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Food production shocks across land and sea

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Sudden losses to food production (that is, shocks) and their consequences across land and sea pose cumulative threats to global sustainability. We conducted an integrated assessment of global production data from crop, livestock, aquaculture and fisheries sectors over 53 years to understand how shocks occurring in one food sector can create diverse and linked challenges among others. We show that some regions are shock hotspots, exposed frequently to shocks across multiple sectors. Critically, shock frequency has increased through time on land and sea at a global scale. Geopolitical and extreme-weather events were the main shock drivers identified, but with considerable differences across sectors. We illustrate how social and ecological drivers, influenced by the dynamics of the food system, can spill over multiple food sectors and create synchronous challenges or trade-offs among terrestrial and aquatic systems. In a more shock-prone and interconnected world, bold food policy and social protection mechanisms that help people anticipate, cope with and recover from losses will be central to sustainability.

Food production shocks pose significant challenges for the United Nations Sustainable Development Goals (SDGs)[1] because of their potential to disrupt food supply and security, livelihoods, and human well-being[2–7]. A wide range of social and ecological pressures on food systems can drive shocks through direct or indirect mechanisms. For example, droughts or floods can rapidly increase the mortality of crops, livestock or farmed fish, whereas sudden outbreaks of violent conflict may prevent farmers or fishers from accessing their production systems[7,8]. Prolonged overfishing can also produce unexpected, sudden losses in catch as exploited fish populations are pushed towards ecological tipping points, after which stock collapse occurs[9]. People's vulnerability to shock events rests on their capacity to adapt, the scale and frequency of shocks, and their dependence on the affected sector[10]. Given that millions of people worldwide simultaneously depend on agricultural and seafood sectors for food and livelihood[11,12], understanding national vulnerabilities to shocks requires a complete picture of exposure across sectors on land and at sea. Yet, studies on food production shocks to date largely deal with agricultural and seafood commodities in isolation[2,7,13]. Integrated understanding is required to assess the cumulative risks to sustainability across all food sectors in the face of environmental change and human population growth.

We investigated historical global trends in exposure to, and drivers of, food production shocks across crop, livestock, fisheries and aquaculture sectors from 1961–2013. We used an established, standardized approach to identify shocks and their drivers in national production data taken from the United Nations Food and Agricultural Organization (FAO) and other published sources. Using local regression models, we identified shocks through breaks in the autocorrelation structure of a time-series, and coupled detection with a literature review of in-country events at the shock point. Here, we map global shock frequency and co-occurrence, and highlight the different ways shocks can permeate multiple food production sectors or drive trade-offs across them.

Global trends in food production shocks

From 741 available food production time-series (crops = 187; livestock = 190; fisheries = 202; aquaculture = 162), we detected 226 shocks across 134 nations. When pooled, we found agricultural sectors (crop and livestock) to be slightly more shock prone than aquatic sectors (fisheries and aquaculture) over the 53-year period (0.31 versus 0.29 shocks per country, respectively). Shock frequencies were regionally distinct within sectors, with some areas experiencing shocks far more frequently than others (Fig. 1). Shock frequencies were highest in South Asia for crops (Fig. 1a), the Caribbean for livestock (Fig. 1b), Eastern Europe for fisheries (Fig. 1c) and South America for aquaculture (Fig. 1d). Importantly, some regions experienced a high frequency in more than one sector. For example, South Asia experienced one of the highest shock frequencies to livestock as well as crops, and the Caribbean experienced a high frequency of fisheries shocks alongside livestock systems. Therefore, while there is varying exposure to production shocks within sectors, in several regions, patterns of high shock frequency overlap and create areas of high cumulative exposure to production shocks across multiple fronts.

The frequency of shocks has increased across all sectors at a global scale. In our results, annual shock frequencies fluctuated considerably over time, yet decadal averages, minimums and maximums increased steadily from the 1960s and 1970s (Fig. 1e–h). We did not detect any shocks to aquaculture production until the early 1980s, probably due to its nascence, but decadal shock rates have risen faster and to a level higher than in any other sector since (Fig. 1h). Increasing shock frequency is a food security concern in itself. Conflict-related shocks across sub-Saharan Africa and the Middle East since 2010, combined with adverse climate conditions, are responsible for the first uptick in global hunger in recent times[4]. While the human impact of shocks depends on the degree to which livelihoods in a region or country depend on food production and the variation in vulnerability among households[4], increased

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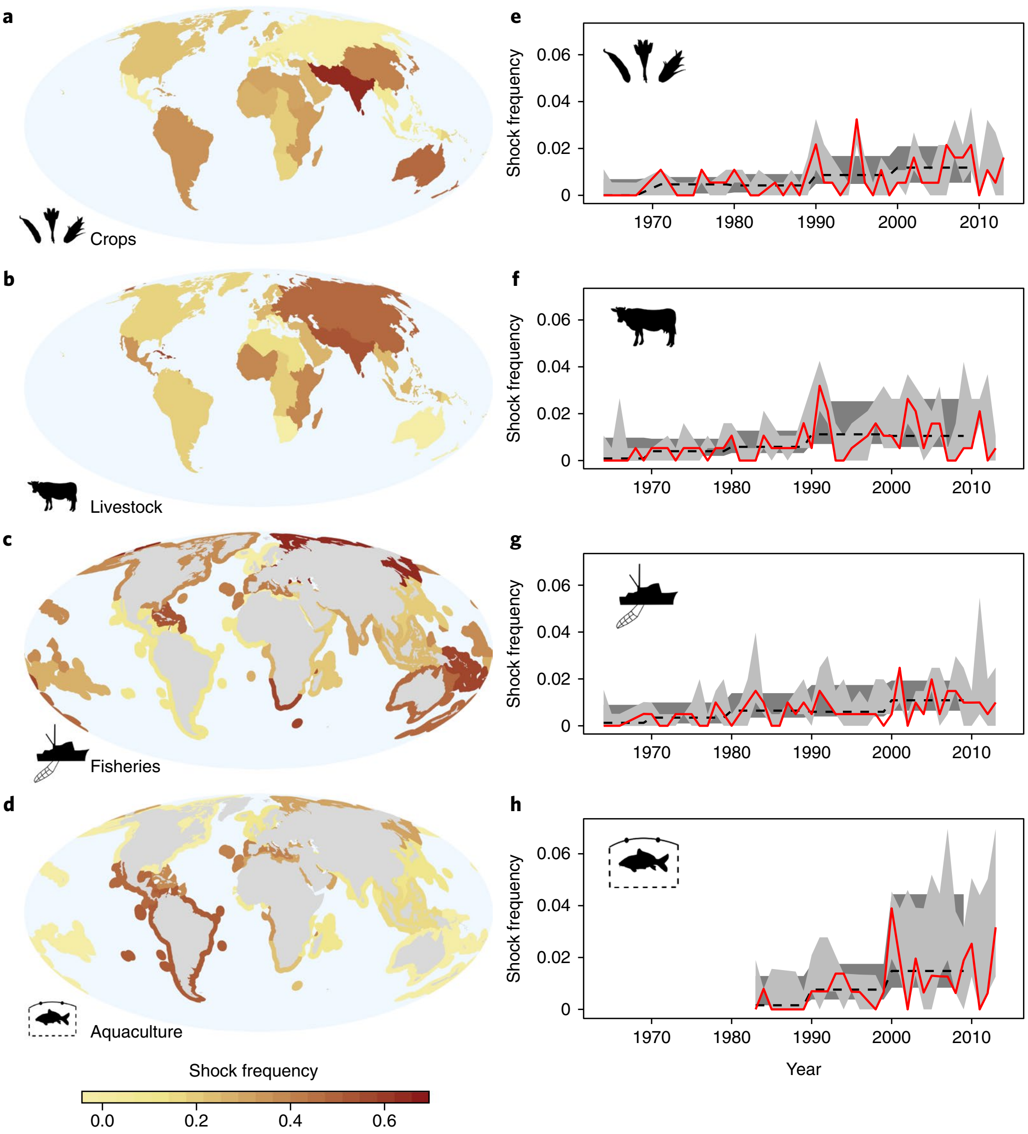

Fig. 1 | Trends in food production shock frequency in crop, livestock, fisheries and aquaculture sectors from 1961–2013. a–h, Spatial (**a–d**) and temporal (**e–h**) trends for crops (**a** and **e**), livestock (**b** and **f**), fisheries (**c** and **g**) and aquaculture (**d** and **h**). Regions include North America, Central America, the Caribbean, South America, Northern Europe, Western Europe, Southern Europe, Eastern Europe, North Africa, West Africa, Central Africa, Southern Africa, East Africa, Western Asia, South Asia, East Asia, Southeast Asia, Melanesia, Micronesia, Australia and New Zealand, and Polynesia. The red lines in the time-series indicate the annual shock frequency from the shocks identified in this study. The light grey confidence interval describes the plausible range of frequencies under different combinations of LOESS model span (0.2–0.8), production baseline durations (3, 5, 7 or 9 years) and types of averaging used for the baseline (mean or median). The dashed black line is the decadal mean of the red line. The dark grey band is the decadal minimum and maximum of the confidence interval.

frequency reduces the time for recovery between events. Smaller windows for recovery hinder coping strategies, such as the accumulation of assets that can be sold during times of hardship, and can ultimately negatively influence the resilience of producers and communities to shocks[4].

Drivers of production shocks across land and sea

Extreme weather events and geopolitical crises were the dominant drivers of shocks in our analysis, but the relative importance of drivers varied across sectors (Fig. 2). Over half of all shocks to crop production systems were a result of extreme weather events (largely drought; Fig. 2), reinforcing concern about the vulnerability of arable systems to climatic and meteorological volatility across the globe[14]. We also found extreme weather to be a major driver of shocks to livestock (23%), particularly where reductions to feed occurred. For instance, severe summertime droughts in Mongolia in 2001 and 2010 reduced fodder and feed availability, compromized livestock condition and led to mass mortality events during cold winter extremes[15]. Diseases such as foot and mouth also contributed to 10% of livestock shocks. However, geopolitical crises, such as economic decentralization in Europe or conflict in sub-Saharan Africa, accounted for the greatest proportion (41%) of the livestock shocks in our analysis (Fig. 2).

In contrast, drivers of seafood production shocks were more diverse than for terrestrial systems (Fig. 2). For fisheries, overfishing was responsible, at least in part, for 45% of shocks detected in landings data. However, geopolitical crises contributed to 23% of fisheries shocks, climate/weather events to 13% and policy changes to 11%. Shocks driven by policy changes can reflect positive interventions, but may also be a response to declining resources. In the

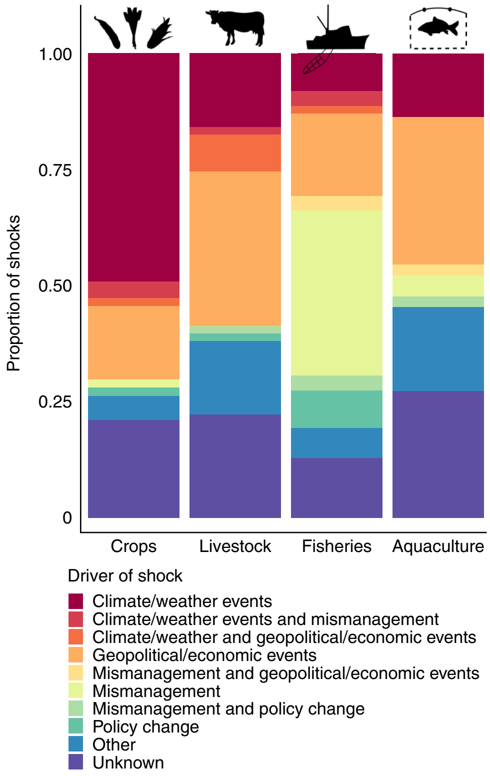

Fig. 2 | Drivers of food production shocks. Relative proportions for the drivers indicated in the legend are shown for the crop, livestock, fisheries and aquaculture sectors.

aquaculture sector, while disease (included in the category 'other') was the most common individual driver (responsible for 16% of shocks overall), a spectrum of geopolitical stressors was behind one-third of aquaculture shocks, from state dissolution to violent conflict and declining competitiveness in export markets.

Patterns of driver influence differed across regions (Supplementary Fig. 1). For example, in South Asia, where agricultural shocks were most frequent, nearly all crop and livestock losses were driven by flood or drought. In contrast, in sub-Saharan Africa, where the greatest burden of hunger still persists[4], geopolitical and economic crises were the leading drivers of agricultural shocks (Supplementary Fig. 1). In seafood sectors, the regional diversity of driver types was more consistent. In wild systems, overfishing and geopolitical drivers contributed to numerous shocks across Europe, sub-Saharan Africa and East Asia. For aquaculture, disease was the primary driver in Europe and Latin America, but geopolitical instability was the main driver of shocks to aquaculture in East Asia, the Middle East and North Africa (Supplementary Fig. 1). Therefore, while we highlight dominant shock drivers for each sector at a global scale, we reiterate that challenges for increasing food production will vary greatly from place to place.

The reason for the increase in shock frequency through time across sectors is not clear, in part because many potential factors (including the quality of reporting) have changed and increased over the time period. However, crop production shocks driven by extreme weather became more frequent in our results over time (Supplementary Fig. 2). In the livestock, fisheries and aquaculture sectors particularly, the diversity of drivers increased from the 1970s (Supplementary Fig. 2). As food systems become increasingly globalized and interdependent, a greater diversity of exogenous shocks may influence them over time[16]. For instance, livestock disease is increasing globally, driven largely by a rapid rise in the demand for meat, the incursion of livestock in natural systems, intense farming practices, and the mass movement of animals and people[17]. The nature of interdependencies among sectors is also changing[18]. Demands for feed now tightly couple aquaculture to both capture fisheries and crop systems[19], and the production challenges each of these encounter are therefore closely linked. Furthermore, financial institutions motivated by socioeconomic drivers disconnected from their geographies of influence increasingly sway producer investments and decisions with complex or unknown consequences for production stability or sustainability[20].

Co-occurrence and spillover across terrestrial and aquatic sectors

Climate events, violent conflict or other social and ecological stressors can create complex synchronous or lagged effects across different systems[4]. Therefore, a single stressor could elicit numerous shocks across different food sectors but not always at the same time. So, while we would not necessarily expect shocks from the same stressor to coincide at the exact shock point (year), we would expect to see clumping of shocks within broader time-periods. Co-occurrence appeared in our data from the early 1990s, and more frequently in the latter half of our time-series (Fig. 3a). Of the 134 nations affected by shocks in our analysis, 22 experienced shocks in multiple sectors during the same five-year period (Fig. 3b). We recognize that these trends are influenced by the length of the time intervals used in Fig. 3 and do not reflect changes in other sectors not detected as a shock (although they may be a response or a driver of shocks detected here). Overlapping shock occurrence in this way allows us to identify and further examine the more detailed conditions underpinning the occurrence of multi-sectoral shocks.

Shocks spanning multiple sectors were often driven by geopolitical events. For example, the loss of Soviet-linked subsidies and reduced export markets in Albania during the fall of communism resulted in large declines in crop, fisheries and aquaculture production[21–23]. North Korea experienced lagged impacts from economic fall-out from the Union of Soviet Socialist Republics dissolution by the mid-1990s, and extreme flooding exacerbated the scale of production losses on land. The resulting famine led to the deaths of over 200,000 people[24,25]. In Mali, internal conflict from 2011 onwards displaced farmers and fishermen alike by limiting access to rivers and farms directly, or through disruption to supply chains[26]. Nonetheless, the geography of the shock, magnitude of the driver, importance of the affected systems for national production, and adaptive (for example, coping strategies), absorptive (for example, reserves, assets and capital) or transformative capacities (for example, governance mechanisms)[4] of affected communities will all influence how a shock manifests across different food systems. Taking further examples from Fig. 3, we illustrate how the social-ecological dynamics of both the country and the shock can yield variable responses across sectors (Fig. 4).

Drivers of shocks can create similar or opposing responses in production across multiple sectors, revealing links between terrestrial and aquatic systems. In both Kuwait (Fig. 4a) and Afghanistan (Fig. 4b), different shock drivers at different scales created similar national-level responses spanning terrestrial and aquatic production. The invasion of Kuwait by Iraq in late 1990 and the subsequent conflict with the United States and its allies was a huge nationwide disturbance, caused widespread devastation to agricultural land, and the removal of the majority of Kuwaiti fishing vessels ceased commercial fishing[27]. Rapid declines in crop, livestock and fisheries production occurred from 1990, with shocks detected in both livestock and fisheries time-series (Fig. 4a). In Afghanistan, a severe drought from 2000–2002 decimated cereal production, particularly in the country's north. Large increases in animal diseases and reduced fodder severely affected production for pastoralists[28], and we detected a shock to fisheries landings at the same point (Fig. 4b). However, the similar declines across sectors disguise the differences

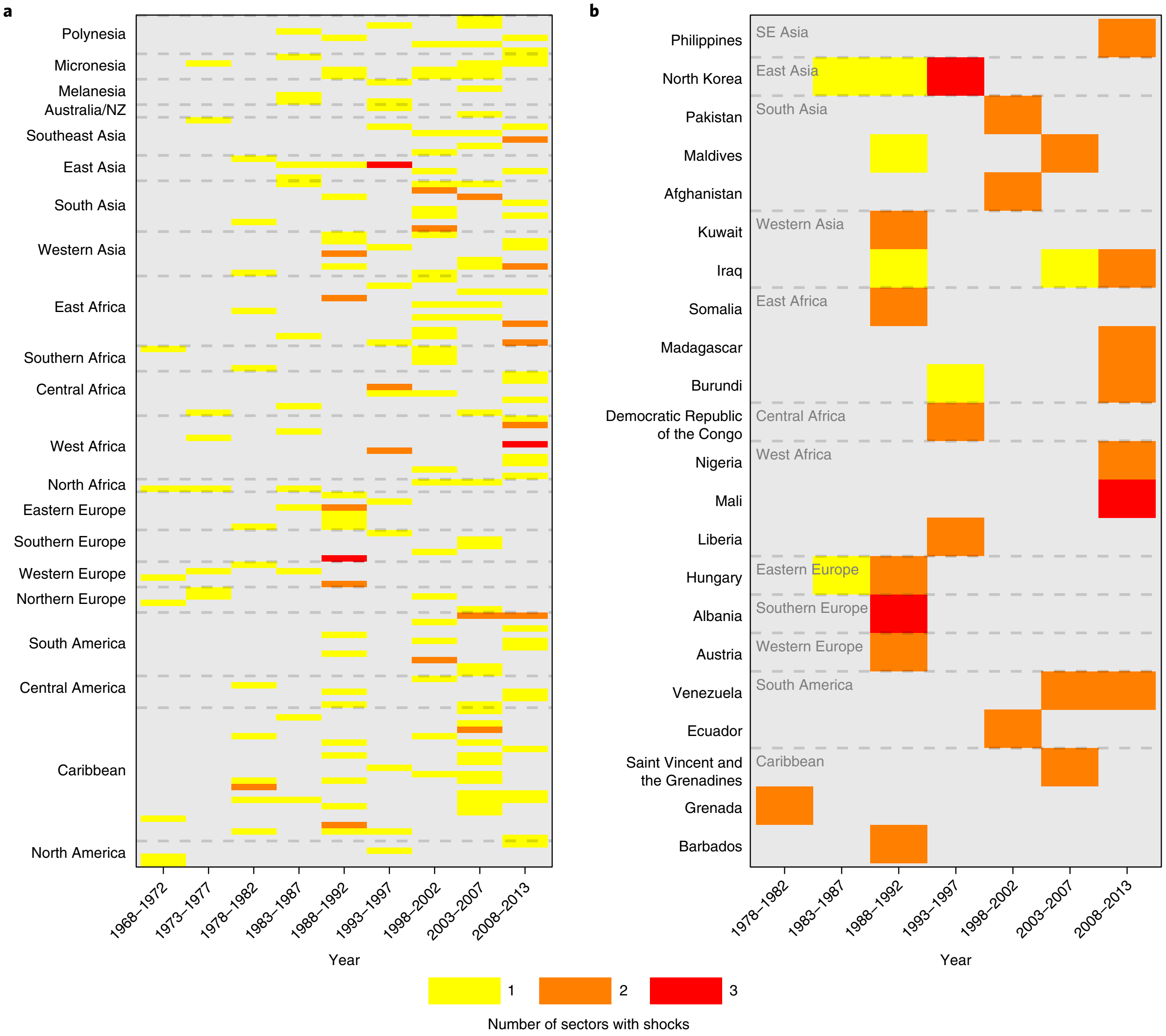

Fig. 3 | Heat map of shock co-occurrence across terrestrial and aquatic food sectors through time. **a**, Global extent of co-occurrence in all countries affected by shocks in our analysis, grouped by subregion. NZ, New Zealand. **b**, Isolated countries where shocks occurred across multiple sectors during the same five-year period.

in vulnerability. Disturbances at the scale of the Gulf War are rare events, whereas droughts are frequent across Western Asia. In Afghanistan, its landlockedness and the absence of marine fisheries leaves national food production more vulnerable to drought.

In contrast, divergent responses to extreme weather in Dominica illustrate the potential for land–sea trade-offs when human adaptation measures shift resource use across sectors. Repeated damage to farmland from tropical storms during the 1970s pushed more of the nation's farmers into fishing for a primary income source[29]. After Hurricane David decimated the banana crop in 1979, fisheries landings increased dramatically from 1980, followed by a rapid decline in 1983 (Fig. 4c), probably driven by overfishing leading to stock collapse in nearshore waters[29]. Shifts between land and sea following a shock were rare in our analysis of national time-series. It is possible that Dominica's small size and high dependence on a single crop for livelihoods of the rural poor (who have few absorptive strategies for coping with crises)[30] contributed to this response. However, it is likely that these switches occur much more widely at smaller scales, given the prevalence of joint dependence on fisheries and agriculture worldwide[11], and because small-scale fisheries are often used to buffer the effects of extreme events[31].

In Ecuador, shocks occurred at similar points in both crop and aquaculture systems, with seemingly unrelated proximate drivers if investigated solely from single-sector perspectives (Fig. 4d). The strong El Niño Southern Oscillation event of 1998 led to widespread flood damage to croplands across Ecuador[32], detected as a shock in our time-series, and at the same time, a large reduction in coastal fisheries landings occurred (Fig. 4d), although this was not detected as a shock due to the variable nature of the Humboldt system[2]. While there were reports of flood damages to shrimp farms in 1998, two years later, we detected a shock to aquaculture production because of dramatic declines in the shrimp industry. These declines are consistent with the reports of a white-spot syndrome outbreak, which severely affected the industry in 2000[33]. We could

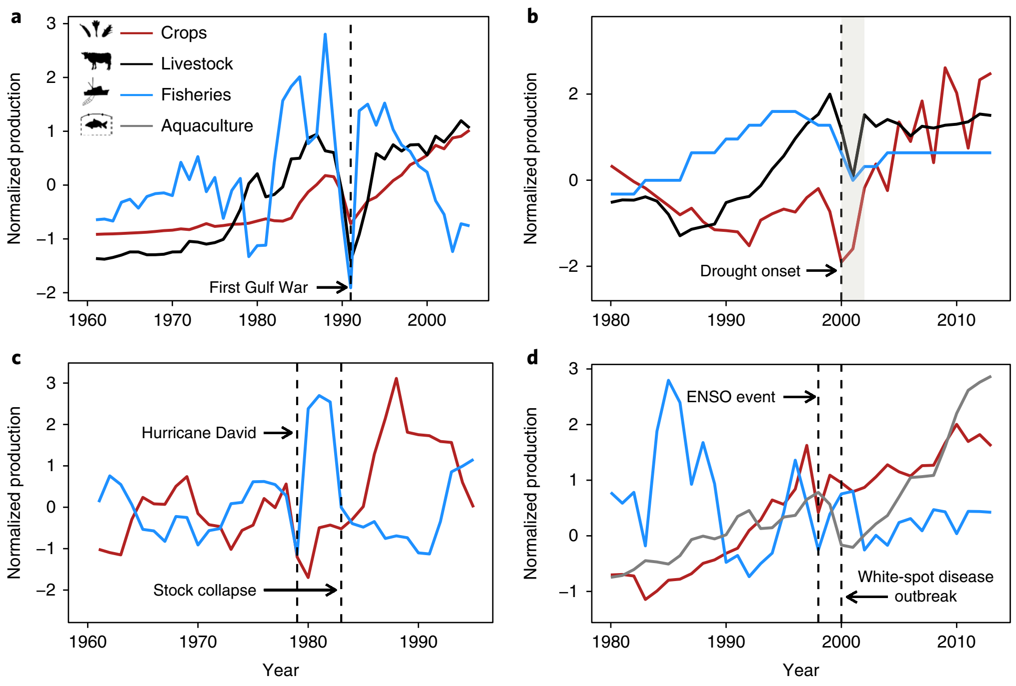

Fig. 4 | Case studies of shock spillover, trade-offs, and co-occurrence across terrestrial and aquatic sectors. a, Invasion of Kuwait during the Gulf War. **b**, Severe drought in Afghanistan. **c**, Land–sea switches following Hurricane David in Dominica. **d**, El Niño-driven floods on land followed by an outbreak of white-spot disease in shrimp farms in Ecuador. ENSO, El Niño Southern Oscillation.

find no documented link between the El Niño event and the disease outbreak; however, abnormally warm coastal waters on the Pacific South American coast are associated with both El Niño events and the rapid spread of the white-spot Syndrome virus[34]. Irrespective of whether these shocks were connected or not, an increased co-occurrence because of linked or independent drivers becomes problematic for communities with a reduced capacity to deal with these dual impacts.

Challenges and potential for sustainable development in a shock-prone world

Shocks across multiple sectors pose significant threats to improving global food security, as well as other sustainability targets. For example, one target within SDG 2 (zero hunger) is to strengthen adaptive capacity in the face of climate change and extreme events[1]. For many people, livelihood diversification between agriculture and fisheries is a key strategy in alleviating the impacts of production shortfalls[11,35,36], yet shocks across multiple sectors compromise these options. A lack of viable alternatives can drive people to derive food or income from other sources, with unpredictable sustainability consequences. The declines in large mammal populations in West Africa during times of low fish supply or after the collapse of agricultural systems in the Soviet Union are clear examples[37,38]. Trade-offs such as this across sectors, including the example from Dominica (Fig. 4c), present significant challenges for achieving other sustainability targets. Unpredictable shifts among sectors create interactions among the goals for life on land, life below water, or responsible production and consumption[1], for instance. Furthermore, as shock rates increase across all sectors, the capacity for shocks to co-occur increases simultaneously.

On a global scale, increased shock frequency may pose a threat to the resilience of the global food system through impacts on trade. Nearly one-quarter of food, agricultural land and freshwater resources are accessed through trade[6], and a number of countries are dependent on imports to meet the food demands of their population[39]. Trade dependency is also becoming more regionally specialized, with some major breadbaskets the sole suppliers of commodities to other nations. For example, Thailand currently provides over 96% of rice imports to a number of West African countries[40]. The high dependence on just a handful of producers for some countries highlights future vulnerability. Producing countries often reduce or ban exports during production crises to protect domestic supply, endangering import-dependent trade partners[5,6,39,40]. If shock frequencies continue to increase and major producing nations are affected, a shift to a state of reduced exports is plausible at a global level. Increased commodity prices linked to global scarcity would favour higher-paying nations[40], leaving low-income, trade-dependent countries in jeopardy. In the case that a higher frequency of shocks is influencing the stability of trade, we might expect to see increased temporal variability in either trade or price data. Whether or not these signals are present in the available data warrants further investigation.

Country-level differences in vulnerability to external or domestic production shocks mean that the challenges posed by them are uneven across regions and commodities. For example, frequent shocks in small Caribbean livestock sectors will have variable consequences across the different regional economies, yet a shock in major producers such as Argentina may influence supply for multiple trade partners around the world[41]. Comparing across commodities, frequent or severe crop shocks in major breadbaskets such as South Asia can have far-reaching consequences for global food availability and access[5], but relatively small shocks to fish landings in small-island developing states may have equally negative effects on nutrition[12,42]. The diverse sources of threat across land and sea from domestic or foreign sources highlights a pressing need to improve resilience to shocks in both agricultural and seafood sectors.

Building resilience at a global level will require more proactive national food and trade policies. Investing in climate-smart food systems that exploit ecosystem services to mitigate extreme -events will be increasingly important[43]. For instance, increasing the diversity of plant and animal breeds/varieties can minimize vulnerability to disease; integrating agroforestry into farm systems and enhancing soil quality can improve recovery times after drought and floods[3,43]. Concerted efforts should be made in import-dependent countries to build domestic food reserves to buffer the effects of supply losses when trade partners reduce exports during production shocks[6]. Moreover, international trade policies should aim to disincentivize behaviours that exacerbate the impacts of production shocks, such as commodity hoarding and export bans. Such policy is especially important for major food producers, such as the USA, India or China, whose trade networks have greater global influence on food supply[6]. Maintaining fair and open trade should be made a priority in addressing global hunger.

In shock-prone areas, a number of social protection mechanisms will be key. These mechanisms may help nations, communities and households prevent and anticipate shocks, cope with them and recover[4]. For example, conflict-related shocks remain the biggest barrier to food security in the world's most food-insecure regions[4,7]. Greater understanding of the causes of conflict in different areas is central to prevention[4]. New early-warning systems for violence are already underway[44]. During times of crisis, timely food and cash transfers, and food or cash for work programmes, show promise throughout sub-Saharan Africa[45]. For those displaced, to speed up recovery and close yield gaps, participatory planning and post-conflict support, such as tools, seeds or skills training, is crucial[4,46]. Weather-indexed insurance is another innovative tool to protect producers against loss of income or food access during adverse conditions[47], and will be particularly important if extreme events become more frequent[48].

Increased investment in food systems research to improve resilience to shocks is urgently required under climate change. Continued development of drought and pest-related resistance in key crops is crucial[49], but understanding and addressing barriers to uptake in food-insecure countries is equally important[50]. The same applies where fish farming could increase resilience to external shocks in vulnerable nations[42], but barriers that limit industry growth must be overcome. In commercial-scale aquaculture systems, improvements in open data and new sequencing technologies can help us understand the microbial conditions surrounding disease emergence, which is fundamental to meeting increasing global seafood demands[51]. Without learning to mitigate and adapt to the effects of increased volatility in food systems, global goals to end hunger and protect our natural ecosystems may be out of reach.

The trends discussed here almost certainly under-represent the frequency of production shocks. Aggregation of production data to the country level smooths out sudden production losses that are locally isolated or restricted to a single food type. This is particularly true in large countries, such as the United States or Australia, where food is grown over large and diverse landscapes. Small-scale, unreported food systems (for example, some inland and marine fisheries or aquaculture, backyard farm systems and wild meat sources) are also not included in the data used in this analysis. Although this is a recognized weakness, the data used here represent the best source of production data with global coverage across multiple sectors. Nevertheless, localized shocks or shocks to small-scale systems are still of concern for the livelihoods and food security of communities dependent on them.

Achieving the SDGs by 2030 will require addressing drivers of food production shocks and derived threats. With shock frequency increasing across sectors, the likelihood of shock co-occurrence increases, particularly in hotspots of shock exposure. Production challenges will be felt most strongly by those with a lower capacity to adapt to or absorb shocks. With extreme weather events predicted to increase into the future, potentially interacting with civil unrest, achieving food security in regions most exposed to shocks may hinge on successful social protection mechanisms to help people cope and recover. Fundamental shifts towards shock-resilient food systems will require considerable but achievable changes to how we grow and trade food. Integrating and understanding the links between land and sea will be critical for programmes and research aiming to affect progress towards food security and sustainable development.

Methods

To identify and compare shock occurrence among fundamentally different systems (agriculture and seafood), we adopted the paired statistical and qualitative approach of Gephart et al.[2]. This method identifies shocks through breaks in the autocorrelation structure of a time-series and combines this with a literature search for the probable driver of the shock. Alternative studies have used pre-published datasets on extreme events to understand responses in production data[31]; however, this skews the focus towards drivers with plentiful data—often terrestrial and biophysical events, such as floods, droughts or cold fronts. Others have also used the trade in virtual water to study shocks in agricultural systems[13], but this largely eliminates the marine component of our food system. Reliance on statistical detection in production data avoids specificity, making it a standardized approach applicable across crop, livestock, fisheries and aquaculture sectors.

Data sources. We used a range of food production data from the FAO, combined with published production datasets, for our analysis. We used crop and livestock data from the FAOSTAT production quantity 1961–2014 dataset (http://www.fao.org/faostat/en/)[52]. Crop types included cereals, coarse grains, fruits, roots and tubers, pulses, tree nuts, and vegetables. Livestock included total meat, milk and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO FishStat database[53] for inland and marine aquaculture production, and inland fisheries landings data (the 1950–2015 Global Production dataset: www.fao.org/fishery/topic/166235/en). We used marine fish landings data from Watson[54] to account for estimates of large-scale, small-scale, and illegal, unregulated and unreported landings. Fisheries data included all landed finfish, crustaceans and molluscs. Aquaculture data included all farmed finfish, crustaceans, molluscs and algae. While we recognize that the under-reporting of small-scale production across all sectors is a limitation of the FAO data, they provide global coverage of production across multiple sectors, and the detection of shocks relies on overall trends in data rather than absolute production values. We obtained country shapefiles used for mapping global patterns from Natural Earth (https://www.naturalearthdata.com/), and adapted exclusive economic zone shapefiles from Marine Regions (http://www.marineregions.org/)[55]. We performed all data analyses using R statistical software[56].

Detecting shocks and identifying drivers. For all countries, we aggregated production to total annual values from 1961–2013 across all of the commodity types described above for crop, livestock, fisheries and aquaculture sectors. We fitted local polynomial regression (LOESS) models with a span of 0.6 to aggregated annual production data for all countries and sectors. We regressed model residuals against lag-1 residuals, and we deemed any outliers in this regression (quantified as data points with a Cook's distance of >0.3) to be shocks (Supplementary Fig. 4). Given that only production losses are of concern for food security, we only considered shock points associated with a loss in production relative to a previous 7-year median production baseline.

Consistent with the approach by Gephart et al.[2], for each shock detected, we calculated the size of a shock and its recovery time for comparisons across sectors and regions (Supplementary Fig. 1). The shock size equals the loss in production (in tonnes) relative to the previous 7-year median baseline. The recovery time for the shock was calculated as the number of years taken to increase back to at least 95% of this baseline. Some shocks did not recover by the end of the time-series and we highlight these individual shocks in Supplementary Table 1. We calculated shock frequencies for each geographical region by dividing the number of shocks detected from 1961–2013 by the number of time-series used for detection. For annual shock frequencies, for every sector, we divided the number of shocks detected for a given year by the number of countries producing in that year. This approach compensates for different numbers of countries within each region, and the increasing number of countries producing through time.

Adopting a qualitative approach to identifying the drivers of production shocks helps account for and recognize the multiple and complex social and ecological factors contributing to an event. For a detected shock, we searched peer-reviewed and grey literature (for example, NGO reports, news articles, and so on) for the probable causes, or drivers, of each individual shock. Each shock was assessed independently, disaggregating production data into individual commodities to identify the species affected and check our analysis, which allowed greater specificity to our search. We only attributed a driver to a shock when our search returned a documented event or set of conditions where a negative effect on agricultural or seafood sectors (dependent on the sector affected) was explicitly mentioned at, or just before, the shock point (that is, the documentation stipulated the link rather than us establishing purely correlative trends). The combination of quantitative and qualitative methods adopted by Gephart et al.[2] provides complimentary approaches where purely data-driven methods may highlight correlative relationships with drivers without causation.

Likewise, purely qualitative analyses may be limited in their capacity to detect shocks because of differences in reporting across regions. We caution that this approach is not meant to provide a comprehensive list of contributing factors for a given shock within the data, but instead highlights the potential drivers of change from the literature we identify. It is plausible that other unidentified factors contribute to the changes seen in the data.

In our analysis, we classify drivers of shocks into five main categories. Climate/weather events include anomalies such as storms, droughts, El Niño Southern Oscillation events or climate-driven ecosystem change. Geopolitical/economic events include disturbances from conflict, state dissolution or financial crises. Mismanagement includes multiple categories, such as overfishing in the ocean, or deforestation and erosion of soils on land. Policy change can refer to, for example, closure of a fishery or abolition of agricultural subsidies. The 'other' category includes a wide range of pressures from production diseases to geological events, such as tsunamis or volcanic eruptions. Due to the complex nature of social and ecological stressors on food systems, we combined many of these categories to explain the drivers of production shocks and highlight these subcategories. The Unknown category contains shocks for which we could not find a documented reason. It is possible that our statistical approach to detection means we identify changes to national reporting methods as a shock. This highlights the importance of the complimentary quantitative and qualitative approaches used here to identify whether a statistical anomaly in production data is reflected by conditions or events reported in reality[2].

We do, however, acknowledge that some of the detected production losses may not be completely unanticipated. Some production losses driven by economic recession or policy changes may be expected by producers. However, to what extent the production losses detected here were anticipated is unclear because of data scarcity. Policy responses to dwindling resources can certainly produce shocks to food supply and livelihoods, as exemplified in the closure of, and subsequent anger surrounding, the North-West Atlantic cod fishery in 1993[57]. However, even if an event is anticipated, the scale of disruption may be unknown (the uncertainty surrounding the economic impacts of the United Kingdom leaving the European Union is a contemporary example). While the uncertainty surrounding whether a statistical shock in production data equates to a shock in reality is a limitation, this method does allow non-biased detection of shocks caused by drivers for which there are scant data (for example, sudden declines from fish stock collapse). Although sensitivity analyses of Cook's distance, LOESS span or production baseline parameters provided confidence intervals, we may not have detected all of the shocks (Supplementary Fig. 3). Furthermore, the shock detection method described here is less sensitive to production changes in highly variable systems where large fluctuations are common within the time-series[2].

Data availability

Crop and livestock production data were accessed through FAOSTAT (http://www.fao.org/faostat/en/). For marine fisheries production, we used the published dataset by Watson[54] at https://www.nature.com/articles/sdata201739. Aquaculture and inland fisheries data were extracted from global production datasets using FishStat software (www.fao.org/fishery/topic/166235/en). All code and data products used for analyses in this study are publicly available through a GitHub repository (https://github.com/cottrellr/shocks). All data that support this study are available from the corresponding author on request.

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Author contributions

R.S.C., J.L.B., K.L.N. and B.S.H. designed the study. R.S.C. conducted the analysis and wrote the paper. T.A.R. assisted with the figures. A.J. assisted with qualitative analysis of shock drivers. All authors contributed to development of the paper through methodological advice, comments and edits of the text and figures.

Competing interests

The authors declare no competing interests.

Additional information

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