



Shocks to fish production: Identification, trends, and consequences

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ABSTRACT

Sudden disruptions, or shocks, to food production can adversely impact access to and trade of food commodities. Seafood is the most traded food commodity and is globally important to human nutrition. The seafood production and trade system is exposed to a variety of disruptions including fishery collapses, natural disasters, oil spills, policy changes, and aquaculture disease outbreaks, aquafeed resource access and price spikes. The patterns and trends of these shocks to fisheries and aquaculture are poorly characterized and this limits the ability to generalize or predict responses to political, economic, and environmental changes. We applied a statistical shock detection approach to historic fisheries and aquaculture data to identify shocks over the period 1976–2011. A complementary case study approach was used to identify possible key social and political dynamics related to these shocks. The lack of a trend in the frequency or magnitude of the identified shocks and the range of identified causes suggest shocks are a common feature of these systems which occur due to a variety, and often multiple and simultaneous, causes. Shocks occurred most frequently in the Caribbean and Central America, the Middle East and North Africa, and South America, while the largest magnitude shocks occurred in Asia, Europe, and Africa. Shocks also occurred more frequently in aquaculture systems than in capture systems, particularly in recent years. In response to shocks, countries tend to increase imports and experience decreases in supply. The specific combination of changes in trade and supply are context specific, which is highlighted through four case studies. Historical examples of shocks considered in this study can inform policy for responding to shocks and identify potential risks and opportunities to build resilience in the global food system.

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1. Introduction

Sudden and unexpected changes, or shocks, in food production and distribution systems can limit access to food and adversely impact local nutrition and food security. Such events can initiate a cascade of effects through the interlinked social-ecological food system. The ability to respond and adapt to such disruptions while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks describes the system's resilience (Walker et al., 2004). Food systems with low resilience have limited responses and capacity for adaptation to disruptions through mechanisms like trade, alternative food sources, backup

distribution, or emergency supplies, causing food shortages of varying degrees of intensity and duration (Schipanski et al., 2016). Even when food production shortages are temporary, periods where essential nutrients are lacking can adversely impact the health of vulnerable populations such as pregnant women, children, and the ill (Block et al., 2004). For example, the drought in the Horn of Africa in 2011 contributed to the food insecurity and malnutrition of over 11 million people, with one in three children suffering from food shortages, widespread decreases in farmer and agribusiness worker incomes, and increased unemployment (UNEP, 2011). Income and asset loss and unemployment throughout the food production chain have lasting impacts for poor families and perpetuate poverty traps (Cuny and Hill, 1999). Therefore, characterizing the nature and frequency of disruptions, or shocks, to food systems is important to understanding the factors contributing to global food security. Ideally, this insight can

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be leveraged to prevent or mitigate the effects of future shocks and build food system resilience.

Shocks to food production can limit local access to food, but can also propagate through the international trade network, impacting prices and availability globally. The dynamics of this type of shock propagation have recently been explored through network models (Gephart et al., 2016; Tamea et al., 2016; Marchand et al., 2016). The 2008 grain crisis provides an example of a shock spreading through the trade network (Puma et al., 2015; Bren d'Amour et al., 2016). During this event, grain prices spiked due to increased demand for biofuels, higher oil prices, decreasing grain stocks, and the weakened US dollar (Headey, 2011). Rising wheat prices led India, the second largest rice producer, to ban exports of non-Basmati rice in 2007, which subsequently led other rice exporting countries, including China, Vietnam, and Egypt, to introduce export bans (Christiaensen, 2009). Some major importers, including the Philippines, responded by purchasing additional rice at increasing prices. Hoarding then further drove up the global price of rice (Christiaensen, 2009). By the end of the crisis, the World Bank reported over 130 million people were driven into poverty and the FAO estimated that an additional 75 million people became malnourished (Headey, 2011). This case illustrates the potential for multiple stressors (e.g. increasing biofuel demand and oil prices, changes in grain stock policies, and financial crises) to cause shocks which propagate on large spatial scales, and also illustrates how different sectors are increasingly interconnected (Homer-Dixon et al., 2015). A greater proportion of food is being traded internationally between more countries than ever before, and this increases the potential for shocks to local food systems to propagate into global crises (D'Odorico et al., 2014; Bren d'Amour et al., 2016).

While droughts and the 2008 grain crisis illustrate the consequences of shocks to agricultural production systems, shocks in fisheries systems are poorly characterized because temporal analyses have tended to focus on long-term trends rather than sudden drops and their resulting impacts. However, the effect of shocks is relevant to seafood production because seafood is among the most highly traded food commodities and is impacted by multiple potential shocks including fishery collapses, natural disasters, oil spills, policy changes, and aquaculture disease outbreaks (Gephart and Pace, 2015). Further, seafood is the source of almost 20% of animal protein consumed globally and an essential source of micronutrients in many coastal developing nations (FAO, 2014; Beveridge et al., 2013). As a result, it is important to identify historical cases of shocks to seafood systems to assess their causes and impacts on trade and domestic seafood supply.

There are a variety of factors that could contribute to either more or fewer shocks over time or in particular regions or systems (Table 1). Increasing exploitation, intensification and connectivity of aquaculture, and natural or environmental disasters could contribute to more shocks while improved capture fishery management or infrastructure, proactive avoidance measures, or stocks collapsing prior to the study period could contribute to fewer shocks (Table 1). Other factors could contribute to either

more or fewer shocks depending on the particular case, such as the increasing connectivity of the global market (which could increase pressure on fisheries or provide a buffer) or increased stock data availability (which could allow for increased intensification or improved management). Climate change also serves as a backdrop to these factors, by potentially making fishery systems more susceptible to shocks, by driving a redistribution of marine catches, and by causing more frequent extreme weather disruptions (Cheung et al., 2013; IPCC, 2014; Gattuso et al., 2015). A pattern in historical shocks would identify potential vulnerabilities in the seafood production system. This creates opportunities to manage measurable risks and supports the need to create buffers to hedge against shocks arising from true uncertainty in these complex systems—i.e. from unknown events impossible to predict (Sumaila, 1998; Lauck et al., 1998). Further, patterns in the impact of shocks on trade and supply inform whether and when a regional shock will have distant impacts through international trade or may impact local human nutrition.

While shocks have been defined and identified in specific systems with known causes or based on long time series, these methods cannot be applied in general when the shock cause is unknown and long time series data are unavailable. This is particularly problematic for food production systems, including fisheries, which are exposed to multiple environmental, policy, and economic shocks. One approach is to use expert or local knowledge to identify events considered shocks to particular systems. While this approach is valuable for studying individual systems, it is difficult to standardize the definition of a shock across systems and may be biased against shocks that are not widely reported on or those which occurred in distant memory. As a result, a data-driven approach can complement system knowledge to identify shocks across systems and over time.

Here we apply a statistical shock identification approach to national fisheries production time series to answer the following questions: 1) have the frequency or intensity of shocks increased; 2) do regions or production systems (capture versus aquaculture) have more, larger, or longer shocks; and 3) how are shocks divided among decreased exports, increased imports, and changes in domestic supply? We discuss four case studies in detail to illustrate the specific trade and seafood supply impacts of shocks which arise from different causes and occur within different contexts.

2. Methods

Shocks can be identified through qualitative approaches based on literature, news reports, and expert knowledge, or through quantitative approaches based on outliers or system-specific definitions. For example, both heat waves and floods are defined as extremes relative to the historical distribution of events, while droughts are identified by indices comparing supply and demand for soil moisture (e.g. the Palmer drought index). However, these methods typically require long time series to generate a distribution or are only relevant for specific types of shocks in a given system. While qualitative approaches are useful for studying individual systems, potential reporting biases, such as less

Table 1

Possible reasons to expect an increase or decrease in the frequency or intensity of shocks in fisheries and aquaculture time series.

Reasons for more shocks	Reasons for fewer shocks
Increasing exploitation	Stocks already collapsed
Increasing intensification and connectivity of aquaculture	Proactive avoidance measures
Increasing natural or environmental disasters	Improved infrastructure
Restrictions to improve capture fishery management	Improved capture fishery management in the past
Increasing connectivity of the global market	Increasing connectivity of the global market
Increased stock data connection and availability	Increased stock data connection and availability

reporting in some regions or over time, can limit the use for making spatial or temporal comparisons. In order to reduce such a bias, we use a quantitative approach to identify shocks and compliment this identification with a search of news, literature, and reports to match shocks with potential causes. Combining quantitative and qualitative approaches balances these advantages and disadvantages by integrating different strengths and limitations. Such a complementary approach has previously been used to detect shocks in macroeconomic time series (Balke and Fomby, 1994).

We analyzed shocks in production time series from FAO FishStat for each country (FAO FishStat, 2014). The “Global Commodities Production and Trade” quantity data was used for the total production shock analysis and the “Global Production by Production Source” quantity data was used for the production system analysis. While this data is known to be incomplete and underestimate catch from small-scale fisheries (Pauly and Zeller, 2016), this analysis is based on the time series patterns rather than the exact production estimates. Nevertheless, some limitations of the FAO statistics inhibit the detection of certain shocks. Specifically, inaccurate national reporting which masks drops in production would prevent the detection of shocks in these time series. As a result, shocks occurring in countries known to inaccurately report fishery data to the FAO, such as China, are not expected to be detected in our analysis (Watson and Pauly, 2001). Changes in national reporting practices could appear as a shock, but concerns of such false positives are minimized by pairing the statistical shock detection with a literature, report, and news search for potential causes. An identified shock due only to a reporting change would then likely have an ‘unknown’ cause. Additionally, the underestimation of small-scale fisheries production in the FAO data means that shocks primarily affecting small-scale fisheries may not be detected, while shocks primarily affecting industrial fisheries do not necessarily translate to impacts on small-scale fisheries. Shock events which impact both fisheries, such as a natural disaster, would be detected, although the sectors may be disproportionately impacted by the event. Despite these limitations, the FAO data provides global coverage of national production time series which enables a systematic detection of shocks.

An existing method commonly used to identify outliers in exploratory spatial statistics was modified to detect shocks based on deviations in the autocorrelation (Anselin, 1995, 1996). The approach is adaptable from spatial to temporal analysis because of the equivalence of the theoretical form of some autocorrelation coefficients between these types of data. The autocorrelation coefficient is an empirical representation of the relationship between temporal measures of production. Deviations identify localized instabilities in the autocorrelation which, conceptually, represent sudden disruptions of the seafood production. Specifically, shocks were identified as outlier deviations, or points with high Cook’s D values (>0.35), in a regression of the residuals and lag-1 residuals from a lowess fit of the time series with a smoother span of $2/3$ (see Fig. 1). The threshold of 0.35 was selected by comparing the total number of shocks identified to the threshold and selecting the point where the curve became relatively flat (Supplementary Fig. 1).

Shocks can be characterized by the frequency at which they occur in a system, the magnitude or intensity of the shock, and the duration or time to recovery. The frequency was defined as the interval at which a shock occurs and the magnitude was defined as the difference between a point and the previous 5-year average. For this analysis, only shocks representing a decrease were selected because these are the most likely to adversely impact food security and economic livelihoods. This means the magnitude is negative for all shocks, but we display the absolute value of the magnitude in all figures. Recovery of production from a shock was defined as

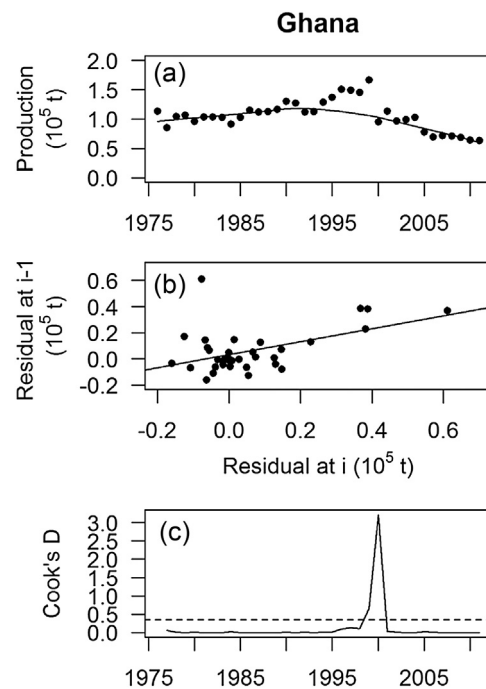


Fig. 1. Steps identifying shocks in time series. (a) A lowess regression was fit to the time series data; (b) residuals were plotted against the time-lagged residuals; (c) Cook’s D was used to identify extreme points in the regression of residuals versus time-lagged residuals. Points with Cook’s D greater than 0.35 were identified as shocks.

the point where production returned to within at least 5% of the pre-shock production level. This measure of recovery does not however imply sustainable harvest. For example, a system may be operating beyond a sustainable level and reduce catch down to a sustainable level (at which point a shock would be detected) and never return to the elevated, unsustainable level (i.e. never recover). Both temporary and lasting drops in production are considered shocks in this analysis because when a shock occurs it is not generally known if or when catch will return to pre-shock levels. Consequently, some shocks appear as a point change, while others appear as a step change.

Since shocks represent sudden drops in production, the detection method does not identify long-term, more gradual reductions in fisheries, which are often of concern for the sustainability of a particular stock. Further, this method does not identify shocks in systems with high variability (the detection limit under different levels of variability is described in the Supplementary information). In systems with high variability, large deviations are frequent and are therefore not considered shocks for this analysis. For example, although the drop in Peruvian anchoveta catch during El Niño is well known, the reported catch data has high variability and a shock is not detected using our method for the strong El Niño event in 1997–1998, despite the drop in catch that year (Supplementary Fig. 2). Since such drops are common and likely more expected in these systems, they are not a shock in the same sense. In fact, regular fluctuations in anchoveta catch are well documented in industry reports and as a result Peru has implemented coping strategies, including simultaneous ownership of fishing fleet and processing factories, low cost intensive monitoring, and rapid flexible management (Schreiber et al., 2001; FAO, 2016). Nevertheless, the high variability in production will have consequences for trade and seafood supply. For example, low catch periods in this fisheries will have rippling effects within the aquaculture sector since this is a unique and critical component for aquafeed production. However, such

impacts within systems with high variability are beyond the scope of this analysis.

We compliment the analysis by searching the literature, reports, and news sources to identify the potential or likely cause(s) of each shock which occurred in the total seafood production time series (Fig. 2, Supplementary Table 2). Positive identification of historical disruptions to fishery production that co-occur with the set of identified shocks strengthens the data-driven shock detection approach. However, the identified causes are not intended to be an exhaustive list of factors contributing to the observed shock. Instead, they only represent the events identified as potential factors in the sources we were able to locate or major disruptions occurring in the country (identified with asterisk in Supplementary Table 2). Shock causes are classified as one or more of the following: political (i.e. country breaking up, war, financial crisis, etc.), overfishing, policy change (related to fisheries), aquaculture disease, natural disaster, or unknown. The trade and supply response was quantified based on the value of imports, exports, and supply at the shock point relative to the previous five-year reference period. FAOSTAT (2014) supply data is calculated as the production and imports minus exports, domestic use as animal feed and waste, plus any change in stocks, divided by the population. Supply therefore represents a proxy of per capita seafood available for consumption, but is not a direct measurement of actual consumption. We focus on the response to a shock within the seafood system and therefore buffering mechanisms, such as use of grain stocks or imports of non-seafood commodities, are beyond the scope of this analysis.

3. Results and discussion

3.1. Patterns and trends in shocks to national seafood production

We detected 48 shocks between 1976 and 2011 within 127 national time series of total seafood production. While regions generally experienced a similar number of total shocks, the shock rate (number of shocks divided by the number of time series) was much higher in some regions (Fig. 3). For example, the shock rate in

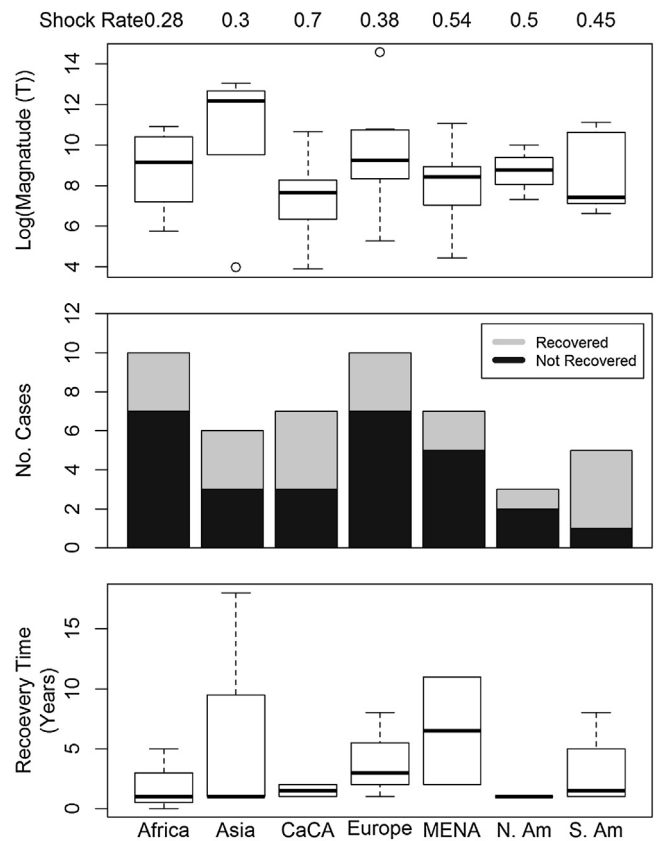


Fig. 3. Shock rate (number of shocks divided by the number of time series in the region), magnitude, number of recovered and not recovered cases, and recovery time by region. Shocks were identified in FAO FishStat total national production time series using the shock detection approach described in the methods. Recovery was defined as returning to within 5% of the previous 5-year average. Note that Africa refers to Sub-Saharan Africa, CaCA refers to the Caribbean and Central America, MENA refers to the Middle East and Northern Africa, N. Am refers to North America, and S. Am refers to South America.

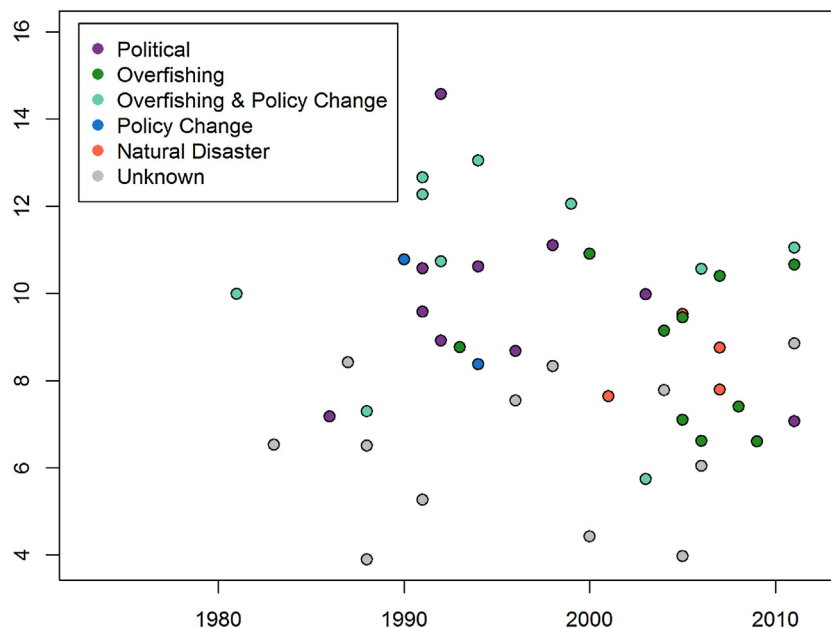


Fig. 2. Shock magnitude for each year in total fisheries production time series for each country. Shocks were identified in FAO FishStat total national production time series using the shock detection approach described in the methods. There is no significant trend in shock magnitude ($p = 0.63$, $r^2 < 0.001$) or number of shocks ($p = 0.31$, $r^2 = 0.005$). Points are colored according to the identified shock cause.

the Caribbean and Central America was two and a half times the shock rate in Africa and about twice the rate in Asia and Europe (Fig. 3). Although the Caribbean and Central America, and South America had among the highest shock rates, they also had a higher percent of cases where the production recovered to pre-shock levels (80%) and the recovery times for these regions were among the lowest. This is compared to only 30% of cases returning to pre-shock levels in Europe, sub-Saharan Africa, and the Middle East and North Africa. Shock magnitudes tend to be fairly similar across regions, but the highest mean magnitudes occurred in Europe, Asia, and sub-Saharan Africa (Fig. 3). In general, the distributions of magnitudes and recovery times are asymmetric, such that most shocks are small and most recoveries are quick, but when they are not the largest shocks are much larger or longer than the medians.

Shocks did not become more frequent or larger in the national seafood production series over time (Fig. 2). This suggests that shocks are a common feature of these production systems. Similarly, Sartori and Schiavo (2015) found no increase in the number of shocks in agricultural systems in the past 25 years. The shocks to seafood production occurred due to a variety of identified causes, but were dominated by political factors, fishery policy changes (e.g. new catch limits), and overfishing, often coupled with a policy change to limit fishing pressure (Fig. 2). No trend analysis within shock-cause categories can be reliably conducted due to the potential bias of the cases with unknown causes. The lack of trends and variety of factors supports a mixture of the hypothesized reasons to expect an increase or decrease in shocks over time (Table 1).

Political factors, such as the breakup of a country, war, or financial crises, were frequently identified as a potential cause of a seafood production shock. In fact, the largest shock identified, the breakup of the USSR (described in more detail below) was a political shock. However, such political disruptions occur at irregular intervals and therefore would not be expected to drive a trend over this period. We expected that overexploitation could be leading to more shocks or that improved management could be reducing shocks. While overfishing and policy measures to avoid overfishing are frequently identified as causes of drops in production, there is not a clear trend over the period considered. Since the policy changes are typically aimed at reducing overfishing, one would expect that these systems will experience fewer shocks due to overfishing in the long run. These cases of shocks may be examples of the short term cost of improving management (i.e. reduced harvests) for long term sustainability.

Countries are likely able to anticipate or prevent shocks to varying degrees in different cases. Slow developing situations leading to shocks, such as overfishing, can be monitored and expected if action is not taken. Such slow drivers offer the possibility of statistical early warning indicators through monitoring that would allow a response or preparations prior to a dramatic change (Litzow et al., 2008; Carpenter et al., 2011; Seekell et al., 2012; Cline et al., 2014). Policy changes which are slowly phased in or have delayed implementation dates also allow the production drops to be expected. Anticipated decreases in seafood production may allow stakeholders to prepare in advance of the shock, which would mitigate the shock's impacts. Other shock causes, such as a disease outbreak or natural disaster, are generally less predictable. This means there is less time for any management intervention or preparation. As a result, the resilience of the food system could be diversified with additional food sources (Troell et al., 2014), maintaining backup distribution mechanisms, or emergency supplies, and building capital to cope with crises in order to reduce the societal impacts of a shock.

When disaggregated into aquaculture and capture fishery time series, the shock magnitude and recovery tended to be similar for capture and aquaculture production systems (Supplementary

Fig. 3). However, the shock rate tended to be higher for aquaculture than capture fisheries from the late 1980s to the present, a period of rapid aquaculture development (Supplementary Fig. 4). While the cause of this difference is unknown, aquaculture is vulnerable to shocks from disease outbreaks and possibly also from rapid growth over-shooting environmental carrying capacity. The propensity for shocks to aquaculture adds caution to suggestions that aquaculture alone will be able to reliably meet future seafood demands (Liu and Sumaila, 2008; Troell et al., 2014). However, the aquaculture sector is highly diverse with a multitude of species and systems under different governance regimes and they differ greatly from a resilience perspective. Further, by diversifying food sources and enabling greater control throughout the production system, aquaculture has the potential to add resilience to the overall food system, particularly when the potential sources of shocks are taken into consideration (Troell et al., 2014).

3.2. Shock impacts on trade and seafood supply

Countries are expected to respond to a shock to seafood production in the short-run through a combination of increased imports, decreased exports, and decreased supply. In the detected shocks, imports increased in over one and a half times as many cases as it decreased. Exports increased and decreased equally commonly, while supply decreased nearly twice as often as it increased (Table 2). The most common combinations were: 1) imports and supply decreases with export increases; 2) increases in all three, and; 3) import increases with export and supply decreases. Counterintuitive increases in exports suggest that some component of the seafood industry is unaffected by the shock. The specific impact on trade and supply is context dependent, with trends in the trade balance and the fishery or fisheries being affected playing a large role in how the shock impacts trade and supply. To illustrate this point, four shock cases and the impact on trade and supply are described below.

3.2.1. Former USSR: a case of political and policy changes

The shock with the largest magnitude occurred in 1992 in the former USSR countries and can be attributed to the breakup of the Soviet Union in 1991. From the 1970s up to 1991 the Soviet Union supported a large coastal and distant fishing industry with an estimated \$30 billion in subsidies (Milazzo, 1998; Österblom and Folke, 2015). This led to an overcapitalization of the Russian fleet and supported high levels of total catch (Fig. 4). The subsidies also

Table 2

Frequency of combinations of increases (+), decreases (–), and no change (o) in imports, exports, and supply at a shock point and total increases, decreases, and no change observed for imports, exports, and supply.

Frequency	Imports	Exports	Supply
10	–	+	–
9	+	+	+
7	+	–	–
5	+	–	+
5	–	–	–
4	+	+	–
4	+	–	o
2	–	–	o
1	–	+	+
1	–	–	+
1	+	+	o
1	o	–	–
Total Increases	30	25	16
Total No Changes	1	0	7
Total Decreases	19	25	27

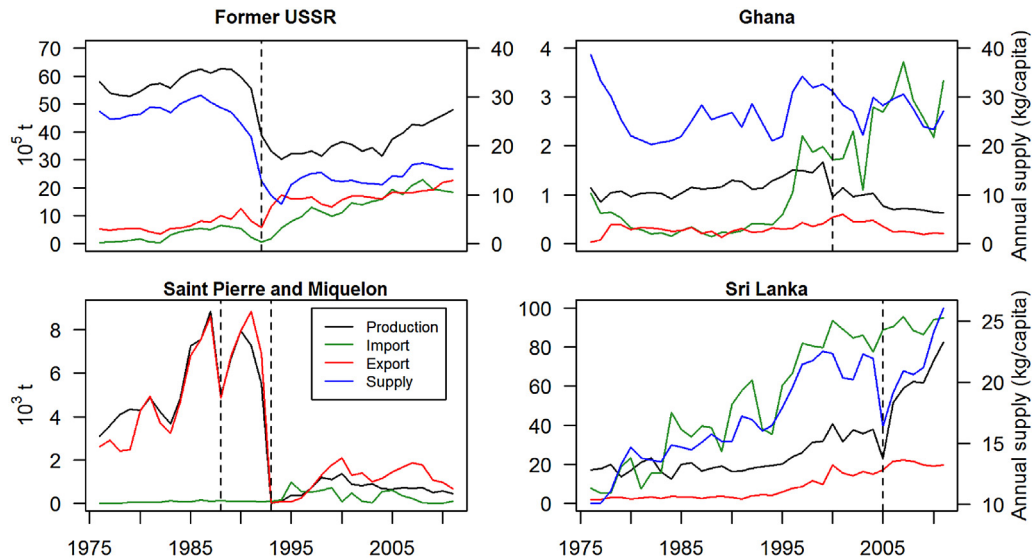


Fig. 4. Time series of production (black), imports (green), exports (red), and per capita supply (blue; right axis scale) for the former USSR, Ghana, Saint Pierre and Miquelon, and Sri Lanka. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

resulted in an inefficient fleet, with Soviet ships landing 1/5 of the catch per ton of fishing fleet compared to the EU or Japan at the end of the Soviet Era (Kravanja and Shapiro, 1993). Financial support for the fisheries rapidly disappeared after the dissolution of the Soviet Union and the aging ships were divided among the newly independent states (Milazzo, 1998). Fish catch dropped precipitously during this transition (Fig. 4). Without the subsidies most fishing operations were no longer profitable and 80–85% of the assessed fishing enterprises were filing or near filing bankruptcy (Milazzo, 1998).

Exports increased gradually during the 1980s after the USSR opened trade to socialist countries, but decreased during the early 1990s during the dissolution of the USSR (Fig. 4). The exports rebounded by the mid-1990s and continued to increase thereafter, coinciding with the former Soviet countries opening to trade with the West. In the period immediately following the dissolution of the Soviet Union the exports as a percent of catch increased dramatically. This situation is exemplified by Estonia, where foreign trade opening within the country caused the price of fish to grow to nearly the level of Western Europe and for fish exports to increase rapidly (Vetemaa et al., 2006). Further, Estonia's independence allowed access to fishing grounds that were previously tightly regulated by Soviet border controls (Vetemaa et al., 2006). The Estonian government passed policies aimed at increasing access to fisheries for household consumption, but high prices for fish resulted in catches being sold to traders for export (Vetemaa et al., 2006). The decreased catch in conjunction with the increased exports can explain the initial drop in per capita seafood supply in 1992 and the further decline through 1994 (Fig. 4). The rebound in supply corresponds to the gradual increase in imports and catch. Nevertheless, the supply and catch do not return to pre-shock levels by the end of the time series (Fig. 4). This case illustrates a large political shock with lasting impacts throughout the fishing industry. Clearly, the breakup of the USSR had impacts far beyond fishery catch, including the dramatic changes in trade policies which can help explain the increases in both imports and exports which may not otherwise be expected at a shock point.

3.2.2. Ghana: a case of overfishing

Ghana has historically been a major fishing nation in West Africa, with a high reliance on seafood for nutrition, employment,

and the national economy (Atta-Mills et al., 2004). Ghana's productive coastal waters in the Gulf of Guinea result from the Central West African upwelling system. There is seasonal variability in the fishery's productivity due to annual upwelling cycles, while interannual variability is driven by large-scale atmospheric pressure systems in the South Atlantic and El Niño events in the tropical Pacific (Perry et al., 2011). Despite this natural variability, the year 2000 represents a shock that falls outside the normal variability of the system and over-exploitation is the most likely explanation for this drop in catch (Fig. 4; Atta-Mills et al., 2004). By the mid-1990s landings of pelagic fish had leveled off and inshore marine resources were fully- or over-exploited (Perry et al., 2011; Atta-Mills et al., 2004). Further, catch per unit effort for demersal species declined through the 1980s and 1990s (Koranteng, 2002). Total catches were maintained through the 1990s by fishing farther off shore or switching gear to target different or new species. Historically, Ghanaian fishermen had adapted to periods of low catch by migrating to new fishing areas, but enforcement of the Economic Exclusive Zones and other policy actions by neighboring countries limited migration opportunities (Atta-Mills et al., 2004).

Despite the drop in total production in 2000, seafood exports remained relatively constant, thereby representing an increase in the percent of seafood exported (Fig. 4). During the mid-1990s when catch per unit effort was declining, imports increased and Ghana became a net importer of seafood. Now, Ghana primarily exports high value species (e.g. shrimp, tuna, cuttlefish) while importing lower value, frozen seafood (Atta-Mills et al., 2004). Around this time per capita supply of seafood began to track the pattern in imports (Fig. 4). Although the catch and supply numbers for Ghana likely underestimate the role of subsistence fisheries (Nunoo et al., 2006; Pauly and Zeller, 2016), the data capture the dominant patterns in production, trade, and supply. This case illustrates historical overfishing, possibly in combination with limitations on fishing in neighboring waters, leading to a drop in production and a long-term trend of increasing imports compensating for stagnating catches.

3.2.3. Saint Pierre and Miquelon: a case of political dispute, policy change, and overfishing

Saint Pierre and Miquelon are French territorial islands off the coast of Newfoundland. The islands' economy has traditionally

been based on fishing and servicing fishing vessels (The World Factbook, 2016). Cod is the most important fishery for the islands and this case illustrates a situation where seafood catch is largely destined for export and the exports trace the annual catch very closely (Fig. 4). France's fishing rights in the waters off Newfoundland date back to the Treaty of Utrecht of 1713, but became a source of dispute in the 1977 when both France and Canada extended their fishing zones to 200 NM from their coasts (McDorman, 1990). This resulted in overlapping claims to waters with productive fisheries and potential hydrocarbon resources (McDorman, 1990). A 1972 agreement allowing France access to 17,500 tons of catch kept the dispute at bay. But, the territorial struggle escalated and peaked in 1987–1988 when Canada claimed France was exceeding its fishing quota, denied the agreement renewal, and blocked French vessels from ports and the fishing grounds (Burns, 1988). Canada then arrested the crew of a vessel registered in Saint Pierre and Miquelon and France retaliated by expelling the Canadian ambassador to France and denying Canadian citizens entry at Parisian airports (McDorman, 1990). The 1988 dispute is identified as the first shock point in Fig. 4. Canada and France reached an agreement through mediation in 1989 and fish catch in Saint Pierre and Miquelon rebounded (McDorman, 1990; Fig. 4). However, in 1993, a much larger shock occurred when the cod stock was near commercial extinction and the entire fishery was closed to rebuild stocks (Hutchings and Myers, 1995). Immediately following the reductions in catch, Saint Pierre and Miquelon's seafood imports increased, before catch increased to a moderate level compared to the pre-shock conditions (Fig. 4). FAO seafood supply information is unavailable for these islands, but the collapse and closure of the cod fishery severely impacted the livelihoods of the people in the region (Milich, 1999). This case illustrates a political dispute and a policy change, both with a back drop of overfishing.

3.2.4. Sri Lanka: a case of a natural disaster

Prior to the December 2004 tsunami, Sri Lankan fisheries employed around 163,000 people, with subsistence fishing providing a livelihood for many unemployed people (Ministry of Fisheries and Aquatic Resources, 2003). Sri Lanka's fisheries are known to have been stressed prior to 2005, but the tsunami and resulting devastation was directly associated with the 2005 shock to production. Ten of the twelve main fishing harbors were severely damaged, along with 65% of the fishing fleet (De Silva and Yamo, 2007). Damage to fishing craft and gear was particularly severe because the event occurred on a holiday when the boats were inshore and received the full impact of the tsunami (Stirrat, 2006). There was also significant damage to the post-harvest sector, including markets and retail stalls, as well as concerns about damaged waste water systems leaking into fishing grounds (De Silva and Yamo, 2007). Immediately following the disaster, a vast range of relief organizations became active in Sri Lanka. After natural disasters, there is an incentive for NGOs to spend money on visible aid, including in this case distributing new fishing gear (Stirrat, 2006). Such actions resulted in the number of boats in some areas of Sri Lanka to exceed the number of boats prior to the tsunami (FAO, 2007). This, along with the new boats having higher catching power than the old boats, can likely explain the sharp jump in seafood production the year following the tsunami (FAO, 2007; Fig. 4).

The majority of seafood produced in Sri Lanka is through small-scale fisheries and is destined for domestic consumption. This is reflected in Fig. 4 where the patterns of per capita supply mirror the patterns of seafood production. Sri Lanka is highly dependent on seafood, with 52% of animal protein derived from seafood and much higher levels of dependency in coastal fishing communities (De Silva and Yamo, 2007). Imported dry and canned fish flooded

the retail markets immediately after the tsunami, but the average prices were substantially higher than the average prices for local fish (Subasinghe, 2005). Overall, there was not an increase in the imports for 2005, but there was a substantial drop in per capita seafood supply at the shock point (Fig. 4). This case illustrates a shock from a natural disaster and the impacts this type of shock can have throughout the seafood system. It also illustrates a case where changes in trade fail to compensate for the drop in production, resulting in a temporary decrease in local seafood supply with possible impacts on the local food security.

3.3. Impacts beyond national seafood supply and trade balance

Shocks to seafood production extend beyond the per capita seafood supply and national trade balance. Capture fisheries employed 58.3 million people in 2012, with 37% of those people employed full time (FAO, 2014). Employment in the fishery sector has grown at a faster rate than the world population and traditional agriculture sector (FAO, 2014). A majority of people employed in fisheries live in Asia and Africa and the FAO estimates that the fisheries sector assures the livelihoods of 10–12 percent of the world's population (FAO, 2014). These figures may underestimate the number of people in the developing world employed through subsistence fishing (Teh and Sumaila, 2013) as well as employment being generated throughout the value chains and associated businesses (Béné et al., 2016). As a result, shocks can impact GDP and unemployment levels at the national scale and can have lasting impacts on those relying on fisheries income.

Declines in fishery catch can also cause shifts in employment, crime, and sources of food. For example, negative economic shocks to fisheries are correlated with an increase in piracy and declining fish harvests have been linked to increases in human trafficking when fishers attempt to minimize production costs (Flückiger and Ludwig, 2014; Brashares et al., 2014). Declines in seafood catch have also been linked to increased hunting in nature preserves and the sale of bushmeat in local markets in West Africa (Brashares et al., 2004). Thus, fishery shocks can reach beyond trade and nutrition, spill over negatively into other resource systems, and impact human trafficking, organized crime, and biodiversity conservation.

While this study focused on the trade balance impacts at the national scale, changes in imports and exports imply shifts in the trade partners' trade balances. A series of recent studies have explored the distant impacts of shocks to primary commodities in the global trade network during the 2008 grain crisis and through network models (Puma et al., 2015; Gephart et al., 2016; Tamea et al., 2016; Bren d'Amour et al., 2016; Marchand et al., 2016). These studies have found import-dependent countries, countries with low production diversity, and regions with low willingness to pay as being more vulnerable to external shocks in the network. Marchand et al. (2016) found that national reserves dampen the propagation of a shock. This suggests that since seafood is not held in reserves in the way grains are, the propagation of a shock originating from the fishery system could be more far-reaching. There are likely other knock-on effects of shocks in substitute food commodity systems which were not studied here, but are important to the overall food security impacts of shocks. Evaluating these distant and knock-on impacts of shocks in historical examples, such as those identified here is an important next step in understanding how shocks may alter the global trade network and impact food security and human well-being.

In addition to adapting to changes in domestic seafood production through trade, countries can replace seafood consumption by increasing the production of agriculture and livestock substitute foods. Such changes operate on a longer timescale than a single year shock and are likely important for step-changes in the

level of seafood production. However, countries' abilities to produce substitute foods is limited by their available land and water resources. For example, Gephart et al. (2014) evaluates the water cost and ability of countries to replace marine protein with terrestrial foods based on current consumption patterns and water resources. Developing coastal African and island nations were the most limited in their ability to replace marine protein through domestic agriculture and livestock production. Projections of changes in consumption of seafood and its substitutes under seafood production declines requires supply and demand modeling. For example, both the International Food Policy Research Institute's International Model for Policy Analysis of Agricultural Commodities and Trade and WorldFish's AsiaFish Model provide tools for projecting changes in consumption patterns under scenarios of seafood production declines (Delgado et al., 2003; Briones et al., 2004). However, such projections focus on gradual change and do not fully capture the short-run changes that immediately follow a shock.

Sudden decreases in seafood production propagate shocks through multiple components of the food production system. Immediate responses are that countries may import more or export less seafood, or domestic seafood supply may drop. Those employed in fishing or fish processing may become unemployed or seek work elsewhere, resulting in potentially unexpected consequences. Decreases in seafood supply likely result in increased consumption of substitute foods, but may also result in restricted nutritional access for those with limited access to substitute foods. In the longer-run, countries which do not recover from the shock may increase the production of substitute foods. However, the ability to do so is limited by available natural resources. The capacity of countries and communities to respond and adapt to shocks to seafood production speaks to their resilience. Learning from historical examples of shock causes, impacts, and responses provide opportunities to build resilience.

4. Conclusion

Shocks are a common feature of seafood production systems which occur due to a variety, and often multiple and simultaneous, causes. Shocks occurred the most frequently in Central America and the Caribbean, the Middle East and North Africa, and South America, but the largest magnitude shocks occurred in Asia, Europe, and Africa. Shocks also occurred more frequently in aquaculture than in capture systems. The complementary quantitative and qualitative methods employed here provide a systematic approach to look back in time to identify shocks and evaluate their impacts in an increasingly globalized system. While the trade balance and food supply response to shocks is context specific, there is a tendency for the imports to increase and the supply to decrease. Historical examples of shocks can inform policy considerations for responding to shocks and learning from these examples helps identify potential risks and opportunities to building resilience in the global food system.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.gloenvcha.2016.11.003>.

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