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

54 worldwide[14,15], and the suite of interactions between them[16], integrating land and sea can

55 illuminate both multisector threats and opportunities for improving food system resilience

56 under global change.

57 Here we present global trends in shock exposure and drivers for national crop, livestock,

58 capture fisheries (herein fisheries) and aquaculture sectors from 1961 – 2013. We use three

59 metrics to describe exposure; shock frequency, shock size, and recovery time (duration of

60 perturbation)[4]. We define shock frequency as the number of shocks detected divided by the

61 number of national production time series used for detection over either space or time. We

62 calculate shock size as the production loss relative to the previous 7-year production average

63 (based on sensitivity analysis, see Methods). Recovery time describes the number of years

64 taken to recover from the shock point to at least 95% of the previous production average. We

65 employ a statistical approach to shock detection applicable across terrestrial and aquatic

66 systems by fitting local regression models to production time series and identifying outliers in

67 the regression between residuals and lag-1 residuals from model fit (Figure S1). We combine

68 this quantitative detection method with a literature search for likely causes, or drivers, of each

69 production shock to balance limitations in data availability and reporting biases over different

70 regions[1].

Trends in food production shocks and their drivers

72 From 741 available time series (crops = 187, livestock = 190, fisheries = 202, aquaculture =

73 162) we detected 226 production shocks. We compare shock exposure indices across eight

74 geographical regions (Latin America and Caribbean, North America, Europe and Central

75 Asia, Middle East and North Africa, Sub-Saharan Africa, South Asia, East Asia, and

76 Oceania). For most sectors, shock frequencies were regionally distinct, with some areas

77 experiencing shocks far more frequently than others **(Figure 1).** For example, shock

78 frequencies in crop and livestock systems in South Asia were higher than any other region in

79 both sectors **(Figure 1a, b).** Shock frequencies in fisheries were more globally homogenous

80 **(Figure 1c)**, whereas in the aquaculture sector, Latin America and the Caribbean sustained

81 the highest frequency of shocks, 1.3 – 3.4 times higher than elsewhere **(Figure 1d)**.

82 We classify the drivers of shocks into five main categories. *Climate/weather events* include

83 anomalies such as storms, droughts, ENSO events, or climate-driven ecosystem change.

84 *Geopolitical/economic events* covers disturbances from conflict, state dissolution or financial

85 crises. *Mismanagement* includes multiple categories such as overfishing in the ocean, or

3

86 deforestation and erosion of soils on land. *Policy change* can refer to, for example, closure of

87 a fishery or abolition of agricultural subsidies. The '*Other*' category includes a wide range of

88 pressures from production diseases to geological events such as tsunamis or volcanic

89 eruptions. Due to the complex nature of social-ecological stressors on food systems, we

90 combined many of these categories to explain the drivers of production shocks, and highlight

91 these sub-categories in **Figure 2.** The Unknown category contains shocks for which we could

92 not find a documented reason. It is possible that our statistical approach to detection means

93 we identify changes to national reporting methods as a shock. This highlights the importance

94 of the complimentary quantitative and qualitative approaches used here to prevent spurious

95 conclusions on cause and effect being drawn from such false positives[1].

96 Extreme weather events and geopolitical crises were the dominant drivers of agricultural

97 shocks **(Figure 2)**. Over half of all shocks to crop production systems were a result of extreme

98 weather events **(Figure 2)**, largely drought, reinforcing the concern about vulnerability of

99 arable systems to climatic and meteorological volatility across the globe[17]. We also found

100 extreme weather to be a major driver of shocks to livestock (23%), particularly where

101 reductions to feed occurred. For instance, severe summertime droughts in Mongolia in 2001

102 and 2010 reduced fodder and feed availability, compromised livestock condition, and led to

103 mass mortality events during cold winter extremes[18]. Diseases such as food and mouth also

104 contributed to 10% of livestock shocks. Geopolitical crises, however, such as economic

105 decentralisation in Europe or conflict in Sub-Saharan Africa, accounted for the greatest

106 proportion (41%) of the livestock shocks in our analysis **(Figure 2)**.

107 In contrast, drivers of seafood production shocks were more diverse than for terrestrial systems

108 **(Figure 2).** For fisheries, overfishing was responsible, at least in part, for 45% of shocks

109 detected in landings data. However, geopolitical crises contributed to 23% of fisheries shocks,

110 climate/weather events to 13% and policy changes to 11%. Shocks driven by policy changes

111 can reflect positive interventions, but may also be a response to declining resources. In the

112 aquaculture sector, while disease (included in '*Other*' category) was the most common

113 individual driver, responsible for 16% of shocks overall, a spectrum of geopolitical stressors

114 were behind a third of aquaculture shocks, from state dissolution, to violent conflict, and

115 declining competitiveness in export markets [19–21].

116 The number of shocks with unknown drivers was greatest in the aquaculture sector. This may

117 be due to a combination of reporting biases. Firstly, aquaculture is still small-scale in most

118 producing countries and no aquaculture shock of an unknown driver exceeded 0.05% of total

119 domestic food production that year. Production losses this small may pose little threat to food

120 supply or security and are likely to go unreported. Second, the majority of shocks with

121 unknown drivers occurred in countries of medium, low or unclassified human development

122 status. In low-income countries, low management and governance capacity limit

123 governmental knowledge of the resource-base [22], and therefore reliable reporting. Therefore,

124 there are likely to be more instances where sudden declines in production go undocumented.

125 Patterns of driver influence differed across regions (**Figure 3**). In South Asia, where

126 agricultural shocks were most frequent, nearly all crop and livestock losses were driven by

127 flooding or drought **(Figure 3a,b)**. Whereas in Sub-Saharan Africa, where the greatest burden

128 of hunger still persists[11], geopolitical or economic crises were the leading drivers of agricultural

129 shocks (Figure 3a,b). In seafood sectors, regional diversity of driver types was more consistent.

130 In wild systems, overfishing and geopolitical drivers contributed to numerous shocks across

131 Europe, Sub-Saharan Africa and East Asia. For aquaculture, disease was the primary driver in

132 Europe and Latin America, but geopolitical conditions more significant for both East Asia or

133 the Middle East and North Africa. Therefore, while we highlight dominant shock drivers for

134 each sector at a global scale, we reiterate that challenges for increasing food production will

135 vary greatly from place to place.

136 The size of a shock seemed dependent on both where it occurs and its driver. Intuitively, the

137 largest shocks tended to occur in regions where large-scale production exists, such as East Asia

138 and Europe, with shocks in Oceania smaller on average (**Figure 3**). However, the largest shocks

139 across all sectors were driven, at least in part, by geopolitical crises. For example in our analysis,

140 the largest shock to crop production occurred in Nigeria during outbreaks of violent conflict in

141 2009 where unsafe working conditions disrupted farmers' access to land, fertilisers, herbicides

142 and seeds[20] (**Figure 3a**). In the livestock sector, the largest shock occurred in Mexico in 1989

143 after successive economic crises exacerbated by drought[23] (**Figure 3b**). Whereas the largest

144 fisheries (USSR) and aquaculture (North Korea) shocks happened during the fall of

145 communism in Europe, as production subsidies, export markets, and consumer demand fell

146 away with the dissolution of the Council for Mutual Economic Assistance[1,24,25] (**Figure 3c,d**).

147 The indirect effects of such geopolitical events reinforce how shocks can propagate through

148 interconnected trade networks.

149 Notably, the largest shocks do not necessarily correspond to slower recovery times (**Figure 3**).

150 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.

184   Furthermore, financial institutions motivated by socioeconomic drivers disconnected from

185   their geographies of influence, increasingly sway producer investments and decisions with

186   complex or unknown consequences for production stability or sustainability[31]. Nevertheless,

187   it is also possible that increased reliability of data reporting since the 1960s may contribute to

188   this trend.

189   On a global scale, increased shock frequency may pose a threat to the resilience of the global

190   food system. Nearly a quarter of food, agricultural land, and freshwater resources are

191   accessed through trade[8] and a number of countries are dependent on imports to meet the food

192   demands of their population[32]. Trade dependency is also becoming more regionally

193   specialised, with some major breadbaskets the sole suppliers of commodities to other nations.

194   For example, Thailand currently provides over 96% of rice imports to a number of West

195   African countries[33]. The high dependence on just a handful of producers for some countries

196   highlights future vulnerability. Producing countries often reduce or ban exports during

197   production crises to protect domestic supply, endangering import-dependent trade

198   partners[8,9,32,33]. If shock frequencies continue to increase and major producing nations are

199   affected, a shift to a state of reduced exports is plausible. Increased commodity prices linked

200   to global scarcity would favor higher paying nations[33], leaving low-income, trade-dependent

201   countries in jeopardy. Whether or not early-warning signals of these changes occur in trade or

202   price data warrants further investigation to help predict any temporal changes to global food

203   system resilience.

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

205   Adapting to a greater frequency of shocks in our food system will hold different meaning

206   across various sectors and regions. The retrospective trends described here are consistent with

207   current threats to agricultural supply from political instability and extreme weather.

208   Internalised conflicts have increased in Sub-Saharan Africa and the Middle East since 2010

209   and are responsible, combined with adverse climate conditions, for the first uptick in global

210   hunger in recent times[11]. Building resilience in conflict affected zones will require multi-

211   faceted efforts to help nations and households prevent, anticipate, cope with and recover from

212   shocks[11]. Greater understanding of the proximate and ultimate causes of conflict in different

213   areas will be central to prevention[11]. Development of novel early-warning systems for

214   violence are already underway[34]. A number of social protection instruments may become

215 increasingly important as coping mechanisms in conflict zones. Timely food and cash
216 transfers, and food or cash for work programmes during times of crisis show promise
217 throughout Sub-Saharan Africa[35]. Participatory planning with, and post-conflict support for,
218 those displaced such as provisioning of tools, seeds or skills training will be crucial in
219 building faster recovery times and closing yield gaps[11,36]. Weather-indexed insurance is
220 another innovative tool that may help protect farmers against income or food access losses
221 during adverse conditions[37], and will be particularly important if predictions of more frequent
222 extreme events are further realised[38].

223 Protective measures need to extend beyond agriculture, however; as the threat from war and
224 climate shocks are not restricted to a single sector but can reach across agricultural and
225 seafood sectors. In Mali, the escalation of violent rebellions in 2012 displaced over 150,000
226 people, producing shocks to crop and fish production alike[20]. Similarly, in Afghanistan a
227 severe drought from 2000 – 2002 decimated cereal production, grain feed for livestock, and
228 rangeland pastures[39] and we detected a significant shock to inland fisheries simultaneously
229 **(Figure 5a).** Given the dual importance of both fishing and farming to many of the world's
230 most food insecure people, social and economic policies must start to recognise the
231 interacting role of aquatic and agricultural commodities[14].

232 There is also a pressing need to understand better the extent and sustainability consequences
233 of livelihood switches among sectors during food shortages. For example, times of fish
234 scarcity in West Africa are known to drive increased bushmeat hunting[40], and upturns in
235 unregulated fishing occurred in Somalia as terrestrial systems failed in the early 1990s[16].
236 Responses to agricultural shocks in Dominica further illustrate the potential for land-sea
237 trade-offs. Repeated damage to farmland from tropical storms during the 1970s pushed more
238 of the nation's farmers into fishing for a primary income source[41]. After Hurricane David
239 decimated the banana crop in 1979, fisheries landings increased dramatically from 1980,
240 followed by a rapid decline in the early 1980s **(Figure 5b),** likely driven by overfishing
241 driving stock collapse in nearshore waters[41]. The unpredictable transmission of human
242 impacts across sectors during crises pose challenges for global sustainability goals such as the
243 2030 Sustainability Agenda or Aichi biodiversity targets which remain sector specific in their
244 focus. Understanding how and why communities react to production crises beyond trade at
245 the national level, remains an element of sustainability research with scant information.

246　For some countries, transitioning to a greater dependence on marine resources may be an

247　attractive option for avoiding volatility in terrestrial production. Given the stagnation in

248　global fisheries landings, the burden of meeting future seafood demands will fall on

249　aquaculture, which now provides over half of global production[42]. Aquaculture diseases

250　remain a significant issue[43], however, representing the largest single driver of aquaculture

251　shocks in our analysis. Domestication of broodstock has been a major step forward in

252　reducing disease transmission, but industry focus on only a few major species in multiple

253　locations has left farmed animals naïve to native pathogens[44]. Open data and new sequencing

254　technologies are also helping, both by further understanding of the complex microbial trophic

255　structures surrounding disease emergence in pond cultures [43], and by accelerating the

256　production of diverse genetic lines and pathogen resistance (which complements the growth

257　in emergency vaccine development allowing more rapid intervention). Understanding

258　vulnerability of feeds under climate change will be an increasingly important aspect of

259　research for the sector too. As aquaculture relies on both agriculture and fisheries for inputs[30]

260　adapting to volatility in current feed production will be an important step in building

261　resilience for the sector.

262　Despite the growing global importance of aquaculture, only 20 countries produce 96% of

263　total production[16], largely in freshwater, meaning capture-based fish production will remain

264　the most important source of local animal protein in many countries (especially in Oceania

265　where animal husbandry and aquaculture potential are limited)[15,45]. Given persistent historic

266　patterns of widespread overfishing [46] and the likelihood that climate change will alter

267　productivity of reef-based fisheries, policy and funding for infrastructure changes will be

268　required to see proportionally more of the valuable returns on investment from pelagic

269　species diverted toward subsistence and local food security[45].

270　Trends discussed here will almost certainly underrepresent the frequency of production

271　shocks due to aggregation of production data at the country level. Sudden production losses

272　may be locally isolated or restricted to a single food type but are still of concern for

273　livelihoods and food security in affected communities. Summing across commodity types

274　tends to smooth out shocks to single food items – particularly in North America where food is

275　grown over such a large and diverse landscape. Given the influence of different parameters

276　used here on our ability to detect shocks, we suggest the results presented are a representative

277　sample of shocks across land and sea **(Figure S3)**. Further, the shock detection method

278　described here is less sensitive to production changes in highly variable systems where large

279 fluctuations are common within the time series (**Table S1**)[1]. While variable production has
280 consequences for food supply and security, in a system where large fluctuations are expected,
281 we do not consider them shocks. Moreover, while shocks remain a significant barrier to food
282 security in many regions, this method does not account for gradual declines in food
283 production, such as those expected to productivity under climate change, which may be more
284 damaging overall. Finally, we limit our analysis to the role of exogenous stressors on food
285 systems. To what extent any of the shocks identified here are driven by inherent internal
286 vulnerabilities within the food system (e.g. low crop diversity) is unclear.

Conclusions

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

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

Methods

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

310 *Data Sources*

311 We used crop and livestock data from FAOSTAT production quantity dataset 1961 – 2014

312 dataset (http://www.fao.org/faostat/en/)[47]. Crop types included cereals, coarse grains, fruits,

313 roots and tubers, pulses, tree nuts and vegetables; while livestock included total meat, milk,

314 and egg production from bovine, poultry, swine, mutton and goat sources. We used the FAO

315 FishStat database[48] for inland and marine aquaculture production, and inland fisheries

316 landings data (1950 – 2015 Global Production dataset,

317 www.fao.org/fishery/topic/166235/en.). We used marine fish landings data from Watson[49] to

318 account for estimates of large-scale, small-scale and illegal, unregulated, and unreported

319 (IUU) landings. Fisheries data included all landed finfish, crustaceans, and molluscs.

320 Aquaculture data included all farmed finfish, crustaceans, molluscs and algae. While we

321 recognise that underreporting of small-scale production across all sectors is a limitation of

322 FAO data, it provides global coverage of production across multiple sectors, and the

323 detection of shocks relies on overall trends in data rather than absolute production values.

324 *Detecting and quantifying production shocks and drivers*

325 For all countries we aggregated production to total annual values from 1961 – 2013 across all

326 commodity types described above for crop, livestock, fisheries and aquaculture sectors. We

327 fitted local polynomial regression (LOESS) models with a span of 0.6 to aggregated annual

328 production data for all countries and sectors. We regressed model residuals against lag-1

329 residuals, and any outliers in this regression (quantified as data points with a Cook's

330 distance > 0.3), we deemed shocks (**Figure S1**). Given only production losses are of concern

331 for food security, we only considered shock points associated with a loss in production

332 relative to a previous 7-year median production baseline. We calculated the size of a shock as

333 the loss in production (in tonnes) relative to this baseline, and recovery time for the shock as

334 the number of years taken to increase back up to at least 95% of this baseline. Some shocks

335 did not recover by the end of the time series and we highlight the relative frequencies of these

336 across regions and sectors in **Figure S2** and the individual shocks in **Table S2**. We calculated

337 shock frequencies for each geographical region, by dividing the number of shocks detected

338 from 1961 – 2013 by the number of time-series used for detection. For annual shock

339 frequencies, for every sector we divided the number of shocks detected for a given year by

340 the number of countries producing in that year. We used this approach to compensate for

341 different numbers of countries within each region, and the increasing number of countries
342 producing through time.

343 Given production shocks may be the result of multiple social-ecological drivers interacting in
344 complex manners, we adopt a qualitative approach to understanding them, searching peer-
345 reviewed and grey literature (e.g. NGO reports, news articles etc.) for the likely causes, or
346 drivers, of each individual shock. The combination of quantitative and qualitative methods
347 provide complimentary approaches where purely data driven methods may highlight
348 correlative relationships with drivers without causation. Likewise, purely qualitative analyses
349 may be limited in their capacity to detect shocks because of differences in reporting across
350 regions. We caution that this approach is not meant to provide a comprehensive list of
351 contributing factors for a given shock, but instead highlights potential drivers of change from
352 the literature we identify.

353 *Sensitivity analyses of shock detection parameters*

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

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

369 To determine a Cook's distance value to use for identifying outliers in all analyses, we tested
370 the number of shocks detected against incremental changes to Cook's distance values
371 between two very different rules of thumb (1 and 4/(n-k-1)). The value of 0.3 is the point in
372 this relationship, reasonable across all sectors, where the number of shocks detected begins to

373   asymptote (**Figure S4**). This is very similar to the value used by Gephart et al [1] and is robust

374   to changes in LOESS model span, baseline duration and average type (**Figure S4**). Note we

375   conducted sensitivity analysis of Cook's distance values separately as we wanted to optimise

376   sensitivity within practical bounds for this study rather than simply selecting a central value.

377   *Effect of time series variability and shock size*

378   We conducted power analysis of the shock detection method across time series of different

379   variance structures as per Gephart et al[1]. To do this we fitted autoregressive integrated

380   moving average models (ARIMA) models to each national time series for all sectors and

381   selected the most common and parsimonious model specification (ARIMA 0,1,0) across all

382   sectors, determined by corrected Akaike's Information Criterion. Using these ARIMA

383   models, we simulated production time series using a range of variance structures (standard

384   deviations from $0.1 - 1$) and imposed different shock sizes $(0 - 6)$ to each simulation. We

385   applied the shock detection approach described above to each simulation and repeated this

386   1000 times for each shock size /standard deviation combination. As Gephart et al [1] found in

387   their study, the sensitivity of shock detection decreases for a given shock size as the

388   embedded variance in a time series increases. Further, across all values of time series

389   standard deviation, larger shocks are more frequently detected **(Table S1).** Type I error rates

390   were very low, with shocks hardly ever detected when no shock was imposed **(Table S1)**.

391   *Code availability*

392   All code for analyses conducted in this study will be made publicly available through Github

393   (linked provided on manuscript acceptance).

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Author contributions

399   RSC, JLB, KLN, and BSH designed the study, and RSC conducted the analysis and wrote the

400   paper. TAR assisted with figures and AJ assisted with qualitative analysis of shock drivers.

401   All authors contributed to development of the paper through methodological advice,

402   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.