culling or fishery closures), foodborne illness and zoonosis (that is, animal-to-human transmission).

Specifically concerning storage, subsistence farmers who have limited growing seasons and depend on stored crops are particularly sensitive to extreme rainfall events affecting food quantity and quality^{27,28}. Aflatoxin levels in crops increase if storage conditions are not sufficiently dry, while bacterial contamination and foodborne disease are common in the absence of cold storage. Broadly, higher temperatures and changes in rainfall patterns can increase the occurrence of bacteria, viruses, parasites and fungi, and their associated foodborne diseases in stored foods^{25,29,30}.

Distribution and market access can also be substantially impacted by environmental variability. Floods can disrupt road networks and food trade, typically leading to losses of more perishable or time-sensitive food items^{31,32}. Compounded by changes in the affordability and diversity of foods available in markets, physical and economic barriers can impact food and nutrition security³³. Flooding and rising sea levels can also increase water runoff and contamination, leading to increased waterborne disease and chemicals in the food supply²⁵. Further, extreme weather events disrupt food distribution by damaging existing infrastructure or slowing food shipments, which can increase risks of food damage, spoilage or contamination³⁴. Compared to fresh perishable foods, processed foods may be better able to withstand the impacts of environmental variability related to spoilage, creating a trade-off between the durability, safety and convenience of processed food and their often lower nutritional quality³⁵.

Consumption may also be impacted by environmental disruptions through shifts in food availability, affordability and

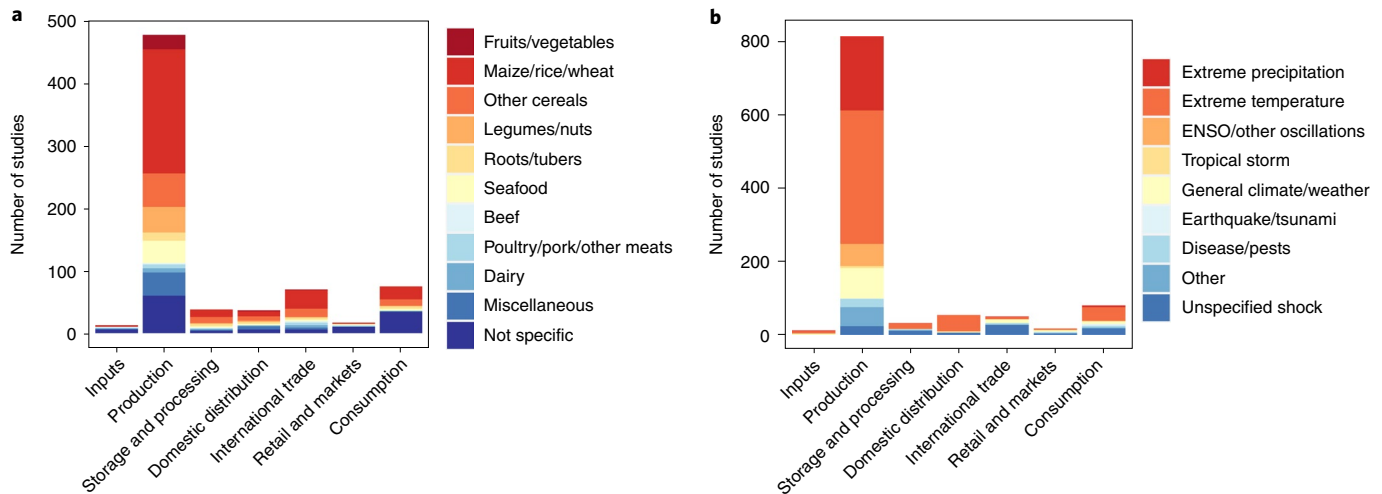


Fig. 2 | Environmental disruptions of food supply chain steps. **a, b**, Literature review results ($n=325$ studies) for each supply chain step disaggregated by food group (**a**) and shock type (**b**). Studies have concentrated on environmental variability related to the production of maize, wheat and rice and have focused on extreme precipitation and temperature. Certain studies examined more than one food item; as such, the number of observations in the figure exceeds the number of studies.

acceptability. For subsistence farmers, such shifts may directly influence the quantity and quality of foods available for consumption within the household. Reduced incomes and higher food prices can have important implications for nutrition, limiting food purchasing power and leading to shifts in dietary intakes, often towards cheaper highly processed foods^{36–38}. Environmental disruptions can also limit the ability to prepare food or to fully absorb nutrients from ingested food, often leading to compromised nutritional outcomes (for example, childhood stunting³⁹). For instance, in Bangladesh, cooking stoves are often located outside on the ground and can be submerged by flood waters³⁵. In Australia, extreme high temperatures were associated with increased risk of intestinal infections and nutritional and metabolic issues among young children⁴⁰. In India, children living in communities exposed to recurring floods were at least 2.3 times more likely to be severely wasted, stunted or underweight^{41,42}.

Propagation of environmental variability. Understanding the impacts of environmental shocks on food security and nutrition requires connecting production to consumption through all supply chain steps. We analysed peer-reviewed literature to investigate which food items, environmental disruptions and supply chain steps have been the focus of research to date. The scientific evidence for the effects of environmental shocks on food systems is highly concentrated on the main staple crops (maize, rice and wheat) and relatively few types of shock (Figs. 2 and 3). Of the 325 papers examined (Supplementary Table 1), nearly half looked at the impact of shocks on maize, wheat and rice (37%) and/or other cereals (10%). Another 18% did not focus on any specific food item (Fig. 2a). The types of food and shock studied are probably interrelated, as there was an emphasis on the temperature (22%) and precipitation (41%) extremes that threaten cereal crops (Fig. 2b). Other shock types, such as cyclones, harmful algal blooms and disease events, were roughly evenly represented in the studies (Fig. 3).

Across the reviewed studies, 42% focused on a subnational scale (that is, a region within a single country), 35% on a national scale (that is, a single country) and 15% on an international scale (that is, multiple countries or global), with the remainder being unspecified about the scale. Of the studies set in a specific country or region, over a quarter were set in Asia and nearly a fifth in Africa. The

subnational focus, particularly in regions where subsistence food production makes up a large portion of the food supply, is highly valuable for understanding the impacts of environmental variability on local food security; yet, as a quarter of all food calories are traded internationally⁴³, our understanding of the novel food security risks arising from increasingly global food supply chains is limited.

Further, we found that studies on environmental shocks are biased towards production; 89% included the production stage and 73% focused on production alone (Fig. 2a). Consumption, here broadly defined as including outcomes related to food expenditure, dietary intake, food security and nutrition outcomes, was included in just 15% of studies. A similar percentage (16%) looked at more than one supply chain stage and only 6% explicitly looked at shock propagation between supply chain steps. Given the heterogeneity of the methods and disciplines that cover the current literature on the propagation of environmental shocks through food supply chains, it was not possible to assess the representativeness or prevalence of specific linkages between environmental variability and food supply chain shock propagation.

In all, our findings indicate that while each step in a food supply chain may be independently affected by environmental variability in various ways (Fig. 1), upstream shocks can be propagated to subsequent supply chain steps under certain conditions—and this variability can be transferred both locally (Box 1) and globally, as exemplified by some studies^{44–50}. For more local systems, as in the case of subsistence households, some of these steps are absent or diminished (Box 2), and environmental variability is more likely to affect their diets depending on the availability of substitutes, the effects on household incomes and the quality of the foods consumed. Smallholder farmers who are unable to sell their produce owing to suboptimal quality (or questionable safety) tend to consume it themselves, possibly compromising the nutritional value and diversity of their diets²⁵. Low-income populations in urban settings may face a similar trade-off and purchase less expensive foods despite lower quality^{35,36} increasing their exposure to aflatoxin and other foodborne illnesses and disease. For more global food supply chains, a range of recent network-based modelling studies have attempted to evaluate the distant impacts of food supply shocks, finding that highly globalized countries⁴⁴, net importers and low-GDP countries^{45–47}, and countries with low strategic reserves⁴⁸

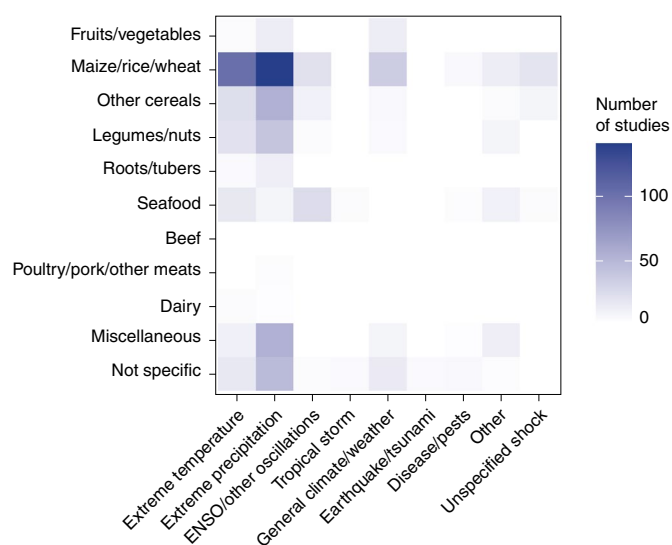


Fig. 3 | Environmental disruptions and food groups. Literature review results disaggregated by shock type and food group ($n = 325$ studies). As a result of the emphasis on staple grain production, studies also heavily focused on related disruptions (that is, extreme temperature and precipitation). Certain studies examined more than one food item; as such, the number of observations in the figure exceeds the number of studies.

are most exposed to external shock events. Other agent-based modelling work has found that shocks travel more easily across networks when the perturbed product is directly traded⁵¹ and that the indirect economic effects of supply chain shocks (for example, firm-to-firm disruptions that a natural hazard causes) can exceed direct impacts (for example, physical damage from the natural hazard)⁵².

One of the primary ways by which shock propagation along supply chains has been examined in the literature is through the effects of disruptions on prices. Price transmission across supply chains informs economic decisions at various stages, but volatile prices can create uncertainty for downstream supply chain actors⁵³. The effect of transmission along a supply chain depends on the structure of the sector and the policy context. Foods with multiple sourcing options, substitute products and longer shelf lives can better buffer supply and dampen variability^{54,55}. Concentrated market power also restricts price transmission when retailers exercise their power to keep consumer prices stable during volatile periods⁵³. Conversely, foods with few substitutes, foods requiring longer grow-out periods, sectors with fewer industry actors and regions with limited infrastructure tend to have lower capacity to dampen supply or price variability, resulting in greater propagation along the supply chain. In cases where variability reaches consumers (often in the form of price fluctuations), physical and economic access dictates that these shortages are not evenly distributed between countries or between individuals. Thus, it is essential to understand not only how environmental variability can lead to instability in food supply but also how economic mechanisms may be used to modulate these fluctuations across the population.

Supply chain actors and their response option space.

Approximately two-thirds of the coping strategies identified through our review focused on the production level. However, there are multiple points across the supply chain where governments, the private sector, intergovernmental, civil society and non-governmental organizations, and individual farmers can act to reduce the negative impact of environmental variability on food security⁷. Indeed, given the interconnectedness of supply chain steps, the full suite

of food system actors will need to intervene—from production to consumption—to counteract the many ways in which environmental variability and extreme events manifest and propagate (Fig. 1). Opportunities to address this variability depend on the actor, the step in the supply chain, the timescale of implementation and the type of environmental variability (Table 1).

Responses at the production level focused on improving farmers' resilience in terms of producing sufficient quantity and quality of food in the presence of environmental variability. While government institutions (including agricultural ministries, national agricultural research centres, and extension and agricultural policy-makers) are the key actors involved in these responses, the private sector, intergovernmental organizations (for example, the World Bank) and other organizations such as CGIAR are also important for enabling stable production⁵⁶. One important way to increase the resilience of agricultural production is by choosing crops, cultivars, species and breeds that are not only less susceptible to stresses such as drought, pests and salinity, but also offer other benefits for livelihoods or nutrition^{17,57}. For instance, subsidy programmes in India aimed at promoting traditional climate-resilient cereals can increase iron and zinc supply, lower farmer input requirements and reduce water, energy and emission footprints⁵⁸. The adoption of biofortified crops can potentially offer similar win-win situations; in sub-Saharan Africa, for instance, orange-fleshed sweet potato is more drought tolerant than other staple crops while also improving vitamin A intake⁵⁹. Overall, programmes to introduce traditional or biofortified foods must consider cultural acceptability and may require promotional efforts to increase the willingness of consumers to shift their tastes to new varieties^{60,61}. Other strategies at the production level include: shifting the timing and patterns of planting⁶²; adopting agroforestry practices⁶³; diversifying farms⁶⁴; increasing the adoption of technology and on-farm infrastructure, agrochemicals and irrigation⁶⁵; water and soil conservation practices⁶⁶; and shifting or expanding growing areas⁶⁷. However, strong extension services are needed to ensure that farmers have the knowledge and skills to change production practices. It is important to note that large multinational companies are often vertically integrated and have increased global connectivity, being more resilient to certain shocks owing to their ability to reallocate production and sourcing in response to climate shocks^{68,69}. In other cases, globalized supply chains with specialized foreign markets are at a greater risk to supply chain disruptions⁷⁰.

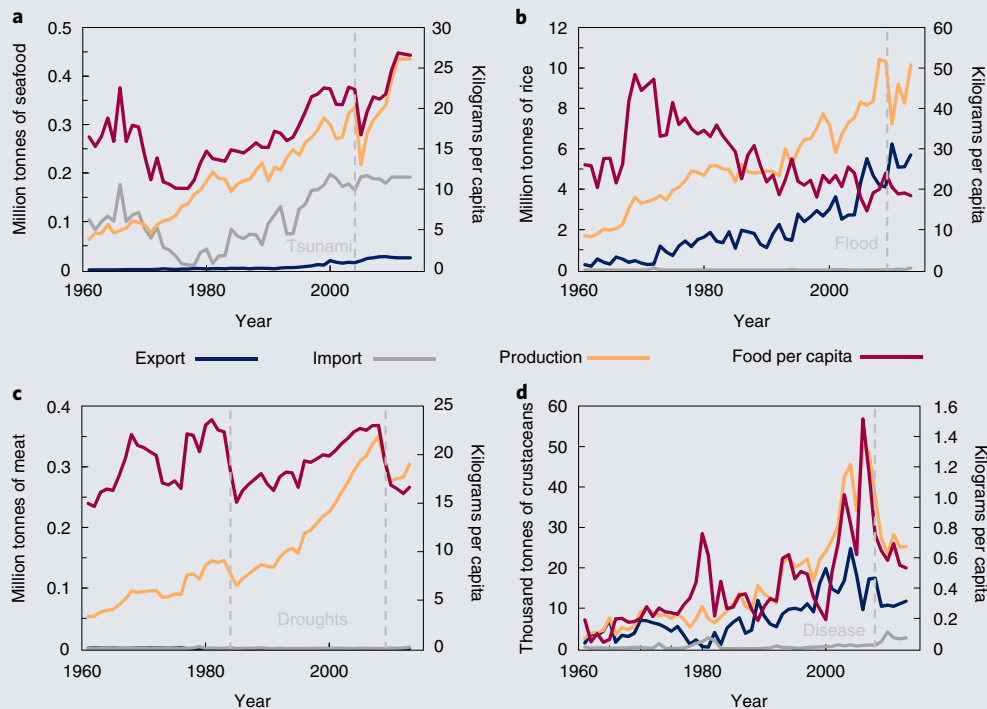
Investment by governments and other actors, including the private sector, can also increase resilience to environmental variability across supply chains. For example, increasing access to irrigation (where sustainable)^{71,72} and promoting water-efficient management practices⁷³ can stabilize production during times of drought⁷⁴, while improvements in storage and road infrastructure can help protect harvested crops and ensure market access under extreme weather events⁷⁵. Crop and index insurance can protect farmer incomes against environmental risk, particularly in low- and middle-income countries, and in some cases enable them to access credit for investing in inputs, higher-value crop varieties⁷⁶ and new technologies⁷⁷. Besides protecting rural livelihoods, such programmes may be crafted to incentivize more sustainable and resilient on-farm choices.

Food processing strategies can help increase the shelf life of perishable foods (for example, fruits and vegetables), while fortification and product reformulation can increase the nutritional quality of foods—both of which can prevent food insecurity in times of limited food diversity and shortages associated with environmental variability. Given that processed foods may be more resilient to price volatility, ensuring that their consumption does not lead to nutritional compromises is essential. Policy options and outreach efforts at both the retail and consumer level can help incentivize consumption shifts, such as subsidies for more, and taxes for less

Box 1 | Production impacts of environmental variability and potential effects on food supply

Food security policies, strategic reserves, trade relations, substitutability and the type of disturbance all determine a government's ability to respond to an environmental disruption. Depending on the ability to enact a timely response, this can ultimately impact food availability to consumers. **a**, For instance, the December 2004 tsunami in Sri Lanka was associated with a marked decline in seafood production⁵. As much of the country's seafood catch is consumed domestically, this resulted in more than a 20% decrease in per capita seafood supply relative to the previous year. As a result of shortages in fresh seafood, imports of more expensive dry and canned fish temporarily jumped, with potential knock-on effects for short-term nutrition security in the country. **b**, Floods in Pakistan in 2010 impacted agriculture with 2.4 million hectares of standing crops, 1 million tonnes of food and seed stocks, and 11 million livestock and poultry either lost or damaged²¹. These impacts on production as well as damage to manufacturing, storage

facilities, and rail and road networks led to widespread declines in domestic food grain stocks (>60% of households lost food grain stocks in the short term), and rice imports increased tenfold compared to those in the previous year (although it should be noted that imports constitute only a small fraction of Pakistan's domestic rice supply). **c**, Droughts in Niger have periodically contributed to substantial declines in livestock production. As nearly all of the meat in Nigerien diets comes from domestic production, these shortfalls have contributed to marked reductions in per capita supply with imports playing no obvious role as a potential buffering strategy. **d**, In Venezuela, Taura syndrome virus produced strong impacts on shrimp production, with knock-on effects for the country's exports and domestic availability. The shocks shown here were identified in work by the Food and Agriculture Organization of the United Nations²¹, Gephart et al.⁵ and Cottrell et al.⁸. The data came from FAOSTAT¹²².



nutritious foods (for example, ultraprocessed foods)^{78–80}. This is particularly important given that food prices are often the primary driver of food choice and shifts in dietary intake when consumers experience shocks⁸¹. Social safety nets (for example, provision of cash transfers and food supplementation) can help mitigate the effects of environmental shocks on both food quantity and quality⁸². Also, strengthening food safety standards across supply chains can help ensure greater accountability among actors, including governmental and international bodies such as CODEX Alimentarius (that is, Food Code). Lastly, our review elicited several individual-level responses to environmental variability, such as suspending cultivation, migrating, seeking off-farm employment and selling assets (Table 1).

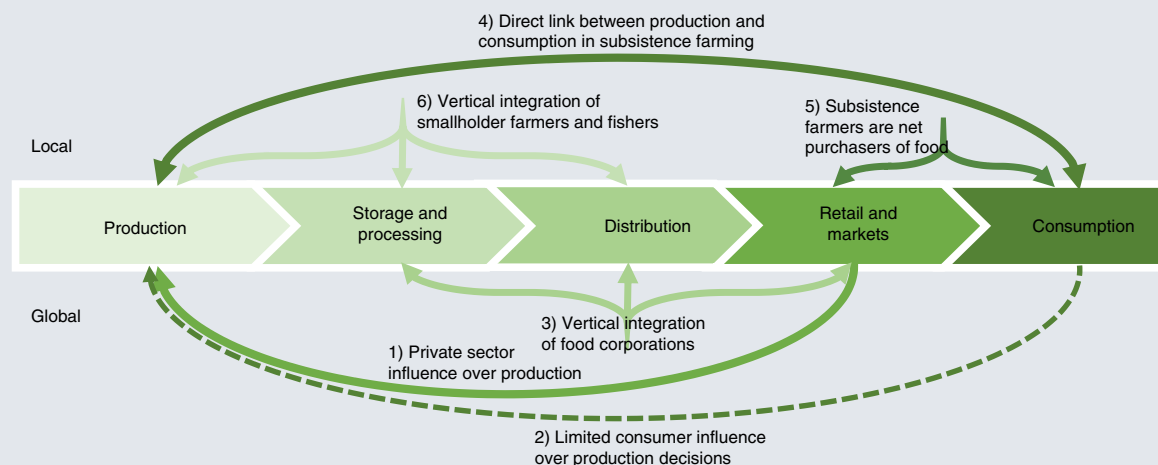
Increasing cohesion among supply chain actors will be necessary to support responses to growing environmental variability. Actors' different goals can create barriers to such responses, which is especially apparent for trade policy. Given the interconnected-

ness of global food systems, a government's policies to support (or thwart) trade can have important implications for their ability—and that of others—to respond to environmental variability⁸³. The private sector responds to variability within the constraints of the policy environment set forth by governments, and the extent to which a company is vertically integrated across multiple steps in a food supply chain also determines its suite of options in responding to environmental variability (Box 2). How governments and the World Trade Organization shape trade policies can restrict certain policy responses. For example, shocks are more readily transmitted to importing countries (and disproportionately so to low-income countries⁴⁷) owing to an intensification of international trade and changes in the distribution of cereal reserves⁴⁸. Countries at risk of experiencing these shocks can potentially respond by increasing their domestic reserves of cereal commodities or importing from a diverse set of suppliers. For exporting countries, embargoes can help maintain adequate domestic food supplies during times of

Box 2 | Feedbacks in the food supply chain

1) Private sector actors exercise substantial influence over the food options available for retail and thereby influence production decisions⁵³. These decisions can either enhance or hinder the resilience of production systems to environmental variability. 2) In more globalized food supply chains, the influence of consumer choice and purchasing on production decisions is limited, and there is therefore less individual control over exposure to remote environmental or economic shocks^{123,124}. 3) Food corporations are often vertically integrated across multiple steps of the supply chain^{68,69}. This can allow a more efficient response to an environmental disturbance (for example, through source switching) but can have serious implications both upstream (for example, promotion of specific varieties/species) and downstream (for example, fewer dietary options for consumers). 4) Subsistence agriculture directly links production and consumption¹⁰. On the basis of expected market prices, growing conditions and dietary needs, smallholders can exercise greater control over their production decisions and their exposure to environmental risk, provided that their food basket is nutritionally adequate and that they have sufficient information/forecasting for

on-field decisions^{76,77}. On one hand, farmers and fishers are afforded flexibility in responding to or anticipating environmental variability. On the other hand, should their adaptive production decisions be imperfect, these households may have fewer alternatives for dietary sourcing compared to more globally connected consumers. 5) Subsistence farmers and fishers are—in general—net purchasers of food and so are still exposed to disruptions in market access and fluctuations in food prices. This can lead to shifts in consumption¹². 6) Many smallholder farmers and fishers are vertically integrated in that they oversee the production, near-term storage and processing, and transport to local markets¹⁰. This exposes subsistence agriculture to multiple forms of environmental risk, the interventions to which can be capital intensive and beyond the financial capacity of individual smallholders⁷⁶. This can present challenges in the case of a ‘good year’ where farmers and fishers have a bumper year¹¹⁴. In this case, because storage capabilities are limited, local markets can be flooded with the supply of a particular food item, meaning that smallholders must settle for lower market prices and cannot fully capitalize on this increased production.



limited production; yet, hoarding and export bans may affect each country's resilience to environmental variability either positively or negatively, depending on the specific actions taken and the commodities targeted¹⁵. The Bali Package represents one recent effort to address this trade-distorting behaviour by which the World Trade Organization seeks to protect the policy space of governments to quickly enact trade strategies to better ensure domestic food security⁸⁴. It is possible that a similar approach can be taken to allow greater flexibility in responses to environmental variability as well.

Moving beyond food production shocks. Our current understanding of the various ways by which environmental variability affects (and propagates through) food systems is insufficient. Expanding our knowledge beyond a focus on production shocks for staple crops will be essential for enhancing the resilience and sustainability of food supply chains. By considering the various steps and interactions of food supply chains, different actors can more effectively develop targeted interventions to cope with environmental variability and avoid unintended consequences within food systems. In particular, adaptive strategies can be improved by understanding the shape and evolution of food supply chains, the potential for surprises and spillovers, and the risk of simultaneous and unprecedented shocks.

The shape and evolution of food supply chains have gradually evolved away from strong local interactions between producers and consumers towards greater complexity and distance. Over the past half-century, globalization and market consolidation have meant that power over global food system decisions has become concentrated^{43,85}. These trends of vertical integration and homogenization have had profound upstream and downstream effects that span supply chains (Box 2)—ranging from ecosystem impacts in areas of production^{68,86} to modified options for consumers^{87,88}—while the growing reliance of many countries on food imports has also left them increasingly vulnerable to shocks that occur beyond their borders^{45,46,89,90}. The increase in processed or multi-ingredient foods has also led to converging and diverging product streams that make it more difficult to link the sources of raw materials to an end product⁹¹. Taken together, such changes have also meant that an individual consumer interested in sustainable purchasing is able to exercise less control over the sourcing of their food and the exposure of their diet's production to environmental risk (Box 2)⁸⁵. Being able to trace food's passage through a supply chain not only ensures quality and sustainability standards but also allows governments to steer companies towards reliable and less vulnerable food supply decisions beyond economic incentives to do so. Substantial progress has been made to promote traceability in some

Table 1 | Potential responses to environmental variability across the supply chain (Continued)

Supply chain steps	Responses	Actors			Timescale			Evidence of use to address climate variability and shocks ^a									
		Individual Government	Private sector	IGOs, NGOs and so on	Short term to decadal	Seasonal	Long term	Floods	Drought	Salination	Extreme temperatures	ENSO and other oscillations	Disease and pests	Natural disasters	Price	Unspecified climate shock	
Storage and processing	Strategic reserves and food storage ^a	x			x			x								x	
	Investment in storage infrastructure (including cold storage)	x	x	x	x		x										
	Fortification of staples and processed foods	x	x	x	x		x										
	Investment in primary processing (for example, solar drying) ^b	x	x	x	x		x		x			x					
	Product reformulation of ultra-processed foods	x			x		x										
Distribution	Strengthen food safety standards	x	x	x	x		x										
	Trade and investment agreements, tariffs and sanctions	x	x	x	x		x										
	Sourcing regulation	x			x		x										
	Investment in road infrastructure	x					x										
	Vertical integration ^b				x		x					x					
Retail and markets	Promotion of alternative products	x			x		x										
	Changes to packaging (including smaller sizes and resistance to high temperatures)	x			x		x										
	Marketing	x			x		x										
	Investment in market infrastructure	x			x		x										
	Taxes and subsidies	x			x		x										
Consumption	Strengthen food safety standards	x	x	x	x		x										
	Behaviour change communication aimed at shifting consumption patterns	x			x		x										
	Social safety nets (for example, conditional cash transfers and so on) ^b	x			x		x										x
	Food supplementation and aid ^a	x			x		x					x					
	Micronutrient powders	x			x		x					x					
Behaviour change communication aimed at improving water, sanitation and hygiene practices	Behaviour change communication aimed at improving water, sanitation and hygiene practices	x			x		x										
	Dietary shifts ^a				x												x

^aA response identified through the scoping review. IGOs, intergovernmental organizations; NGOs, non-governmental organizations; CSOs, civil society organizations.

countries (for example, the UK, the Netherlands and Japan) and for selected products (for example, the livestock sector in Uruguay and dairy products in France and the UK); however, for most countries and food items, understanding the steps connecting producers and consumers remains a critical obstacle to enhancing the resilience and adaptability of food supply chains to short-term environmental variability⁹². To address this, a host of innovative approaches offer opportunities to enhance information-sharing capabilities⁹³, facilitate real-time responses to supply chain disruptions, couple environmental externalities with production⁹⁴, account for the challenges of monitoring and reporting across countries, and recognize the differences in supply chains between countries and across food items. Key corporate actors that are increasingly influential in the dynamics of food systems⁹⁵ can mobilize independent of governments to address food sustainability and resilience challenges and ultimately benefit from the outcomes^{96–98}.

Surprises and spillovers can result from environmental variability due to direct and indirect interactions throughout a supply chain, among different foods and across spatial and temporal scales³. Such unexpected events are typical of complex systems, and models fail to capture the range of possible behaviours or the emergent properties of many actors interacting. Actors' behavioural responses may differ within each specific disturbance context, including the prices of substitute foods, the broader economy and responses of other actors^{99,100}. Price spikes of an input to food production due to environmental variability can lead actors to substitute resource inputs or consumers to substitute food products, creating spillovers into other supply chains (Fig. 1).

Substitution depends on the availability and affordability of suitable substitutes and can affect production of foods with seemingly little connection. For example, fishmeal and fish oil are important ingredients for some farmed fish and livestock feeds. The vast majority of fishmeal and fish oil is produced along the west coast of South America, and catch is heavily influenced by El Niño conditions, leading to price fluctuations. While alternative feed ingredients are easily available for poultry feeds, there are few nutritionally equivalent alternatives available for some farmed fish, so fluctuations in the fishmeal-oriented fisheries have a greater spillover effect into aquaculture than poultry. While identifying past surprises and spillovers is an important step towards anticipating potential food system responses to environmental variability, such events are difficult to predict. Fostering general resilience through enhancing production and trade diversity, maintaining food reserves and production buffers, managing feedbacks within the food system and supporting leadership and trust at multiple levels^{101,102} offers a path towards maintaining food system function in the face of surprises.

Simultaneous and unprecedented shocks can pose novel risks to global food systems. Agricultural trade agreements have been based on the premise that a disruption in supply can be compensated by increased sourcing from non-impacted areas (and to a limited extent by strategic reserves for certain commodities^{103,104}). This paradigm, widely adopted by countries and corporations alike, assumes that shocks in one region occur independent of those in other places and will not be large enough to overwhelm the available pool of food supply and storage⁴⁸. Yet, evidence suggests that large-scale climate teleconnections^{105–107} as well as a changing climate and increasing variability¹⁰⁸ can lead to simultaneous and/or compounded^{109,110} impacts on crop production. For instance, rising temperatures are expected to increase the likelihood of simultaneous maize production losses in major production areas¹¹¹. Global climate oscillations significantly influence productivity in two-thirds of the world's croplands¹¹². Synchronized climate anomalies associated with the trans-Pacific El Niño/Southern Oscillation (ENSO) have led to concurrent influences on major crop yields in geographically distant regions¹¹³. These studies suggest that maintaining asynchrony and diversity in areas of food production and sourcing—combined with

food storage during bumper years—can limit instability in food supplies under increasing climatic and environmental variability¹¹⁴. These global teleconnections point to the possibility of coordinated risks that have yet to be adequately incorporated into climate-smart food security strategies. Examining the probability of synchronized extreme climate events and their linkages with agricultural output anomalies can better inform adaptive strategies of food supply chain actors¹¹⁵. More broadly, this scoping review points to a lack of investigation of numerous combinations of co-occurring environmental disruptions and the need to understand their effects on (and propagation through) food supply chains.

Conclusions

Our analysis shows that most research to date has focused on the associations between environmental variability and production. Although there is a growing body of evidence on the associations between environmental variability and nutrition outcomes, little research exists on the exact pathways by which these shocks influence nutrition. In some cases, we know that agriculture can influence nutrition outcomes through food production, income and women's empowerment pathways¹¹⁶, but these have not been adequately examined in the context of environmental variability. Moreover, it is unclear the extent to which environmental variability affects nutrition outcomes due to shifts towards poorer-quality diets and/or increased disease risk leading to disruptions in the absorption of nutrients in different contexts. Without this evidence, little can be done to identify the most appropriate responses to environmental variability.

Also, little research has examined the propagation of shocks through food supply chains and their subsequent effect on consumption. This limits our understanding of the true effects of environmental shocks on the food system as a whole and how local shocks can have global impacts (and vice versa). Given the interconnectedness of food systems, a shock that influences one step of the food supply chain will undoubtedly impact subsequent steps. Likewise, a shock in one country or region can have serious implications for another. As our global food systems become more integrated, understanding the dynamics of propagation across supply chains through empirical research is critical to inform adequate interventions.

Our assessment of coping strategies identified a suite of actions that various supply chain actors can adopt in preparation for or in response to environment variability. Our findings indicate that multiple strategies across the food system will be needed in response to environmental variability, but that our ability to identify the most appropriate package of strategies to adopt remains limited. Understanding the specific interventions that can be taken within a variety of contexts to dampen the effects and propagation of environmental variability along food supply chains is critical to link food systems research with actionable outcomes. Moreover, additional research is needed that examines the interaction between people and their food system in response to shocks; these interactions are probably multifaceted and can have important implications for food security, diets and nutritional outcomes.

Finally, increasingly complex and globalized supply chains are exposed to environmental variability and extreme events at multiple points, leading to the possibility of shock propagation, spillovers and simultaneous shock events. The literature on these types of event is relatively scarce, but insights from resilience literature point towards the importance of production and sourcing diversification and strengthening internal feedbacks for enhancing the resilience of the global food production system¹¹⁷. Although not an environmental shock, the COVID-19 pandemic has revealed how a shock in one country can have a ripple effect across the globe and how a single event can simultaneously impact multiple geographies and points along the supply chain. Such shocks can produce differential

effects on food availability (for example, unharvested fields due to reduced on-farm labour), physical (for example, restricted movement and transportation) and economic (for example, loss of livelihoods) access, and intake (for example, dietary shifts towards highly processed foods with an extended shelf life)^{15,16,118}. This underscores the urgent need to expand our understanding of shock events beyond their impacts on production, to minimize systemic risks and enhance the capacity to cope with future disruptions.

Methods

We conducted a systematic scoping review to examine the propagation of environmental shocks throughout food supply chains (Extended data Fig. 1). Scoping reviews apply a systematic approach to reviewing the literature to map the evidence on a given topic and identify the main concepts, theories and knowledge gaps¹¹⁹. Given the heterogeneity of the methods and disciplines that cover the literature on the propagation of environmental shocks through food supply chains, a scoping review was chosen as the most appropriate approach to summarize findings from the existing literature^{119–121}. We used the PRISMA checklist for scoping reviews to guide our methodological approach (Extended Data Table 1).

The scoping review was conducted in June 2019, with guidance from a medical librarian, using the Web of Science database and the following search terms: environmental variability (or climate variability, shock, propagation, weather, extreme event, disaster); crop (or food, livestock, fish); and production (or nutrition, food security, diet, access, availability, system, supply, trade, price transmission, price volatility). Our inclusion criteria included studies that: were published in English in 2008 or later (to capture articles published after the 2008 global food crisis); examined supply chains in the 1950s or later; measured an outcome that is directly part of the food system (for example, yield, catch, price, production, infrastructure, food quality and safety, and diets (nutrition through the diet pathway)); and focused specifically on an aspect of environmental variability (for example, disasters, temperature/precipitation/humidity extremes, disease or pest outbreaks, algal blooms and ENSO). We also included studies examining price shocks given that many of these shocks are related to environmental variability. We excluded books and book chapters as well as studies that solely assessed climate risks or vulnerability as well as those that examined the impacts of slow-moving climate on food supply chains. To ensure that our search was sufficiently sensitive to identify articles that met our inclusion criteria, we employed an iterative approach to refine the final search strategy. Specifically, we performed a first-iteration identification utilizing a set of initial search terms and examined whether known articles^{5,8,11,24,44–49,89,90,105,111} that met the inclusion criteria were retrieved. We then repeated the refinement of search terms until the search strategy captured all of the known articles that met our inclusion criteria. The exact search terms were coded in Web of Science as: (“climate varia*” OR “environment* varia*” OR “shock*” OR “propagat*” OR “weather” OR “extreme event*” OR “disaster*”) AND (“crop*” OR “livestock” OR “fish*” OR “food*”) AND (“production” OR “nutrition*” OR “security” OR “diet*” OR “access” OR “availability” OR “system” OR “supply” OR “trade” OR “price transmission” OR “price volatility”) NOT (“food web*”).

The records identified through our search ($n = 15,271$) were imported into R and any duplicates were removed. All three authors screened the titles and abstracts to assess whether they met our inclusion criteria. Two authors then independently reviewed all abstracts that met our inclusion criteria to verify the screening process. In the event that there was disagreement among the two authors, the third author was consulted and a decision on its inclusion was reached by consensus. We extracted data from articles in two stages: at the abstract and at the full-text review stage. We examined the abstracts that met our inclusion criteria to identify whether the study examined the food supply chain beyond production (that is, yields, productivity and production quality). If the study focused only on production, we extracted data related to the food/crops examined as well as the type of shock. At this stage, we also assessed whether the study solely focused on coping strategies. If the study focused on short-timescale (for example, within a growing season) or intermediate-timescale (for example, switching crops for the following season) coping strategies, we extracted data related to the coping strategies used at this stage as well. The studies that focused solely on coping strategies were then excluded from the full-text review, given that the focus of this paper is on the propagation of shocks across supply chains.

In the second stage of data extraction, we reviewed the full texts of the remaining articles that met our inclusion criteria ($n = 325$). If there was uncertainty regarding whether the study met our inclusion criteria on the basis of the full-text review, the authors jointly discussed the article and came to a consensus on its inclusion. Of the studies that met our inclusion criteria after the full-text review, we extracted information regarding the food/crops examined, the steps of the supply chain considered in the analysis, the type and year of the shock, whether there was propagation and information related to the study methods including the primary outcomes assessed and the study setting. The information extracted from the included studies allowed us to summarize the existing literature and identify gaps in the knowledge base. More specifically, we used the extracted data to quantitatively summarize the types of crop and environmental variability, the supply

chain step examined and evidence of propagation along the supply chain. Given the heterogeneity of the included studies, we complemented the quantitative data collection with examples from the included studies to contextualize our findings. All extracted data were recorded into an Excel spreadsheet. We first piloted the data extraction spreadsheet with a small number of articles and made necessary adjustments before completing the data extraction process. Once the extraction was completed, we reviewed the data to ensure that there was consistency in the coding of output variables (for example, crop name and type of environmental variability).

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The data that support the findings of this study are available on GitHub (<https://github.com/jagephart/enviro-shocks-review>). The full list of the 325 papers included in this review is provided in Supplementary Table 1.

Code availability

The code that supports the findings of this study is available on GitHub (<https://github.com/jagephart/enviro-shocks-review>).

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Author contributions

All authors contributed equally to the study. K.F.D., S.D. and J.A.G. designed and performed the research, analysed the data and wrote the paper.

Competing interests

The authors declare no competing interests.

Additional information

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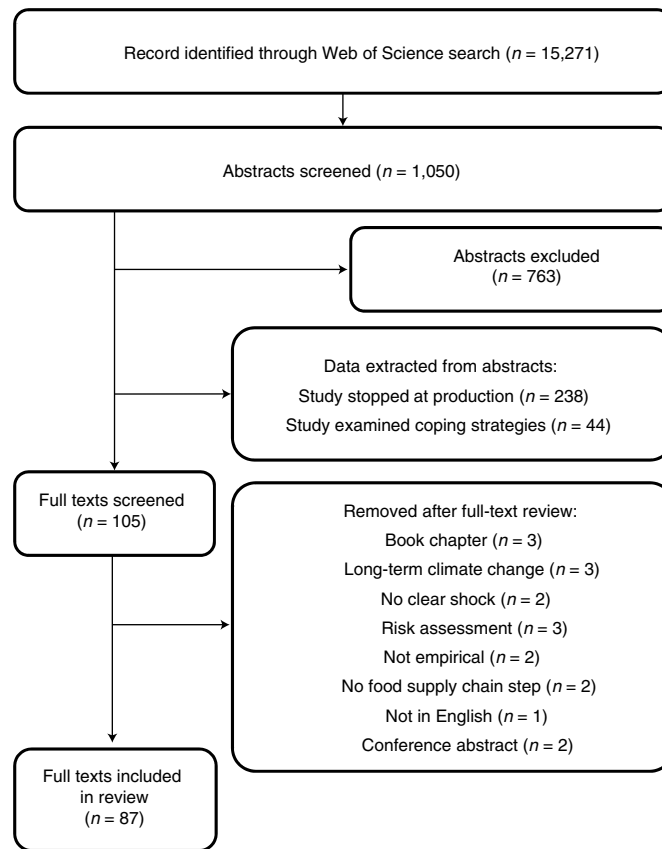
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Extended Data Fig. 1 | A diagram of the steps in the scoping review. Each step indicates the number of studies identified in parentheses.

Extended Data Table 1 | Adherence to PRISMA-ScR scoping review checklist¹¹⁹; inclusion of each item within our systematic scoping review is indicated with a Yes (Y), No (N), or Not applicable (N/A)

Section	PRISMA-ScR Checklist item	Included
TITLE		
Title	Identify the report as a scoping review.	N
ABSTRACT		
Structured summary	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	N/A
INTRODUCTION		
Rationale	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	Y
Objectives	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	Y
METHODS		
Protocol and registration	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	N
Eligibility criteria	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	Y
Information sources*	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	Y
Search	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	Y
Selection of sources of evidence†	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	Y
Data charting process‡	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	Y
Data items	List and define all variables for which data were sought and any assumptions and simplifications made.	Y
Critical appraisal of individual sources of evidence§	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	N/A
Synthesis of results	Describe the methods of handling and summarizing the data that were charted.	Y
RESULTS		
Selection of sources of evidence	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Y
Characteristics of sources of evidence	For each source of evidence, present characteristics for which data were charted and provide the citations.	Y
Critical appraisal within sources of evidence	If done, present data on critical appraisal of included sources of evidence (see item 12).	N/A
Results of individual sources of evidence	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	Y
Synthesis of results	Summarize and/or present the charting results as they relate to the review questions and objectives.	Y
DISCUSSION		
Summary of evidence	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	Y
Limitations	Discuss the limitations of the scoping review process.	Y
Conclusions	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	Y
FUNDING		
Funding	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	N/A

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