**Food production shocks across land and sea**

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**Abstract** (150)

Sudden and unpredictable losses, or ‘shocks’, to food production can endanger national food supply and negatively affect multiple aspects of local food security. Understanding which food sectors are more shock-prone, where and why, can therefore inform wider discussion on strategies for food-system development and resilience. We investigate historical trends in the size, frequency, recovery time, and drivers of production shocks across land and sea. We show political instability and extreme weather to be the dominant causes of shocks on land, disease in aquaculture and overfishing in wild fisheries the primary drivers in aquatic systems. Geopolitical crises, such as conflict, tended to produce bigger shocks and longer recovery times than other shock types. Further, single external stressors, including extreme-weather events, can reach across multiple food sectors, creating complex adaptation challenges during crises. Critically, we highlight increasing shock rates across all production sectors, posing questions for global food system resilience.

**Main** (3500)

Abrupt and unexpected declines in food production, defined here as shocks, pose a significant challenge for achieving zero hunger because of their potential to disrupt food supply1,2. Exposure, sensitivity and capacity to adapt to such production losses determine a food systems’ vulnerability to shocks across local, regional and national scales3,4. Combined differences in these three aspects of vulnerability mean the consequences of production shocks can vary considerably among regions and through time. The huge contrasts in loss of life and livelihood during severe droughts across Sub-Saharan Africa compared to developed and shock-prone countries such as Australia, provide stark examples5–7. Beyond reducing domestic production, shocks can also influence food availability, access and stability indirectly by propagating through trade-networks8, driving rapid price changes6,9, or posing recurrent barriers to economic development and investment at a national scale5,10–12. Production shocks have a number of possible causes, and understanding which food sectors are more shock-prone, which regions experience more shocks, and why will be fundamental to developing effective food system policy into the future.

Understanding global patterns in both terrestrial and aquatic shocks and their drivers is critical in building a complete picture of exposure to production crises. Given differences in national dependence on agriculture and fisheries worldwide13,14, and the suite of interactions between them15, integrating land and sea can illuminate both multisector threats and opportunities for improving food system resilience under global change. Yet studies on food production shocks to date deal largely with agricultural and seafood commodities in isolation1,2,10,16

Here we present global trends in shock exposure and drivers for national crop, livestock, capture fisheries (herein fisheries) and aquaculture sectors from 1961 – 2013. We use three metrics to describe exposure; shock frequency, shock size, and recovery time (duration of perturbation)4. We define shock frequency as the number of shocks detected divided by the number of national production time series used for detection over either space or time. We calculate shock size as the production loss relative to the previous 7-year production average (based on sensitivity analysis, see Methods). Recovery time describes the number of years taken to recover from the shock point to at least 95% of the previous production average. We employ a statistical approach to shock detection applicable across terrestrial and aquatic systems by fitting local regression models to production time series and identifying outliers in the regression between residuals and lag-1 residuals from model fit (see Figure S1). We combine this quantitative detection method with a literature search for causes of each production shock to balance limitations in data availability and reporting biases over different regions1.

***Trends in food production shocks and their drivers***

From 741 available time series (crops = 187, livestock = 190, fisheries = 202, aquaculture = 162) we detected 216 production shocks. We compare shock exposure indices across eight geographical regions (Latin America and Caribbean, North America, Europe and Central Asia, Middle East and North Africa, Sub-Saharan Africa, South Asia, East Asia, and Oceania). For most sectors, shock frequencies were regionally distinct, with some areas experiencing shocks far more frequently than others over the 53-year period **(Figure 1).** For example, shock frequencies in crop and livestock systems in South Asia were higher than any other region in both sectors (**Figure 1a, b).** Shock rates in fisheries were more globally homogenous **(Figure 1c)**, whereas in the aquaculture sector, Latin America and the Caribbean sustained the highest frequency of shocks, 1.3 – 3.4 times higher than other regions **(Figure 1d)**.

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**Figure 1 – Shock frequency across geographical regions for crop, livestock, fisheries and aquaculture sectors from 1961 – 2013.** Shock frequency calculated as total number of shocks detected in a region divided by the number of national time series analysed from the region. Regions include North America, Latin America and Caribbean, Europe and Central Asia, Middle East and North Africa, Sub-Saharan Africa, South Asia, East Asia, and Oceania.

We classify the causes, or drivers, of shocks into five main categories. *Climate/weather events* include anomalies such as storms, droughts, ENSO events, or climate-driven ecosystem change. *Geopolitical/economic events* covers 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 to prevent collapse 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 (see supplementary informationfor full breakdown). Due to the complex nature of social-ecological stressors on food systems, reports of multiple drivers leading to production shocks were common. Therefore, we combine a number of these categories to explain the causes of food production shocks, and highlight these sub-categories in **Figure 2.** The Unknown category contains shocks for which we could not find a documented reason. One potential source for these may be that our purely statistical approach to detection means that we identified changes to national reporting methods as a shock. The complimentary quantitative and qualitative approaches taken should minimize the number of such false positives in our analysis1.

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**Figure 2 – Drivers of food production shocks for crop, livestock, fisheries and aquaculture sectors.**

Extreme weather events and geopolitical crises were the dominant drivers of agricultural shocks **(Figure 2)**. Over half of all shocks to crop production systems were a result of extreme weather events **(Figure 2)**, largely drought, reinforcing the concern about vulnerability of arable systems to climatic and meteorological volatility across the globe17. We also found extreme weather to be a major driver of shocks to livestock production (31%), particularly where reductions to feed occurred. For instance, severe summertime droughts in Mongolia in 2001 and 2010 reduced fodder and feed availability, compromised livestock condition, and led to mass mortality events during cold winter extremes18. Geopolitical crises, however, such as economic decentralisation in Europe or conflict in Sub-Saharan Africa, accounted for the greatest proportion (46%) of the livestock shocks in our analysis **(Figure 2)**.

In contrast, the causes of seafood production shocks were more diverse than for terrestrial systems, particularly in aquaculture **(Figure 2).** While disease (included in ‘*Other*’ category) was the most common individual driver, responsible for 16% of shocks overall, a spectrum of geopolitical stressors were behind a third of aquaculture shocks, from the break-up of the Soviet Union, to violent conflict in the Congo, and declining competitiveness in export markets 19–21.For wild fisheries, overfishing was responsible, at least in part, for 45% of shocks detected in landings data. Nevertheless, geopolitical crises contributed to 21% of fisheries shocks, climate/weather events to 13% and policy changes to 11%. Shocks caused by policy changes can reflect positive interventions, but may also be a response to declining resources.

The number of shocks with unknown causes was greater in fisheries and aquaculture production than crop or livestock. This may be due to a combination of reporting biases. First, greater research attention is paid to agriculture than to seafood sectors from a food security perspective22 and thus food production crises are better documented. Second, the majority of shocks with unknown drivers occurred in countries of medium, low or unclassified human development status. In low-income countries, low management and governance capacity limit governmental knowledge of the resource-base 23, and therefore reliable reporting. Consequently, there are likely to be more instances where sudden declines in production go undocumented, particularly in small-scale aquaculture systems. Third, the statistical presence of a shock does not necessarily translate to a food supply crisis. Where quantity of fisheries or aquaculture production is small, production losses may pose little threat to food security and go unreported. Of the aquaculture shocks of unknown cause, all amounted to less than 0.05% of total domestic food production that year.

Geographical patterns in the size of shocks were similar across sectors. Intuitively, the largest shocks tended to occur in regions where large-scale production exists, such as East Asia and Europe, with agricultural and aquaculture shocks in Oceania smaller on average (**Figure 3a,c**). In contrast, the size of fisheries shocks were relatively uniform across regions (**Figure 3e**). Median recovery times tended to be similar across regions for all sectors at 1-5 years. However, many shocks took far longer to recover (range 1-16 years for full recovery), representing step rather than point changes in production1. Indeed, numerous shocks did not recover during the study period even after 40 years, and recovery times shown represent the number of years between the shock point and the end of the time series. We present relative frequencies of shocks that did not recover among regions and sectors in **Figure S2.**

Beyond *where* it occurs, the size of a production shock seems to depend to an extent on the driver type. While the biggest shocks did not necessarily correspond to the longest recovery times, both the largest shocks and the slowest recovery times were associated with geopolitical events in all sectors (**Figure 3)**. The largest shock detected in crop production was in Nigeria in 2009 – a result of violent conflict in rural areas causing unsafe working conditions for farmers and disrupted access to fertilisers, herbicides and seeds24 (**Figure 3a**). For livestock, fisheries and aquaculture sectors, the largest shocks were a result of the fall of communism in Eastern Europe. In East Germany, the breakdown of central planning across member states within the Council for Mutual Economic Assistance meant export markets for meat and dairy were lost, and German consumers started demanding western products. The subsequent decreases in demand dropped producer prices and so livestock production fell away25 (**Figure 3c**). In the former USSR, fisheries landings dropped precipitously as the Soviet Union collapsed, oil subsidies for distant water fleets ceased and years of overexploitation in coastal waters left a depleted resource for domestic use1 (**Figure 3e**). In North Korea, the cessation of subsidised agricultural inputs such as oil, fertiliser and steel from the Soviet bloc sent all food sectors into swift decline26 and produced the largest shock to aquaculture production detected in our analysis (**Figure 3g**). The multisector impacts of this trade reduction combined with extreme events on land resulted in a severe famine across North Korea26.



**Figure 3 – Shock size, recovery time and drivers across geographical regions for crop (a,b), livestock (c,d), fisheries (e,f) and aquaculture (g,h) sectors.** Shock sizes (a,c,e,g) and recovery times (b,d,f,h) plotted across regions with colour of points associated with categories of shock drivers. LACa = Latin America and Caribbean, EuCA = Europe and Central Asia, MENA = Middle East and North Africa, SSA = Sub-Saharan Africa. Country labels represent the largest shocks and the shocks with the longest recovery times for each sector.

The shocks with the longest recovery times, across all sectors, highlight step changes in production that resulted from mismanagement or prohibitive geopolitical/ economic conditions (**Figure 3,b,d,f,h**). For example, urban expansion and salinization of groundwater in Bahrain has limited production since the 1980s leading to dramatic declines in agricultural output27. Environmental volatility and the low profitability of agricultural livelihoods in Guam led to the abandonment of farms across the territory, causing the collapse of livestock production in the late 1980s28. While poor economic conditions during the transition to a market-based economy in Hungary halved aquaculture production during the 1980s, undermining recovery for decades19. In fisheries, severe and persistent overfishing in the North Sea led to declines in a number of fish stocks since the 1970s leading to the longest recovery time in the sector29,30.

In theory, recovery times from shocks have the capacity to provide insight into regional differences into food system resilience, that is the rate the system returns to its previous state after a perturbation31. Systems of low resilience tend to take longer to recover to their previous state31,32. We found recovery times from shocks were longer on average in the Europe and Central Asia region for livestock, fisheries and aquaculture, and in East Asia for crop production (**Figure 3b,d,f,h)**. However, it is not clear whether these differences exist because of *when* these shocks occur (i.e., general system resilience to similar shocks may be changing through time) and/or *why* they occur (i.e., specific resilience to one shock type may be different to another, particularly across regions). As different shock-types may have more or less damaging consequences for national economies and food security, understanding temporal patterns in the occurrence at a global level is important to establish any systemic threat to food production.

We find annual shock frequencies fluctuated considerably over time for each sector, yet in our results decadal averages, minima and maxima increased steadily since the 1960s and 70s (**Figure 4a**,**c,e,g**). We did not detect any shocks to aquaculture production until the early 1980s likely due to its nascence before this, but decadal shock rates have risen faster and to a level higher than in any other sector since **(Figure 4g)**.

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**Figure 4 – Temporal trends in shock frequency and drivers in global crop (a,b), livestock (c,d), fisheries (e,f) and aquaculture (g,h) production from 1961 – 2013.** Annual shock frequencies calculated as total number of shocks in a sector divided by the total number of producing countries in a given year. Red line describes the annual shock frequency from the shocks identified in this study. Light grey confidence interval around the red line describes the plausible range of annual shock frequencies under different combinations of LOESS model span (0.2-0.8), production baseline durations (3,5,7, or 9 years) and production average types (mean or median). Dashed black line is the decadal mean of shock and the dark grey band is the decadal minima and maxima of the confidence interval. Shock drivers described in bar plots correspond to baseline model from plots above, with light-grey dashed line representing decadal diversity of shock types. Diversity indices are limited to 1970 – 2010 to ensure consistent temporal comparisons.

The reason for the increase in shock frequency across all sectors is not clear, in part because many potential factors have changed and increased over the time period**.** In crop systems, shocks caused by extreme weather (largely drought) became more frequent in our results over time (**Figure 4b**). Additionally, as food systems become increasingly globalized and interdependent, a greater diversity of exogenous shocks may influence them over time 33. For instance, livestock disease is increasing globally, driven largely by a rapid rise in demand for meat, the incursion of livestock in natural systems, intense farming practices and the mass movement of animals and people34. The nature of interdependencies among sectors are also changing. Demands for feed now tightly couple aquaculture to both capture fisheries and crop systems35, and the production challenges each of these encounter. 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 sustainability36. This theory is supported by the greater diversity of shock types in the 2000s compared to the 1970s in livestock, fisheries and aquaculture **(Figure 4b,d,f,h).** Nevertheless, it is possible that increased reliability of data reporting since the 1960s may also contribute to this trend.

On a global scale, increased shock frequency may pose a threat to the resilience of the global food system. Nearly a quarter of food, agricultural land, and freshwater resources are accessed through trade8 and a number of countries are dependent on imports to meet the food demands of their population37. 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 countries38. 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 partners8,9,37,38. If shock frequencies continue to increase and major producing nations are affected, a shift to a state of reduced exports is plausible. Increased commodity prices linked to increased global scarcity would favor higher paying nations38, leaving low-income, trade-dependent countries in jeopardy. Whether or not early-warning signals of these changes occur in trade or price data warrants further investigation to help predict any temporal changes to global food system resilience.

***Adapting to food production shocks across land and sea***

Adapting to a greater frequency of shocks in our food system will hold different meaning across various sectors and regions. The retrospective trends described here are consistent with current threats to agricultural supply from political instability and extreme weather. Internalized conflicts have increased in Sub-Saharan Africa and the Middle East since 2010 and are responsible, combined with adverse climate conditions, for the first uptick in global hunger in recent times11. Building resilience in conflict affected zones will require multi-faceted efforts to help nations and households prevent, anticipate, cope with and recover from shocks11. Greater understanding of the proximate and ultimate causes of conflict in different areas will be central to prevention11. Development of novel early-warning systems for violence are already underway39. A number of social protection instruments may become increasingly important as coping mechanisms in conflict zones. Timely food and cash transfers, and food or cash for work programmes during times of crisis show promise throughout Sub-Saharan Africa40. Participatory planning with, and post-conflict support for, those displaced such as provisioning of tools, seeds or skills training will be crucial in building faster recovery times and closing yield gaps11,41. Weather-indexed insurance is another innovative tool that may help protect farmers against income or food access losses during adverse conditions42, and will be particularly important if predictions of even more frequent extreme events are further realized43.

Protective measures need to extend beyond agriculture, however; as the threat from war and climate shocks are not restricted to a single sector but can reach across agricultural and seafood sectors. In Mali, the escalation of violent rebellions in 2012 displaced over 150,000 people, producing shocks to crop and fish production alike24. Similarly, in Afghanistan a severe drought from 2000 – 2002 decimated cereal production, grain feed for livestock, and rangeland pastures44 and a significant shock to inland fisheries occurred simultaneously **(Figure 5a).** Given the dual importance of both fishing and farming to many of the world’s most food insecure people, social and economic policies must start to recognize the interacting role of aquatic and agricultural commodities13.



**Figure 5** – **Food production shocks can bridge agriculture and seafood sectors. a**. Drought in Afghanistan from 2000-2002 (shaded area) causes sizeable production losses across agriculture and inland fisheries. **b**. Crash in Dominica’s banana crop following Hurricane David in 1979 precedes spike in marine fish landings and stock collapse 4 years later. Dashed vertical lines highlight the shock driver.

There is also a pressing need to better understand the extent and sustainability consequences of livelihood switches among sectors during food shortages. For example, times of fish scarcity in West Africa are known to drive increased bushmeat hunting45, and upturns in unregulated fishing occurred in Somalia as terrestrial systems failed in the early 1990s15. Responses to agricultural shocks in Dominica further illustrate the potential for land-sea trade-offs. Repeated damage to farmland from tropical storms during the 1970s pushed more of the nation’s farmers into fishing for a primary income source46. After Hurricane David decimated the banana crop in 1979, fisheries landings increased dramatically from 1980, followed by a stock crash in the early 1980s **(Figure 5b),** likely driven by overfishing in nearshore waters46. The unpredictable transmission of human impacts across sectors during crises pose challenges for global sustainability goals such as the 2030 Sustainability Agenda or Aichi biodiversity targets which remain sector specific in their focus. Understanding how and why communities react to production crises beyond trade at the national level, remains an element of sustainability research with scant information.

For some countries, transitioning to a greater dependence on marine resources may be an attractive option for avoiding volatility in terrestrial production. Given the stagnation in global fisheries landings, the burden of meeting future seafood demands will fall on aquaculture, which now provides over half of global production47. Aquaculture diseases remain a significant issue48, however, representing the largest single driver of aquaculture shocks in our analysis. Domestication of broodstock has been a major step forward in reducing disease transmission, but industry focus on only a few major species in multiple locations has left cultured animals naïve to native pathogens49. Open data and new sequencing technologies are also helping, both by further understanding of the complex microbial trophic structures surrounding disease emergence in pond cultures 48, and by accelerating the production of diverse genetic lines and pathogen resistance (which complements the growth in emergency vaccine development and more rapid intervention). Understanding vulnerability of feeds under climate change will be an increasingly important aspect of research for the sector too. As aquaculture relies on both agriculture and fisheries for inputs35, volatility in production of feed ingredients will be an important step in building resilience for the sector.

Despite the growing global importance of aquaculture, only 20 countries produce 96% of total production15, largely in freshwater, meaning capture-based fish production will remain the most important source of local animal protein in many countries (especially in Oceania where animal husbandry and aquaculture potential are limited)14,50. Given persistent historic patterns of widespread overfishing 51 and the likelihood that climate change will alter productivity of reef-based fisheries, policy and funding for infrastructure changes will be required to see proportionally more of the valuable returns on investment from pelagic species diverted toward subsistence and local food security50.

Trends discussed here will almost certainly underrepresent the frequency of production shocks due to aggregation of production data at the country level. Sudden production losses may be locally isolated or restricted to a single food type but are still of concern for livelihoods and food security in affected communities. Summing across commodity types tends to smooth out shocks to single food items – particularly in North America where food is grown over such a large and diverse landscape. Given the influence of different parameters used here on our ability to detect shocks, we suggest the results presented here are a representative sample of shocks across land and sea **(Figure S3)**. Further, 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 (**Table S1**)1. While variable production has consequences for food supply and security, in a system where large fluctuations are common, we do not consider them shocks. Moreover, while shocks remain a significant barrier to food security in many regions, this method does not account for gradual declines in food production such as those expected under other climate change pressures, which may be more damaging overall. Finally, we limit our analysis to the role of exogenous stressors on food systems. To what extent any of the shocks identified here are caused by inherent internal vulnerabilities within the food system (e.g. low crop diversity) is unclear.

**Conclusions**

Achieving zero hunger by 2030 will require addressing the underlying causes of shocks to food production. Political instability and extreme weather conditions have been the dominant causes of agricultural shocks since 1960, and both factors remain a source of significant disturbance in regions where the highest burden of hunger persists. With adverse weather predicted to increase into the future, potentially interacting with civil unrest, achieving food security in the most exposed regions may hinge on successful social protection mechanisms to help people cope and recover.

Meanwhile improving availability and access to seafood for a growing global population will require significant advances in aquaculture disease prediction and management, which remains a significant hurdle for the sector. In fisheries-dependent nations, bold domestic and international policy changes that prioritise food security over revenue may be the only mechanisms for sustainably diversifying and increasing fish supply from wild sources. Whether or not increasing shock frequency at a global level across all sectors is threatening the resilience of trade-linked food systems also requires closer examination.

**Methods (3000)**

To identify and compare shock occurrence among fundamentally different systems (agriculture and seafood), we adopt and extend the statistical approach of Gephart et al.1. This method identifies shocks through breaks in the autocorrelation structure of a food production time-series rather than using sector specific indices, making it a standardized approach applicable across crop, livestock, fisheries, and aquaculture sectors. We apply it to a range of data from the UN’s Food and Agricultural Organization (FAO) combined with published datasets.

***Data Sources***

We used crop and livestock data from FAOSTAT production quantity dataset 1961 – 2014 dataset (<http://www.fao.org/faostat/en/>). Crop types included cereals, coarse grains, fruits, roots and tubers, pulses, tree nuts and vegetables; while livestock included total non-indigenous and indigenous meat, milk, and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO FishStat database for inland and marine aquaculture production, and inland fisheries landings data (1950 – 2015 Global Production dataset, [www.fao.org/fishery/topic/166235/en](http://www.fao.org/fishery/topic/166235/en).). We used marine fisheries data from Watson (2017) to account for estimates of large-scale, small-scale and illegal, unregulated, and unreported (IUU) landings. Fisheries data included all landed finfish, crustaceans, and molluscs. Aquaculture data included all farmed finfish, crustaceans, molluscs and algae. While we recognize that underreporting of small-scale production across all sectors is a limitation of FAO data, it provides global coverage of production across multiple sectors, and the detection of shocks relies on overall trends in data rather than absolute production values.

***Detecting and quantifying production shocks and drivers***

For all countries we aggregated production to total annual values from 1961 – 2013 across all 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 any outliers in this regression (quantified as data points with a Cook’s distance > 0.3), we deemed shocks (**Figure S1**). Given 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. We calculated the size of a shock as the loss in production relative to this baseline, and recovery time for the shock as the number of years taken to increase back up to at least 95% of this baseline. 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. We used this approach to compensate for different numbers of countries within each region or the increasing number of countries producing each year.

Given production shocks may be the result of multiple social-ecological drivers interacting in complex manners, we adopt a qualitative approach to understanding them, searching peer-reviewed and grey literature (e.g. NGO reports, news articles etc.) for causes of each individual shock. The combination of quantitative and qualitative methods provide 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.

***Sensitivity analyses of parameters***

The sensitivity of the detection method outlined above depends on the values for a number of parameters used including LOESS model span, Cook’s distance threshold, duration of the production baseline, and the average type used (i.e. mean or median). This becomes particularly important when looking at temporal trends in shock frequency and understanding how sensitive these trends are to changes in each parameter.

To establish a reasonable combination of parameters that allow us to account for uncertainty in shock detection, particularly in temporal analyses, we constructed a confidence interval of shock frequencies over time. We ran the shock detection analysis using a range of values for LOESS span (0.2 – 0.8, by 0.1), duration used for production baseline average (3, 5, 7, and 9 years) and average type (mean or median). The minimum and maximum of annual shock frequencies produced by changing these parameters yielded a plausible range of shock frequencies over time. To select the combination to apply to our analysis of shock size, frequency, recovery times, and drivers, we identified the combination that minimised the sum of squared residuals with the mean of this range through time. This combination was a LOESS span of 0.6, and 7-year median production baseline (**Figure S3**).

To determine a Cook’s distance value to use for identifying outliers in all analyses, we tested the number of shocks detected against incremental changes to Cook’s distance values between two very different rules of thumb (1 and 4/(n-k-1)). The value of 0.3 is the point in this relationship, reasonable across all sectors, where the number of shocks detected begins to asymptote. This is very similar to the value used by Gephart et al 1 and is robust to changes in LOESS model span, baseline duration and average type (**Figure S4**). Note we conducted sensitivity analysis of Cook’s distance values separately as we wanted to optimise sensitivity within practical bounds for this study rather than simply selecting a central value.

***Effect of time series variability and shock size***

We conducted power analysis of the shock detection method across time series of different variance structures as per Gephart et al1. To do this we fitted autoregressive integrated moving average models (ARIMA) models to each national time series for all sectors and selected the most common and parsimonious model specification (ARIMA 0,1,0) across all sectors, determined by corrected Akaike’s Information Criterion. Using ARIMA (0,1,0) models, we simulated production time series using a range of variance structures (standard deviations from 0.1 – 1) and imposed different shock sizes (0 – 6) to each simulation. We applied the shock detection approach described above to each simulation and repeated this 1000 times for each shock size /standard deviation combination. As Gephart et al 1 found in their study, the sensitivity of shock detection decreases for a given shock size as the embedded variance in a time series increases. Further, across all values of time series standard deviation, larger shocks are more frequently detected **(Table S1).**  Type I error rates were very low, with shocks hardly ever detected when no shock was imposed **(Table S1)**.

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**Author contributions**

RSC, JLB, KLN, and BSH designed the study, and RSC conducted the analysis and wrote the paper. EAF, AF, RAW, and SH contributed to developing the paper through practical approaches for analyses and ideas for necessary conceptual inclusions. TAR and SPC assisted with refining the methods surrounding sensitivity analyses and AJ assisted with qualitative analysis of shock drivers. All authors contributed to development of the paper through comments and edits of the text and figures.

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**Figure S1 - Statistical shock detection method. a.** Local polynomial regression (LOESS) model fitted to food production time-series **b.** Regression of model residuals against lag-1 residuals **c.** Production shock in 1991 identified as outlier from regression in b using Cook’s Distance measures

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**Figure S2 – Proportion of shocks recovered or not during study period in crops, livestock, fisheries and aquaculture sectors across geographic region.**



**Figure S3 – Shock frequency through time across all sectors for a range of parameter combinations.** Light grey confidence interval represents range of plausible shock frequencies dependent on span, baseline and average type used in shock detection. Dashed black line is mean of the confidence interval frequencies. Solid red line represents parameter combination that minimizes the sum of squared residuals with the confidence interval mean (parameters selected for this analysis).

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**Figure S4– Comparisons of number of shocks detected in crop, livestock, fisheries and aquaculture time series with incremental changes to Cook’s distance values.** Lines represent either the combination of model parameters used in this study (‘Selected Model’, LOESS span = 0.6, production baseline = 7 years and average type used = median), or repeated with changes to model span, production baseline or average type.

**Table S1 – Proportion of imposed shocks detected in simulated time series for different time series standard deviations and shock size combinations.**

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | Standard deviation | | | | | | | | | |
|  |  | **0.1** | **0.2** | **0.3** | **0.4** | **0.5** | **0.6** | **0.7** | **0.8** | **0.9** | **1** |
| Magnitude | **0** | 0.003 | 0.001 | 0.001 | 0.001 | 0.003 | 0.001 | 0.002 | 0.001 | 0.001 | 0.003 |
| **0.5** | 0.82 | 0.159 | 0.043 | 0.023 | 0.018 | 0.012 | 0.006 | 0.006 | 0.006 | 0.006 |
| **1** | 1 | 0.805 | 0.345 | 0.161 | 0.061 | 0.036 | 0.018 | 0.017 | 0.008 | 0.01 |
| **1.5** | 1 | 0.995 | 0.786 | 0.459 | 0.246 | 0.122 | 0.089 | 0.052 | 0.035 | 0.026 |
| **2** | 1 | 1 | 0.982 | 0.81 | 0.526 | 0.352 | 0.22 | 0.133 | 0.082 | 0.065 |
| **2.5** | 1 | 1 | 0.997 | 0.97 | 0.781 | 0.603 | 0.408 | 0.273 | 0.177 | 0.131 |
| **3** | 1 | 1 | 1 | 0.994 | 0.954 | 0.813 | 0.651 | 0.469 | 0.301 | 0.22 |
| **3.5** | 1 | 1 | 1 | 1 | 0.99 | 0.934 | 0.813 | 0.666 | 0.506 | 0.41 |
| **4** | 1 | 1 | 1 | 1 | 1 | 0.973 | 0.911 | 0.802 | 0.652 | 0.565 |
| **4.5** | 1 | 1 | 1 | 1 | 1 | 0.995 | 0.974 | 0.906 | 0.824 | 0.668 |
| **5** | 1 | 1 | 1 | 1 | 1 | 1 | 0.99 | 0.957 | 0.902 | 0.821 |
| **5.5** | 1 | 1 | 1 | 1 | 1 | 1 | 0.997 | 0.984 | 0.952 | 0.878 |
| **6** | 1 | 1 | 1 | 1 | 1 | 1 | 0.999 | 0.995 | 0.976 | 0.942 |

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