Food production shocks across land and sea

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Abstract

Sudden and unpredictable losses (shocks) to food production can threaten food security and livelihoods across land and sea. Yet our understanding of global exposure to production shocks is limited by a lack of standardized assessment across agricultural and seafood systems. Here we investigate historical global trends in frequency, size, recovery times and drivers of shocks to crop, livestock, fisheries, and aquaculture production. Despite large geographical differences in frequency and driver influence, we show extreme weather and political instability to be the dominant drivers of shocks on land, with overfishing and aquaculture disease primary drivers in seafood systems. Geopolitical crises tended to produce larger shocks and longer recovery times than other drivers. Critically, we demonstrate increasing shock frequency and diversity across all food sectors through time. In a more shock-prone world, where individual crises can reach across multiple sectors, social protection measures and bold domestic food policies may be central to adaptation.

Main

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 supply and security[1,2]. Exposure, sensitivity and capacity to adapt to such production losses determine a food systems' vulnerability to shocks across local, regional and national scales[3,4]. 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 countries such as Australia, provide stark examples[5–7]. Beyond reducing domestic production, shocks can also influence food availability, access and stability *indirectly* by propagating through trade-networks[8], driving rapid price changes[6,9], or posing recurrent barriers to economic development and investment at a national scale[5,10–12]. 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. Yet studies on food production shocks to date deal largely with agricultural and seafood commodities in isolation[1,2,10,13]. Given differences in national dependence on agriculture and fisheries worldwide[14,15], and the suite of interactions between them[16], integrating land and sea can illuminate both multisector threats and opportunities for improving food system resilience under global change.

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 (Figure S1). We combine this quantitative detection method with a literature search for likely causes, or drivers, of each production shock to balance limitations in data availability and reporting biases over different regions[1].

Trends in food production shocks and their drivers

From 741 available time series (crops = 187, livestock = 190, fisheries = 202, aquaculture = 162) we detected 226 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 **(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 frequencies 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 elsewhere **(Figure 1d)**.

We classify the 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 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-ecological stressors on food systems, we combined many of these categories to explain the drivers of production shocks, and highlight these sub-categories in **Figure 2.** 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 prevent spurious conclusions on cause and effect being drawn from such false positives[1].

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 globe[17]. 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, compromised livestock condition, and led to mass mortality events during cold winter extremes[18]. Diseases such as food and mouth also contributed to 10% of livestock shocks. Geopolitical crises, however, such as economic decentralisation in Europe or conflict in Sub-Saharan Africa, accounted for the greatest proportion (41%) of the livestock shocks in our analysis **(Figure 2)**.

In contrast, drivers of seafood production shocks were more diverse than for terrestrial systems **(Figure 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 aquaculture sector, 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 state dissolution, to violent conflict, and declining competitiveness in export markets [19–21].

The number of shocks with unknown drivers was greatest in the aquaculture sector. This may be due to a combination of reporting biases. Firstly, aquaculture is still small-scale in most producing countries and no aquaculture shock of an unknown driver exceeded 0.05% of total domestic food production that year. Production losses this small may pose little threat to food supply or security and are likely to go unreported. 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 [22], and therefore reliable reporting. Therefore, there are likely to be more instances where sudden declines in production go undocumented.

Patterns of driver influence differed across regions (**Figure 3**). In South Asia, where agricultural shocks were most frequent, nearly all crop and livestock losses were driven by flooding or drought **(Figure 3a,b)**. Whereas in Sub-Saharan Africa, where the greatest burden of hunger still persists[11], geopolitical or economic crises were the leading drivers of agricultural shocks (Figure 3a,b). In seafood sectors, 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 conditions more significant for both East Asia or the Middle East and North Africa. 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 size of a shock seemed dependent on both where it occurs and its driver. Intuitively, the largest shocks tended to occur in regions where large-scale production exists, such as East Asia and Europe, with shocks in Oceania smaller on average (**Figure 3**). However, the largest shocks across all sectors were driven, at least in part, by geopolitical crises. For example in our analysis, the largest shock to crop production occurred in Nigeria during outbreaks of violent conflict in 2009 where unsafe working conditions disrupted farmers' access to land, fertilisers, herbicides and seeds[20] (**Figure 3a**). In the livestock sector, the largest shock occurred in Mexico in 1989 after successive economic crises exacerbated by drought[23] (**Figure 3b**). Whereas the largest fisheries (USSR) and aquaculture (North Korea) shocks happened during the fall of communism in Europe, as production subsidies, export markets, and consumer demand fell away with the dissolution of the Council for Mutual Economic Assistance[1,24,25] (**Figure 3c,d**). The indirect effects of such geopolitical events reinforce how shocks can propagate through interconnected trade networks.

Notably, the largest shocks do not necessarily correspond to slower recovery times (**Figure 3**). 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 perturbation[26]. Systems of low resilience tending to take longer to recover [26,27]. The longest recovery times across all sectors represent step changes in production where no recovery occurred before the time-series end (we present relative frequencies in full vs no recovery in **Figure S2**). For crop production, recovery was longer on average in East Asia where flooding was the driver for almost all shocks (**Figure 3a**). For livestock, fisheries and aquaculture, recovery was longest on average in Europe and Central Asia, largely because of shocks associated with the Soviet Union collapse or overfishing in wild stocks (**Figure 3b,c,d).** It is important to exercise caution with interpretation of these results, however. Longer recovery times (or lack of recovery) may reflect a range of social, political, ecological, or economic conditions and decisions. For example, a shock to fisheries proceeded by management interventions that reduce quota over time means landings may intentionally never return to previous levels. Therefore, slow or no recovery may not reflect the systems' *capacity* to recover but instead capture changes in the underlying social-ecological system.

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)**.

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**.** However, crop production shocks driven by extreme weather became more frequent in our results over time (**Figure 4b**). In livestock, fisheries and aquaculture sectors particularly, the diversity of drivers increased from the 1970s (**Figure 4d,f,h**). As food systems become increasingly globalised and interdependent, a greater diversity of exogenous shocks may influence them over time [28]. 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 people[29]. The nature of interdependencies among sectors are also changing. Demands for feed now tightly couple aquaculture to both capture fisheries and crop systems[30], 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 sustainability[31]. Nevertheless, it is also possible that increased reliability of data reporting since the 1960s may 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 trade[8] and a number of countries are dependent on imports to meet the food demands of their population[32]. Trade dependency is also becoming more regionally specialised, 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[33]. 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[8,9,32,33]. 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 global scarcity would favor higher paying nations[33], 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. Internalised 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 times[11]. Building resilience in conflict affected zones will require multi-faceted efforts to help nations and households prevent, anticipate, cope with and recover from shocks[11]. Greater understanding of the proximate and ultimate causes of conflict in different areas will be central to prevention[11]. Development of novel early-warning systems for violence are already underway[34]. 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 Africa[35]. 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 gaps[11,36]. Weather-indexed insurance is another innovative tool that may help protect farmers against income or food access losses during adverse conditions[37], and will be particularly important if predictions of more frequent extreme events are further realised[38].

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 alike[20]. Similarly, in Afghanistan a severe drought from 2000 – 2002 decimated cereal production, grain feed for livestock, and rangeland pastures[39] and we detected a significant shock to inland fisheries 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 recognise the interacting role of aquatic and agricultural commodities[14].

There is also a pressing need to understand better 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 hunting[40], and upturns in unregulated fishing occurred in Somalia as terrestrial systems failed in the early 1990s[16]. 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 source[41]. After Hurricane David decimated the banana crop in 1979, fisheries landings increased dramatically from 1980, followed by a rapid decline in the early 1980s **(Figure 5b),** likely driven by overfishing driving stock collapse in nearshore waters[41]. 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 production[42]. Aquaculture diseases remain a significant issue[43], 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 farmed animals naïve to native pathogens[44]. 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 [43], and by accelerating the production of diverse genetic lines and pathogen resistance (which complements the growth in emergency vaccine development allowing 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 inputs[30] adapting to volatility in current feed production 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 production[16], 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)[15,45]. Given persistent historic patterns of widespread overfishing [46] 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 security[45].

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 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 expected, 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 to productivity under climate change, 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 driven 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 drivers of shocks to food production. Political instability and extreme weather conditions have been the dominant drivers 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 considerable 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 requires closer examination.

Methods

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 standardised 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/)[47]. Crop types included cereals, coarse grains, fruits, roots and tubers, pulses, tree nuts and vegetables; while livestock included total meat, milk, and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO FishStat database[48] for inland and marine aquaculture production, and inland fisheries landings data (1950 – 2015 Global Production dataset, www.fao.org/fishery/topic/166235/en.). We used marine fish landings data from Watson[49] 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 recognise 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 (in tonnes) 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. Some shocks did not recover by the end of the time series and we highlight the relative frequencies of these across regions and sectors in **Figure S2** and the individual shocks in **Table S2**. 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, and the increasing number of countries producing through time.

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 the likely causes, or drivers, 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. We caution that this approach is not meant to provide a comprehensive list of contributing factors for a given shock, but instead highlights potential drivers of change from the literature we identify.

Sensitivity analyses of shock detection 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 median 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 (**Figure S4**). 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 al[1]. 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 these ARIMA 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)**.

Code availability

All code for analyses conducted in this study will be made publicly available through Github (linked provided on manuscript acceptance).

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Author contributions

RSC, JLB, KLN, and BSH designed the study, and RSC conducted the analysis and wrote the paper. TAR assisted with figures and AJ 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.

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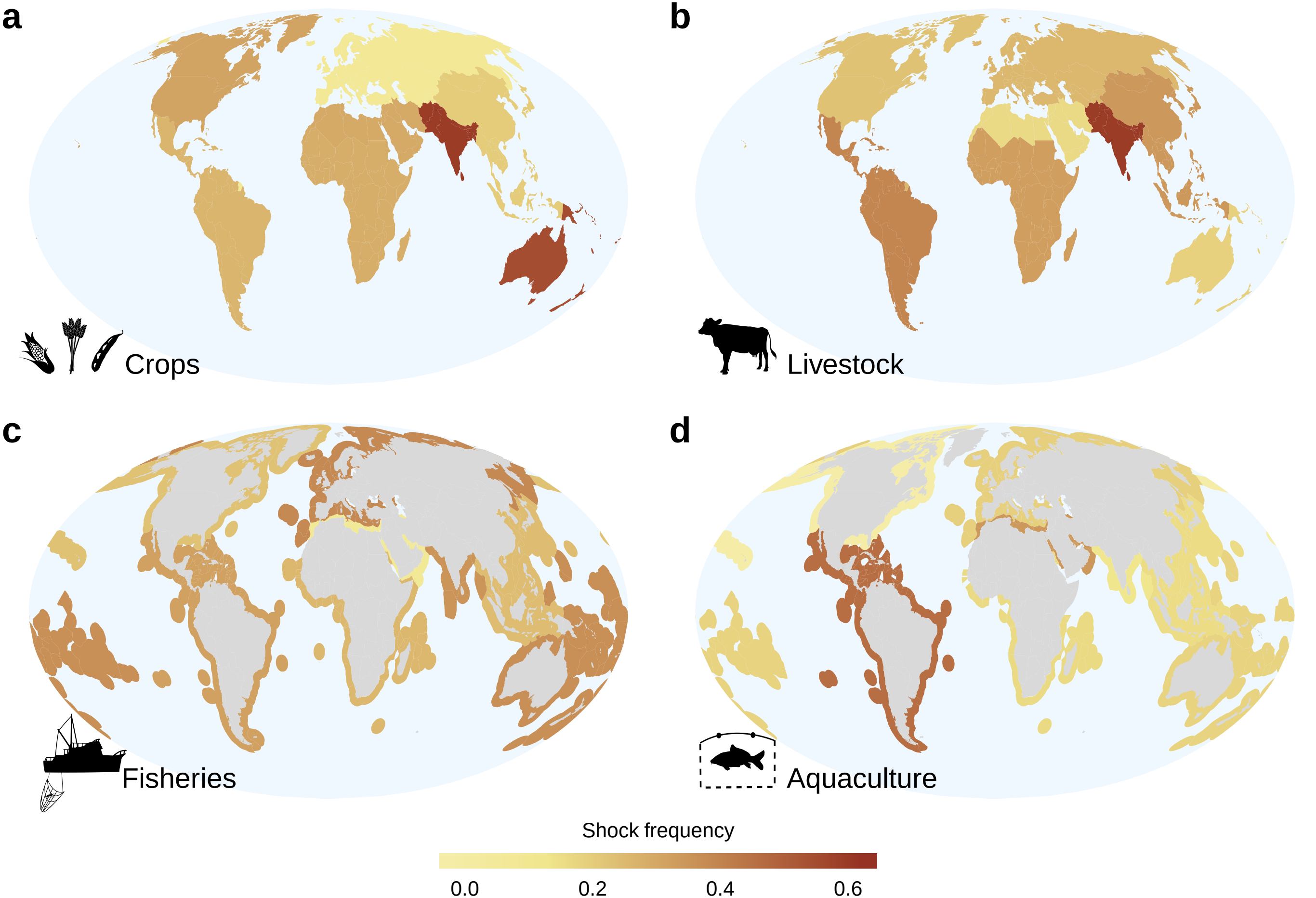
Figure 1 – Shock frequency across geographical regions for crop, livestock, fisheries and aquaculture sectors from 1961 – 2013. Shock frequency calculated as total number of shocks detected in a region divided by the number of national time series analysed from the region. Regions include North America,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

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

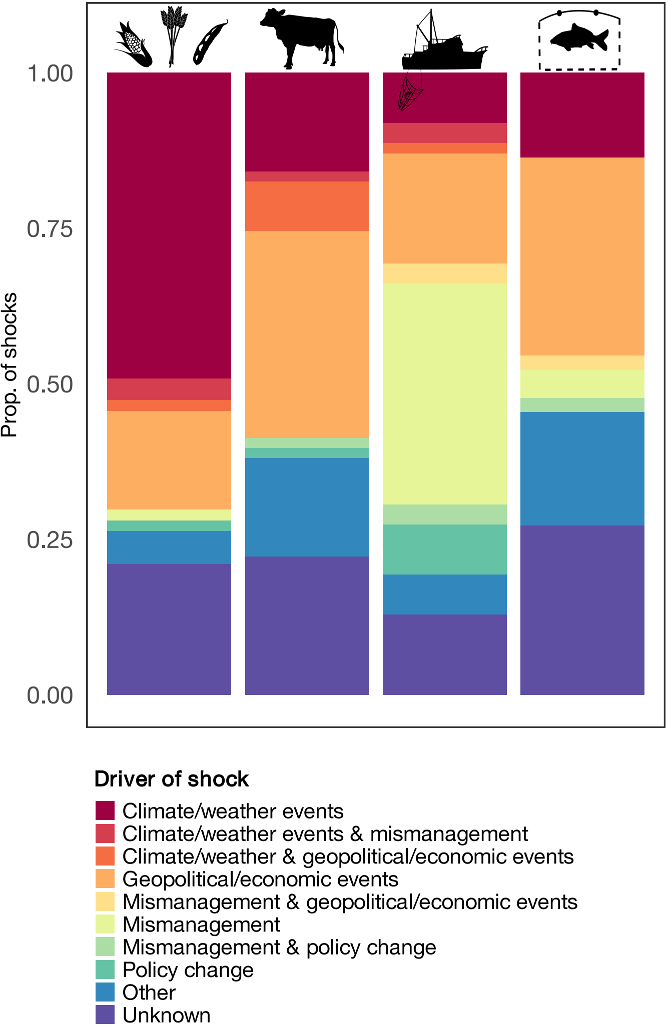
Figure 3 – Shock size, recovery time and drivers across geographical regions for crop (a), livestock (b), fisheries (c) and aquaculture (d) sectors. Each shock represented by a chord flowing from a driver to a region. Shock sizes indicated by width of the chord (tonnes x10^7), recovery times indicated by chord transparency, and chord colour indicates driver type. Dashed lines lines highlight the biggest shock detected for each sector.

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 average types used for baseline (mean or median). Dashed black line is the decadal mean of the red line 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 exclude shocks with unknown drivers.

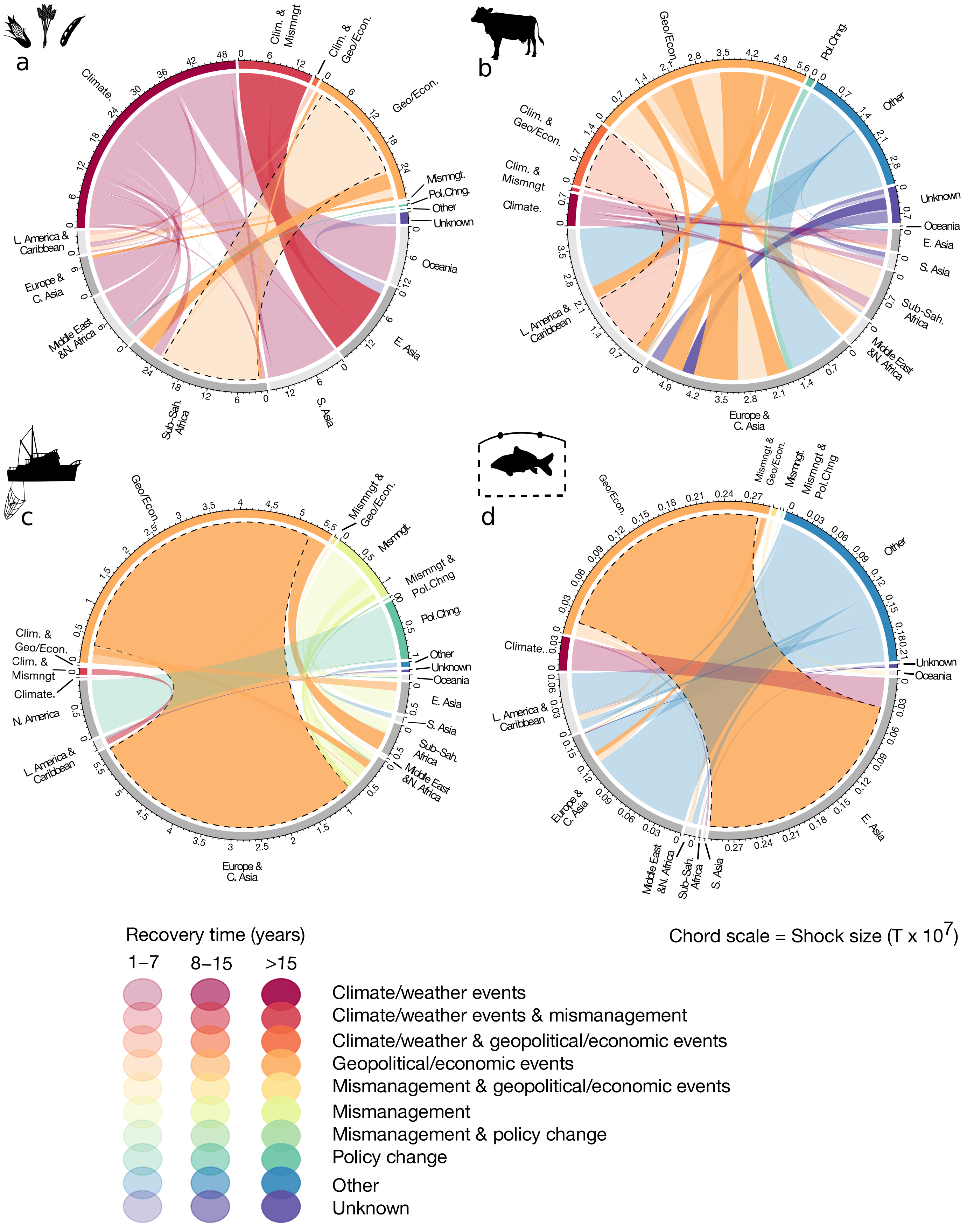
Figure 5 – **Food production shocks can bridge agriculture and seafood sectors. a**. Drought in Afghanistan from 2000-2002 (shaded area) drives sizeable production losses across agriculture and inland fisheries. **b**. Crash in Dominica's banana crop following Hurricane David in 1979 precedes spike in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

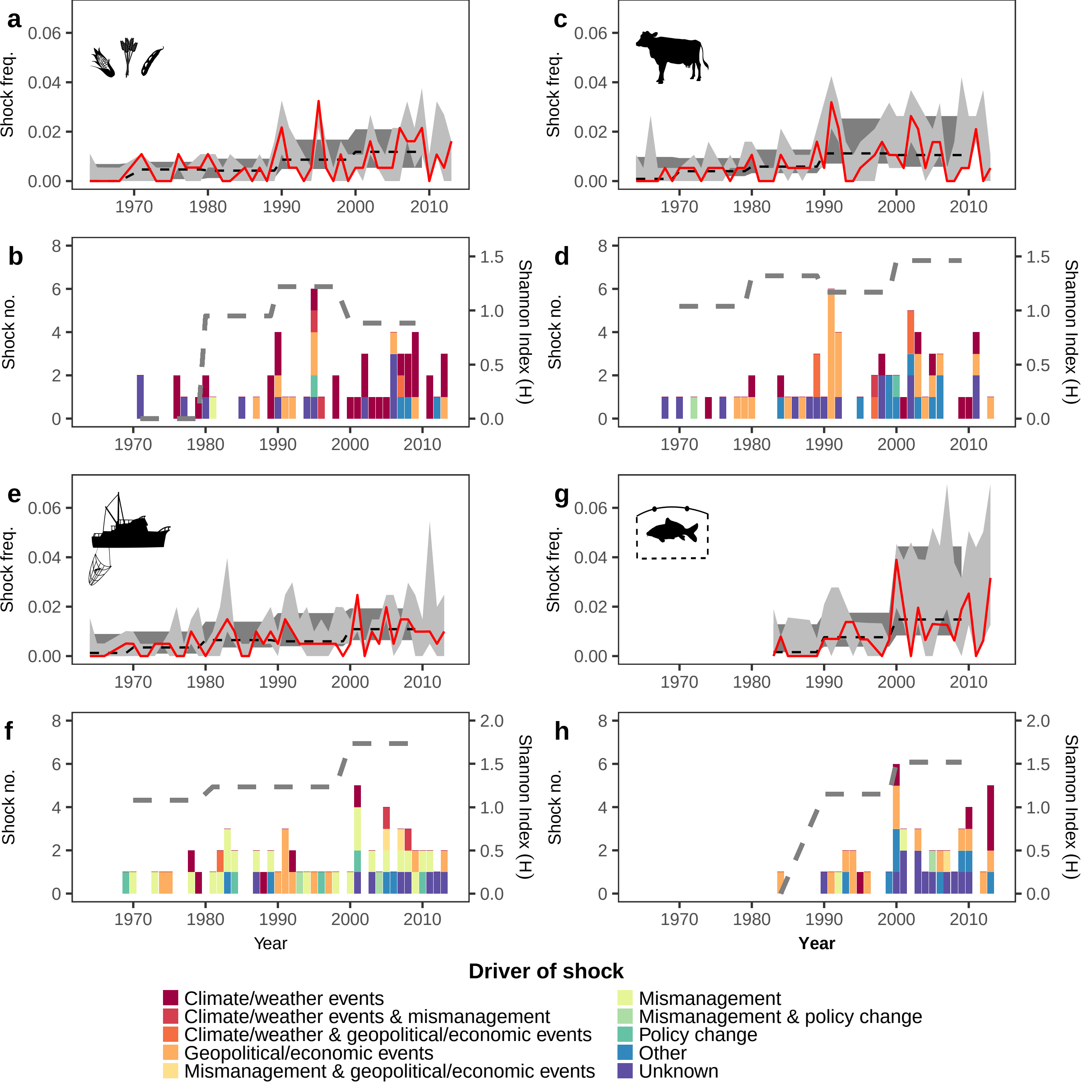


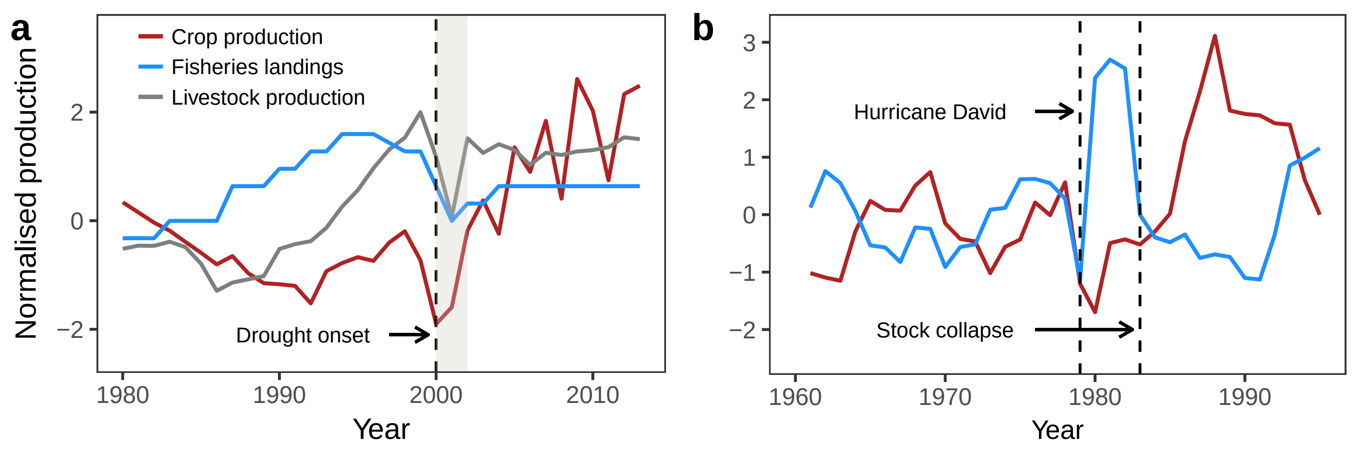
a
Crops
b
Livestock
c
Fisheries
d
Aquaculture
Shock frequency
0.0
0.2
0.4
0.6



1.00
0.75
0.50
0.25
0.00
Prop. of shocks
Driver of shock
Climate/weather events
Climate/weather events & mismanagement
Climate/weather & geopolitical/economic events
Geopolitical/economic events
Mismanagement & geopolitical/economic events
Mismanagement
Mismanagement & policy change
Policy change
Other
Unknown


a
Climate.
Clim. & Mismngt
Clim. & Geo/Econ.
Geo/Econ.
Mismngt.
Pol.Chng.
Other
Unknown
Oceania
E. Asia
S. Asia
Sub-Sah. Africa
Middle East &N. Africa
Europe & C. Asia
L. America & Caribbean
b
Pol.Chng.
Other
Unknown
Geo/Econ.
Clim. & Geo/Econ.
Clim. & Mismngt
Climate.
Oceania
E. Asia
S. Asia
Sub-Sah. Africa
Middle East &N. Africa
Europe & C. Asia
L. America & Caribbean
c
Geo/Econ.
Mismngt & Geo/Econ.
Mismngt.
Mismngt & Pol.Chng
Pol.Chng.
Other
Unknown
Oceania
E. Asia
S. Asia
Sub-Sah. Africa
Middle East &N. Africa
Europe & C. Asia
L. America & Caribbean
N. America
Climate.
Clim. & Mismngt
Clim. & Geo/Econ.
d
Geo/Econ.
Mismngt & Geo/Econ.
Mismngt.
Mismngt & Pol.Chng
Other
Unknown
Oceania
E. Asia
S. Asia
Sub-Sah. Africa
Middle East &N. Africa
Europe & C. Asia
L. America & Caribbean
Climate..
Recovery time (years)
1–7
8–15
>15
Climate/weather events
Climate/weather events & mismanagement
Climate/weather & geopolitical/economic events
Geopolitical/economic events
Mismanagement & geopolitical/economic events
Mismanagement
Mismanagement & policy change
Policy change
Other
Unknown
Chord scale = Shock size (T x 10^7)


a
b
c
d
e
f
g
h
Shock freq.
Shock no.
Shannon Index (H)
0.06
0.04
0.02
0.00
8
6
4
2
0
1.5
1.0
0.5
0.0
2.0
1970
1980
1990
2000
2010
Year
Driver of shock
Climate/weather events
Climate/weather events & mismanagement
Climate/weather & geopolitical/economic events
Geopolitical/economic events
Mismanagement & geopolitical/economic events
Mismanagement
Mismanagement & policy change
Policy change
Other
Unknown


a
Crop production
Fisheries landings
Livestock production
Normalised production
Drought onset
Year
b
Hurricane David
Stock collapse
Year