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LETTER

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Abstract

Trade can allow countries to overcome local or regional losses (shocks) to their food supply, but reliance on international food trade also exposes countries to risks from external perturbations. Countries that are nutritionally or economically dependent on international trade of a commodity may be adversely affected by such shocks. While exposure to shocks has been studied in financial markets, communication networks, and some infrastructure systems, it has received less attention in food-trade networks. Here, we develop a forward shock-propagation model to quantify how trade flows are redistributed under a range of shock scenarios and assess the food-security outcomes by comparing changes in national fish supplies to indices of each country's nutritional fish dependency. Shock propagation and distribution among regions are modeled on a network of historical bilateral seafood trade data from UN Comtrade using 205 reporting territories grouped into 18 regions. In our model exposure to shocks increases with total imports and the number of import partners. We find that Central and West Africa are the most vulnerable to shocks, with their vulnerability increasing when a willingness-to-pay proxy is included. These findings suggest that countries can reduce their overall vulnerability to shocks by reducing reliance on imports and diversifying food sources. As international seafood trade grows, identifying these types of potential risks and vulnerabilities is important to build a more resilient food system.

1. Introduction

Currently, about one fourth of the world's food production is internationally traded (D'Odorico *et al* 2014) and this proportion continues to grow. The increasing globalization of food is driven by decreasing costs of communication and transportation (Iapadre and Tajoli 2014), as well as the benefits of international trade. These benefits include increased competition and variety in international markets, access to capital investments and larger markets, and buffering against local supply shocks (sudden losses). Buffering against local supply shocks occurs when international trade provides access to food following a sudden decrease in food production in one region. However, there are also disadvantages to international trade, such as potential loss of jobs, loss of commodities domestically to higher price

opportunities abroad, and exposure to shocks in other parts of the trade network.

Exposure to a shock could be realized by decreased exports from a region, which would alter the commodity prices and imports in other regions. Shock propagation in networks has previously been studied through models in financial markets, ecosystems, and in simulated networks (e.g. Callaway *et al* 2000, Dunne and Williams 2009, Gai and Kapadia 2010, Kali and Reyes 2010). Recently, several studies analyzed the impacts of the 2008 grain crisis on trade, highlighting the importance of shock propagation within the food-trade system for food security and vulnerability (e.g. Heady 2011, Acemoglu *et al* 2015). Nevertheless, few studies have analyzed this phenomenon for food-commodity trade networks. In order to evaluate the forward propagation of a shock (transmitted through changes in exports) in a food-trade network, we

develop a model that utilizes empirical data on trade flows and includes basic economic realism through proxies for goods substitution and willingness to pay.

We apply our model to the global trade network of fish and other aquatic foods (hereafter seafood) to quantify exposure to external shocks. While such an approach could be taken with other food commodities, we selected seafood because it is among the most highly-traded food commodities, making up around 10% of all trade (Food and Agriculture Organization 2014a, 2014b) and is increasingly globalized, with a 4.5% annual real growth rate, increasing trade connectivity and is being consumed at increasingly distant locations from where it is sourced (Food and Agriculture Organization 2014a, 2014b, Gephart and Pace 2015, Watson *et al* 2015a, 2015b). Further, seafood plays an important role in food security, making up nearly 20% of animal protein consumption (Kent 2003) and is impacted by multiple potential shocks including natural disasters, fishery collapses, policy changes, and price spikes in inputs (such as fossil fuels). We are interested in shocks which occur suddenly, with little warning, such that regions cannot increase production on a time-scale relevant to the time-scale of the perturbations. This framework is reasonable for many real shocks because capture fisheries generally operate at or near the highest production permitted and aquaculture requires investment and time to increase production. Within a longer time frame, aquaculture production would be expected to change in response to the shocks studied. A general equilibrium model that incorporates price responses and demand elasticity would be more appropriate to model the impacts of longer-term changes (e.g. Delgado *et al* 2003). However, focusing on sudden shocks is of particular interest because even temporary decreases in protein and micronutrient availability can have important food security and development impacts. While micronutrient deficiency is less apparent than staple crop shortages, this 'hidden hunger' also plays a critical role in development and food security (McClanahan *et al* 2013).

Hypothetical shocks are analyzed to observe the behavior of shock propagation in the system, but represent real scenarios. For example, fishery collapses or closure of fisheries to prevent collapses can both serve as a shock to the fish trade network. Natural disasters also cause a shock when fishing gear and infrastructure are destroyed. This occurred in 2004, when the Caribbean experienced four large hurricanes that damaged or destroyed over 140 of the 720 fishing vessels and harmed fishing trade infrastructure (Westlund *et al* 2007). Similarly, in 2002, a typhoon in the Philippines damaged pond infrastructure and resulted in an estimated 2000–3000 metric tonnes of lost fish production (Westlund *et al* 2007). Environmental disasters are also a source of shocks. For example, the Exxon Valdez oil spill in 1989 resulted in the complete closure

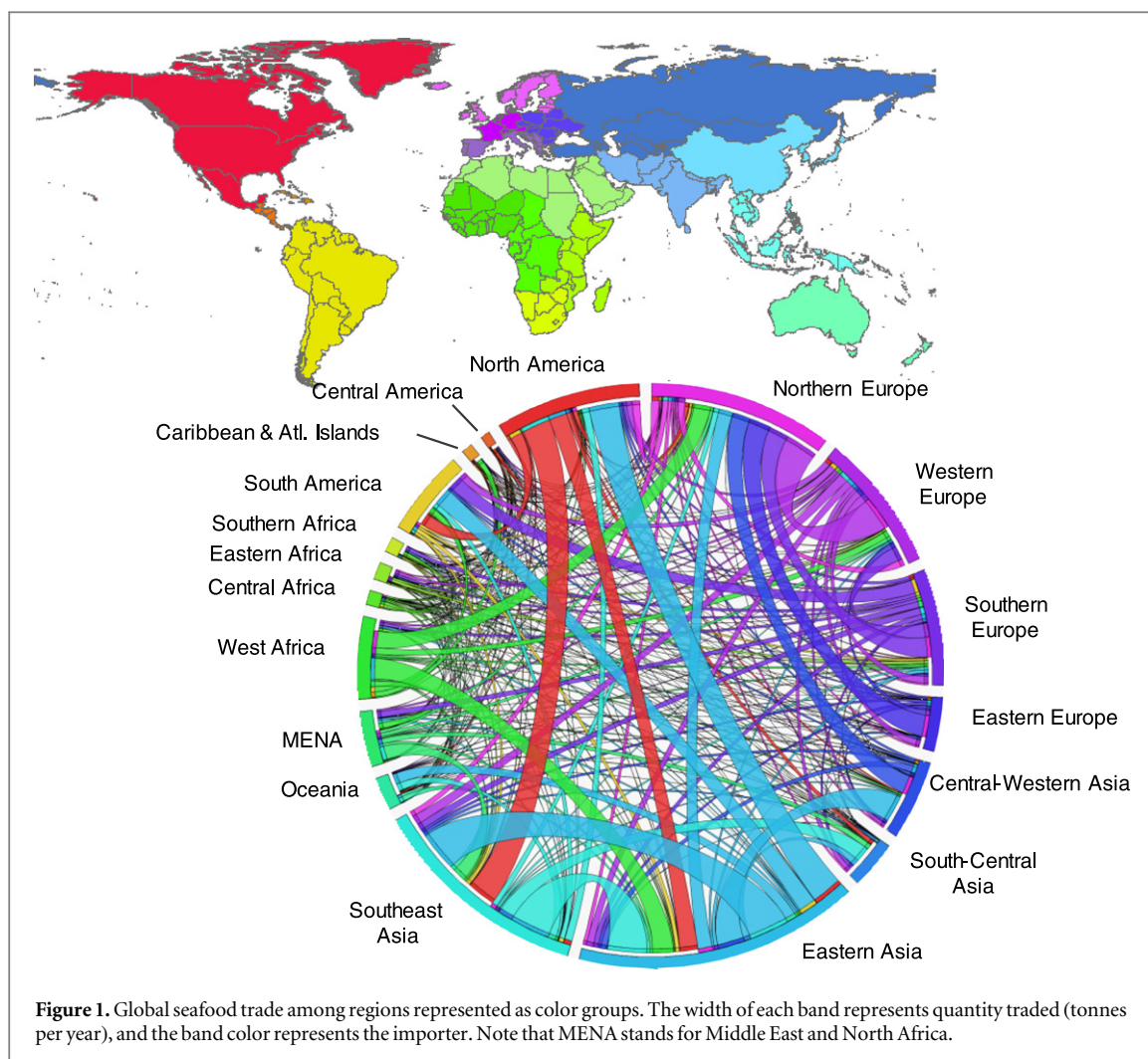
of the Alaskan fishery, which annually had produced 240 000 tons of fish (Westlund *et al* 2007). Aquaculture production is subjected to shocks as well, including extreme cold temperatures during winter that kill fish in ponds (Westlund *et al* 2007), and diseases that spread rapidly through fish farms. Since many aquaculture and capture fishery systems are heavily-dependent on fossil fuels, energy price spikes could impose a shock to seafood production (Pellitier *et al* 2014).

In order to assess the food security implications of sudden shocks, in this study we consider the results within the vulnerability framework used by Allison *et al* (2009), which is an extension of the Intergovernmental Panel on Climate Change vulnerability framework (IPCC 2001). They highlight three components of vulnerability: exposure, intrinsic sensitivity, and adaptive capacity. Exposure measures the impact that a region is likely to experience, intrinsic sensitivity represents the economic and food security dependence on the natural resource, and adaptive capacity indicates the ability for the impacts in the region to be offset. In our study we measure the exposure as the percent of a shock that ends up in each region. This is quantified through a shock propagation model. However, the food security outcomes of decreased seafood supply likely differ for regions consuming luxury seafood products versus non-luxury goods and the degree to which individuals have access to substitute foods. As a proxy to account for this, we compare modeled regional exposure to data on intrinsic sensitivity (dependency on seafood, calculated as the percent of animal protein derived from seafood). We then also compared our modeled exposure and the calculated sensitivity to existing adaptive capacity indices to account for regions' abilities to offset shocks through governance, infrastructure, and socio-economic factors in order to reveal overall regional vulnerabilities to shocks in the network.

2. Methods

2.1. Data description

We construct the global seafood trade network using the United Nations' Comtrade database (Comtrade 2010) following Gephart and Pace (2015). This database contains self-reported annual import and export bilateral trade flows (in US dollars). This network represents seafood products destined for human consumption (selected from Harmonized System codes 03 and 16) during the year 2011. In order to convert the trade flows from dollars to quantities, average tonnes imported per dollar is calculated for each country using the Food and Agricultural Organization (FAO) FishStat database (2013), which provides total tonnes and value (in US dollars) imported for each country. This conversion factor is then applied to each country's imports to



generate a network of seafood trade in tonnes. A linear regression of the sum of the quantity of imports in the resulting network versus the reported total imports in the FishStat database indicated a close-to-linear relationship ($r^2 = 0.96$) with a slope of 0.91 (p -value < 0.001). The regression between the sum of the quantity exported and the exports reported in FishStat also shows a close relationship ($r^2 = 0.98$, slope = 0.94, p -value < 0.001). The slopes near one and high r^2 indicate that the magnitude and patterns of the network used for this analysis agree well with FishStat. The trade network is depicted in figure 1 using Circos (Krzyszowski *et al* 2009).

Per capita calculations use 2011 population size from the FAO (2014b) database. In order to evaluate the effect of allowing wealthier regions with higher willingness to pay to pass on more of the shock, gross national product (GDP) per capita data for 2011 from The World Bank (2014) is used to modify the distribution of shock (described below). To evaluate vulnerability, we compared exposure to the percent of animal protein derived from fish from FAO (2014b).

2.2. Model description

The spread of shocks within the seafood trade network and resulting changes in fish supply are investigated using a forward-propagation model. Our model builds on the ecosystem model of energy perturbations by Hannon (1973). We modify this approach so that the fish exports from one region are decreased to represent a perturbation, and this shock to the system is then propagated throughout the network based on the network structure and basic economic features. Shocks are transmitted by decreased exports from one region reducing the flows to importing regions. Regions with reduced imports can then either reduce their own exports, thus passing on the shock, or reduce their domestic fish supply, thus absorbing the shock locally. The resulting model is structurally similar to a recent, independently-developed model evaluating shocks in the virtual water-trade network (Tamea *et al* 2016).

In reality the reduction of exports versus reduction of domestic consumption depends on the volume of exports available to reduce, available substitute goods, and the local price sensitivity to changes in seafood price that result from decreased supplies. In our model, substitutability is accounted for by decreasing

the percent of the shock being passed on at each iteration, while willingness to pay is represented as a function of GDP per capita. Since many of the necessary economic parameters to model substitution and price sensitivity are unavailable, the amount of shock being passed on (parameter q), and the influence of GDP per capita on how the shock is distributed (parameter α) are each varied to explore the influence of substitution and price sensitivity on which regions absorb the shock (see equation (5)). A decrease in seafood supply through the portion of the shock which is not passed on ($1 - q$) encompasses both substitution with non-seafood commodities and a decrease in seafood consumption which is not replaced by other foods. In order to identify the cases where decreased supply is likely more relevant to food security, the decreased supply (exposure) is compared to dependence on seafood (sensitivity).

We consider n trading partners and let F_t be the matrix of trade flows between the partners at each discrete iteration $t = 1, 2, \dots$. Depending on the context, we refer to a trading partner as a node, an exporter, or an importer. The column sums of F_t represent the total exports from each exporter, $e_{t,k} = \sum_{j=1}^n F_{t,jk}$, and the row sums represent the total imports to each importer, $i_{t,j} = \sum_{k=1}^n F_{t,jk}$. We assume that the initial trade flows, F_0 , are determined from the United Nations' Comtrade database as described in the previous section, i.e. $F_0 = F^{\text{data}}$.

To investigate the effect of a perturbation to the trade network, we assume that a shock at iteration $t = 1$ reduces the exports of a node \hat{j} by a fraction s , $0 \leq s \leq 1$. Specifically, $e_{1,\hat{j}} = (1 - s)e_{0,\hat{j}}$ while $e_{1,j} = e_{0,j}$ for $j \neq \hat{j}$. Thus the shock received by node \hat{j} at iteration $t = 1$ is given by $\Delta i_{1,\hat{j}} = i_{1,\hat{j}} - i_{0,\hat{j}}$. We assume that a proportion q , $0 < q < 1$, of a received shock is passed on from imports to exports in each iteration and the amount of passed shock is distributed over its receivers through the altered trade flows according to a given transfer matrix T_t . So, an amount $(1 - q)\Delta i_{1,\hat{j}}$ of the shock is absorbed at node \hat{j} and the remaining part $q\Delta i_{1,\hat{j}}$ is to the extent possible passed forward to trading partners. Nodes are unable to pass on the shock when their exports become zero. At that point, any additional shock passed to that node is absorbed locally rather than being passed on. Specifically, we let $F_{1,jk} = [T_{jk}(e_{0,j} - q\Delta i_{1,j})]^+$ be the new trade flow from node j to node k ; here and in what follows superscript plus sign is used to indicate the maximum of the value in the parenthesis and 0. Iteratively, we define the 'perturbed' dynamics as follows

$$F_{t+1,jk} = [T_{jk}(e_{t,j} - q\Delta i_{t+1,j})]^+, \quad (1)$$

$$\Delta i_{t+1,j} = i_{t+1,j} - i_{t,j}. \quad (2)$$

Iterations are continued until all of the shock has been distributed ($t = t^{\text{equil}}$). The change in fish supply, or exposure of a node to a shock, is given by

$$c_k = \sum_{t=1}^{t^{\text{equil}}} [(1 - q)\Delta i_{t,k} + (q\Delta i_{t,k} - e_{t,k})^+]. \quad (3)$$

There are different ways to define the transfer matrix T ; in the simplest case we assume that the received shock is passed on in proportion to exports. Proportional propagation of shocks is empirically supported (Tamea *et al* 2016). In this case the elements of the transfer matrix are given by

$$T_{jk} = \frac{F_{0,jk}}{e_{0,j}}. \quad (4)$$

In order to incorporate the effect of larger willingness to pay of richer countries, we modify (4) as follows

$$T_{jk} = \frac{F_{0,jk}g_k^\alpha}{\sum_{k'=1}^n F_{0,jk'}g_{k'}^\alpha}, \quad (5)$$

where g_k is the per capita GDP of country k , serving as a proxy of the country's willingness to pay; $\alpha \geq 0$ is the degree of per-capita GDP influence on the distribution of the shock. When $\alpha = 0$, the transfer of the shock does not depend on per-capita GDP and is proportional to exports. As α increases, the adjusted trade flows will be increasingly directed to countries with higher per-capita GDP. In this way, we account for consumers in high-income countries that tend to be less price-sensitive and therefore their seafood purchases may not be substantially reduced by the higher prices, resulting in more of the shock being passed to the lower per capita GDP countries. Although this means that the trade flows will be altered even in the absence of a shock, α values were selected to have a limited impact on the distribution of trade in t^{equil} iterations. The end result of using this expression for the transfer matrix is similar to that of a larger degree of the shock being transmitted to countries with lower per capita GDP. While α is varied to assess the impact of including a willingness to pay proxy, α is set to zero for all other results presented.

It should also be noted that for the case of small shocks, a closed formula can be derived (See appendix for formula and derivation). This closed formula applies for shocks which are small enough such that no node reaches the threshold point of not being able to further reduce its exports.

The above model was run for a range of parameter values from 0 to 1 in increments of 0.1 for s , q , and for the values 0, 0.01, 0.05, 0.1, 0.5, 1, 5, and 10 for α . The different values of s represent different degrees of shock, to explore the effect of shocks of different magnitudes that could occur, whereas different values of q and α are explored because their values are unknown and difficult to parameterize empirically.

2.3. Model robustness

In our simulations 50% of the shock was absorbed for all q values after 10 iterations and 80% was absorbed after 20 iterations. The shock is absorbed much more rapidly when the percent of shock being passed on at each iteration is decreased (see supplementary figure

A1). In addition to decreasing the percent of the shock remaining at each iteration, increasing the percent of the shock passed on at each iteration shifts the distribution of countries absorbing the shock (see supplementary figure A2). For example, when little shock is passed on (a low degree of spread), the majority of the shock is absorbed by the regions importing from the perturbed regions. However, when more of the shock is passed on at each iteration (a high degree of spread, q), the shock is absorbed by only a few regions, notably West Africa and Central Africa. We assume that all regions have the same propensity for passing on shocks, i.e., each are assigned the same value of the parameter q , but the present model could be extended by allowing different values of q . We show that the main model results are robust to reasonable and independent variation in q across regions in the supplementary information.

Further, while larger shocks generate larger decreases in fish supply, the propagation and distribution of the shock is robust to the degree of the shock imposed (see supplementary figure A3). Although extreme degrees of shock may be unlikely to occur, studying hypothetical extremes is useful to understand system behavior and resilience (Ilmola *et al* 2013). The remaining analyses represent an average over a uniform distribution of the degree of shock, but the patterns observed are scalable to smaller or larger perturbations. In order to illustrate the variation in the impact of shock across the parameters, regional exposure is explored across parameter values for the percent of shock passed on, with the GDP influence held at zero (see supplementary figure A3), and then is explored for the median percent of shock passed on, with varying GDP influence (figure 4).

3. Results

At the regional level trade links exist between nearly all pairs of regions (figure 1). Regions with the largest total imports and exports, including Northern Europe, North America, and Eastern and Southeast Asia, are indicated by the wide flow bands. The largest trade flows are from Eastern and Southeast Asia to North America, from North America to Eastern Asia, from Southeast Asia to Eastern Asia, and from Northern Europe and Eastern Asia to West Africa.

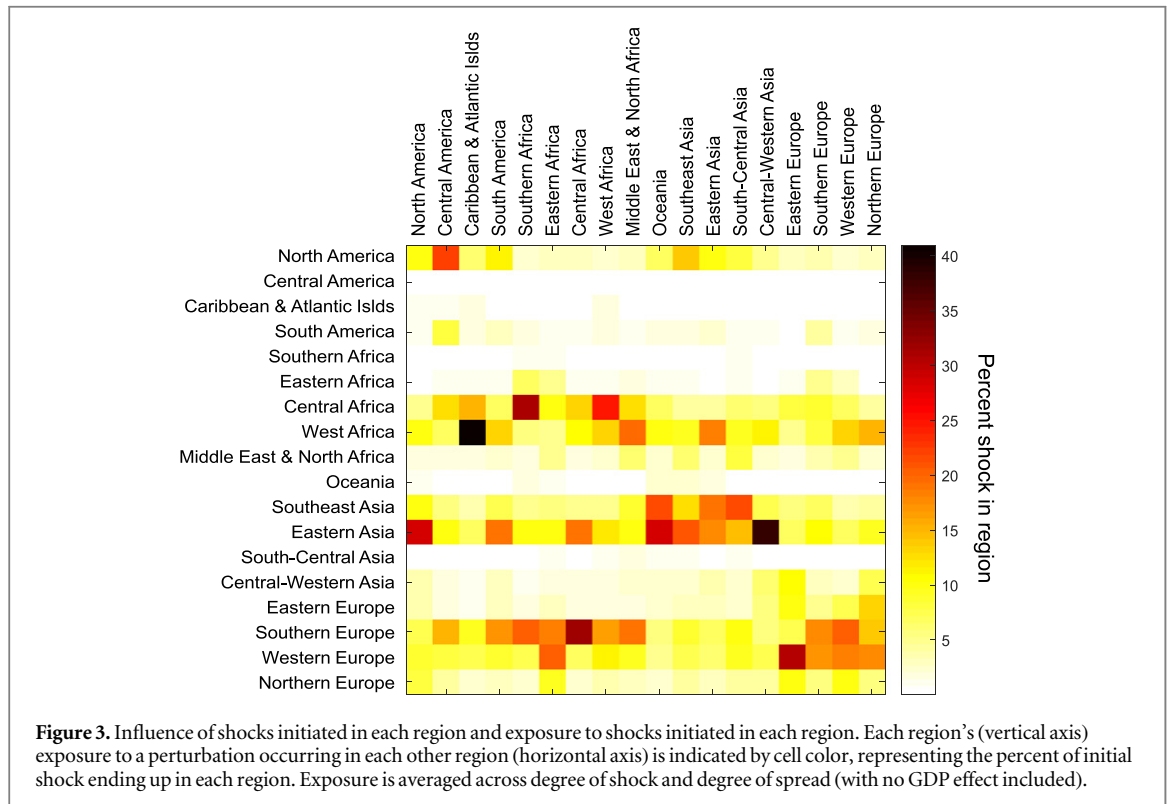
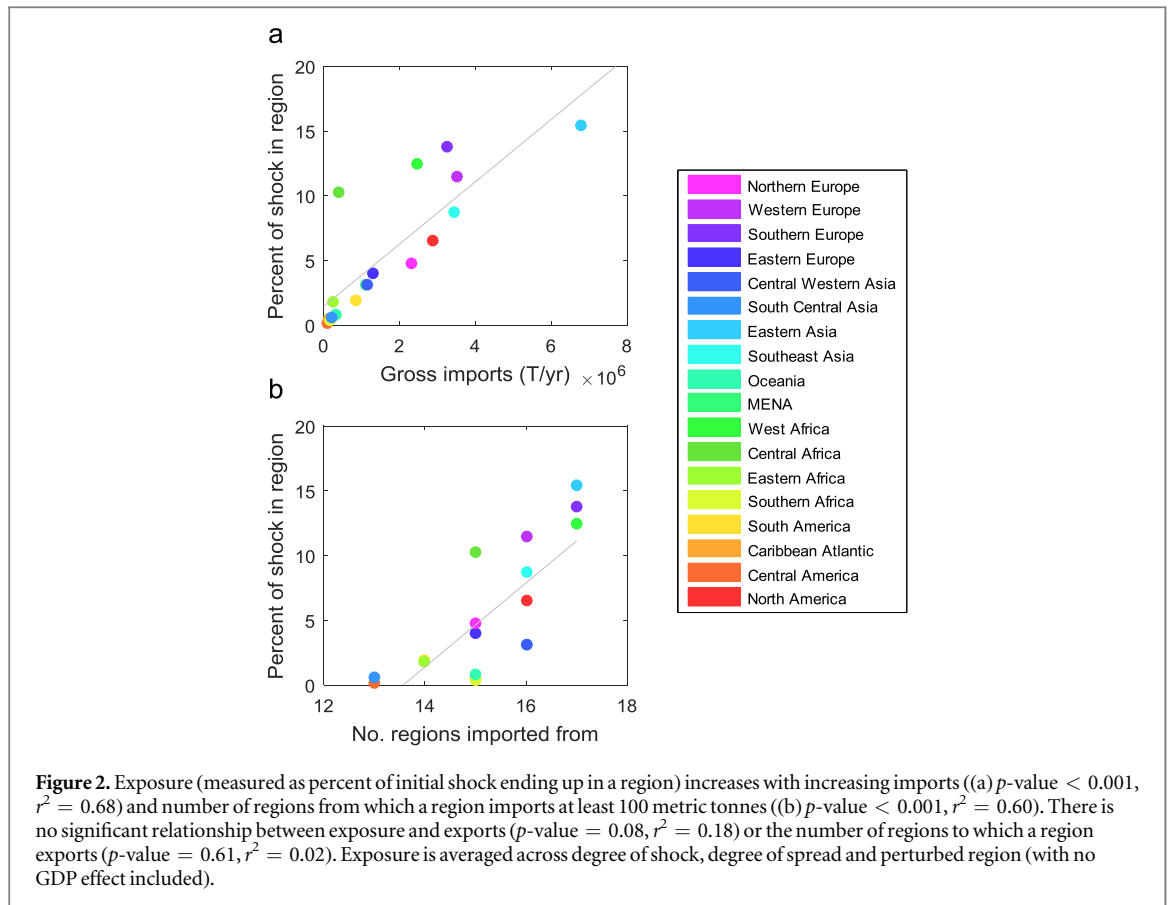
3.1. Net importers and regions importing from more regions are more exposed to shocks

A feature of the model is that exposure increases with increasing imports and number of regions from which a region imports (figure 2). These two features are intuitive given that regions which import large volumes of seafood can be passed more of a shock and regions importing from more regions are passed shocks more often and from more directions. The regions with the highest exposure to external shocks

are West Africa, Eastern Asia, and Southern and Western Europe. Each of these regions falls relatively high in gross seafood imports and in the number of regions from which they import (figure 2). While there is no significant linear relationship between gross seafood exports and exposure, low exports can help explain the high exposures of Central and West Africa. Regions with low exports are more likely to reach the threshold point where they cannot decrease their own exports and pass the shock on. Instead, at this threshold all shock passed to them must be absorbed locally as a decrease in seafood supply. This feature of the model supports previous findings that dependence on imports for staple crops increased countries' exposures to grain shocks, specifically the 2008 grain crisis (Puma *et al* 2015). Thus despite the food security benefits that arise from international trade, over-reliance on importing major food commodities exposes countries to external shocks.

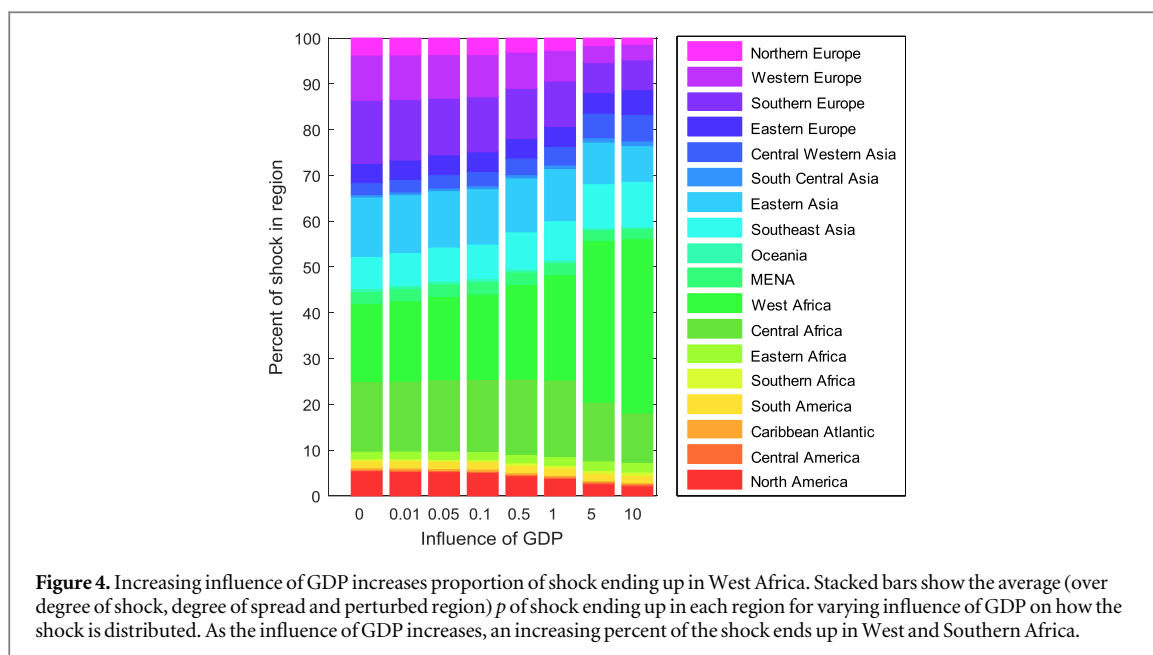
The regions which are most exposed to shocks initiated in any given region are Central and West Africa, Eastern Asia, and Southern and Western Europe, indicated by the row of dark cells in figure 3. However, some regions are highly exposed to shock in particular other regions. For example, 44% of a shock initiated in the Caribbean and Atlantic ends up in West Africa, 36% of a shock initiated in Central Western Asia ends up in Eastern Asia, and 33% of a shock initiated in Eastern Europe ends up in Western Europe (figure 3). As a result, the effect of a particular shock is dependent on the network structure and can have a relatively large impact on a region that does not have high exposure on average. However, these regions are not necessarily the largest importers from the region where the shock was initiated, which agrees with the findings by Tamea *et al* (2016). There is also variation in the effect of a particular shock based on the percent of shock passed on at each step, particularly for West and Central Africa (see supplementary figure A4).

Exposure is quantified as the percent of a shock ending up in each region, but regions with greater exports can impose a larger shock on the network. When multiplied by the magnitude of the initial shock, the largest supply decreases occur due to the Northern Europe, Eastern Asia, and Southeast Asia, implying these regions exhibit the most influence, or power, within the trade network. Specifically, the largest supply decreases occur in West Africa (from a shock initiated in Northern Europe or Eastern Asia), in Eastern Asia (from a shock initiated in Southeast Asia), or in North America (from a shock initiated in Southeast Asia). The next largest decreases across the parameters occurred in Western Europe (from shocks initiated in Western or Northern Europe, or Southeast Asia) and in West Africa (from shocks initiated in Southeast Asia, South America, West Africa, or Western Europe). This finding is robust across the range of values for the propensity to pass shock on and for the influence of GDP.



Regions with higher GDPs would likely also have a higher average willingness to pay for seafood and could purchase the seafood at a higher price under a shock scenario. This would cause shocks to dissipate in

that region. To explore regional exposure in the case where regions that are less price-sensitive receive less of the shock, a GDP effect was incorporated by altering the distribution of the shock (represented in the model



by increasing α). As the influence of GDP increases, the distribution of the shock shifted such that the poorest countries absorbed more of the shock (figure 4). This caused an increasing percent of the shock to end up in West Africa, making West Africa even more exposed to shocks.

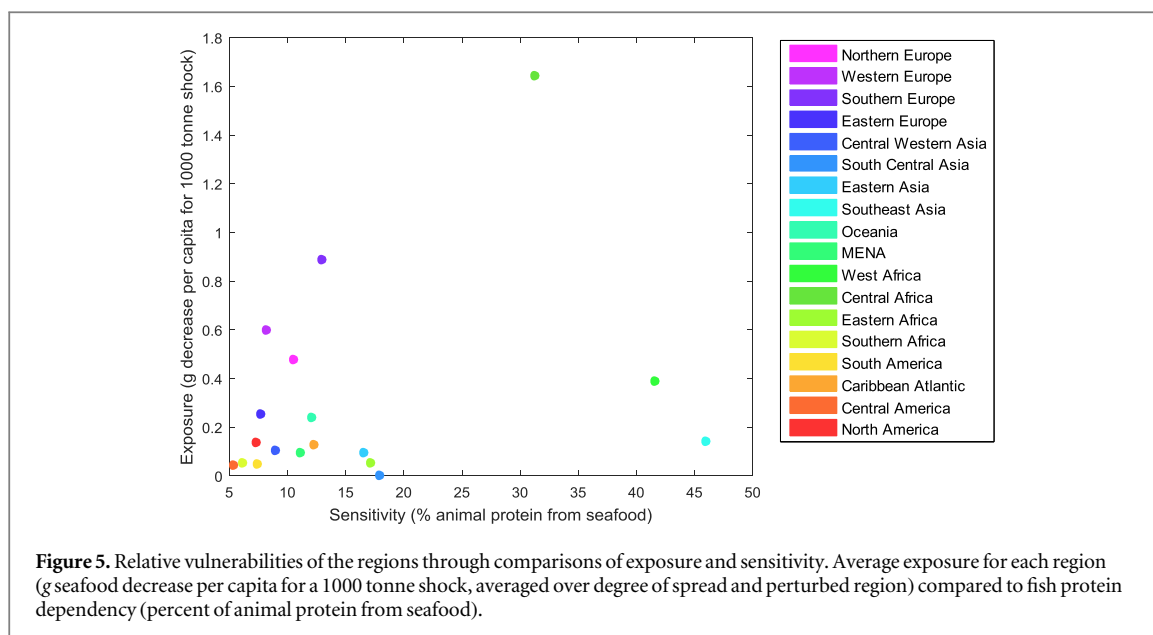
3.2. Central and West Africa are the most vulnerable to shocks

Comparing exposure within the trade network to intrinsic sensitivity reveals several general features of vulnerability to shocks to seafood exports (figure 5). West and Central Africa stand out as having relatively high exposure and sensitivity to shocks. While Western, Northern, and Southern Europe are also among the most exposed regions, they have relatively low sensitivity since a small percent of dietary animal protein is derived from seafood. Conversely, Southeast Asia has high sensitivity, but low exposure for most parameter values, which is partially explained by the region's comparatively high net exports. This result is an average over the region where the shock is initiated, but there can be higher vulnerability for specific perturbed regions (e.g. West Africa has high exposure to a shock originating in the Caribbean and Atlantic Islands). These comparisons only consider relative vulnerabilities. Moving from relative vulnerability to absolute vulnerability requires analysis with data on domestically-produced seafood protein, demographic distribution within each region, and the distribution of access to alternative protein sources. The demographic distribution and corresponding protein requirements is an important consideration for assessing vulnerability in more absolute terms because children, pregnant women, and individuals engaging in physical labor require higher intake of protein (National Research Council 2005).

Since the parameters controlling the spread and influence of GDP shift the distribution of the shock at equilibrium and the resulting exposure within the network, these parameters can change which regions are most vulnerable within the network. While the results of figure 5 depict an average over the degree of spread and do not include the influence of GDP, one can infer the effects of shifting these parameters on vulnerability from see supplementary figures A2 and A4. A higher degree of spread would result in West and Central Africa being more exposed, which would result in increased relative vulnerability. When a GDP effect is included, more of the shock ends up in West Africa. This would increase the exposure of each of these regions, which is particularly important for West Africa's vulnerability due to its high dependence on fish protein. (West Africa has the second highest fish protein dependency.)

The third component of vulnerability is adaptive capacity, or the potential, or ability of a system to adjust in response to a change (IPCC 2001). A region's adaptive capacity is comprised of factors such as levels of societal and human capital, and the effectiveness of governance structures (Allison *et al* 2009). In a study of the vulnerability of national economies to the effects of climate change on fisheries, Allison *et al* (2009) used an adaptive capacity index consisting of healthy life expectancy, education, governance, and size of economy. The lowest adaptive capacity indices were concentrated in Africa and tropical Asia. The low adaptive capacity of nearly all countries in Africa combines with the high exposure and sensitivity of African regions observed in this study to reveal relatively high overall vulnerability of these regions.

With relatively high exposure, high sensitivity, and low adaptive capacity, we find West and Central Africa to be the most vulnerable to shocks in the seafood



trade network. This finding adds to previous research on the impacts of international seafood trade on the poor in sub-Saharan Africa. While Béné *et al* (2010) found no direct benefits or negative impacts from international seafood trade on the poor in sub-Saharan Africa, our results suggest potential indirect negative impacts of international trade on West and Central Africa. This finding also agrees with Puma *et al* (2015) that least developed countries suffer the greatest losses due to supply disruptions in highly connected networks.

4. Discussion

The results of this study suggest a number of general implications for reducing national vulnerabilities to external shocks. The first is to reduce exposure to shocks by improving a country's trade balance and domestic production. Future seafood production is projected to come from aquaculture, but sub-Saharan Africa has been lagging in aquaculture development and currently represents less than one percent of the world's aquaculture production (Food and Agriculture Organization 2014a, 2014b). This is particularly relevant since West and Central Africa are among the most vulnerable regions to shocks. However, the region's significant land and water resources suggest the potential for substantial aquaculture growth (Subasinghe *et al* 2009). As a result, future support for aquaculture development in these regions may reduce these countries' exposure to external shocks.

Vulnerability to shocks can also be lessened by reducing sensitivity and increasing adaptive capacity. Sensitivity can be reduced by increasing food source diversity through both trade and domestic production. Since adaptive capacity indices represent multiple social and economic factors, including healthy life expectancy, education, governance, and size of

economy, there are no single or simple recommendations for improving adaptive capacity. However, by building adaptive capacity countries will reduce vulnerability to other threats, including climate change and some components of this increased adaptive capacity would contribute to other aspects of food security.

Since major exporters can impose larger shocks within the network, international trade policy should aim to minimize potential primary or secondary shocks originating in these regions. This study did not consider any secondary shock scenarios, but a potential secondary shock would be a country imposing export bans to protect domestic access to seafood. For example, a protectionist act similar to India's non-Basmati rice export ban in 2007, which contributed to the 2008 grain crisis. This ban on exports was enacted to protect domestic consumers from high wheat prices following a poor harvest season (Christiaensen 2009). Another potential secondary shock could occur if higher fish prices that result from decreased supply lead to increased pressure in other fisheries in the network and cause a collapse. While not explored here, such secondary shocks could occur in the system and would intensify the impacts of an initial shock, particularly when occurring in an influential country.

Vulnerability to external shocks should be considered as indirect risks of trade when crafting seafood trade policies, particularly when shocks are disproportionately experienced by developing countries. However, indirect risks must be considered on balance with the direct benefits countries can experience from seafood trade. These direct benefits from trade can vary greatly between countries. For example, seafood trade benefits food security in some countries with large offshore fisheries, such as Namibia, but not in countries with coastal fisheries, such as Ghana, Philippines, and Kenya (Kurien 2004). These benefits of seafood trade to food security are largely derived from

employment in the fishery sector, which promotes economic growth and the ability to purchase other foods (Jaunky 2011). Further, each of the vulnerability assessments presented represents an average over a number of countries, ignoring the heterogeneity in exposure and sensitivity within countries. While this study focused on the regional and national level, promoting food security at the subnational level requires policies which ensure the benefits of trade across socioeconomic groups.

Our method represents an alternative approach to models of the economic impacts of disasters using input–output models, which use the interrelationships of sectors to model shock propagation through intermediate changes in consumption and demand (Hallegatte 2008). By modeling the fish imports and exports based on how much of the shock is being passed on and how the shock is distributed, we imply interdependencies with other sectors, but do not assess the impact of a shock to fisheries on these other sectors explicitly. For example, while not studied here, shocks to seafood production would also disrupt employment and income in fisheries sectors. This would likely have negative impacts on the nutrition and wellbeing of local fishery workers. Our approach allows for the analysis of patterns of exposure to shocks that hold for most parameter values and arise from the network structure and trade flows. While the model and results we have presented demonstrate vulnerabilities based on the trade network structure and some basic economic features, more detailed quantification of substitution, evaluation of the percent of shock passed on and context-specific modeling is needed to develop specific seafood trade policies that reduce risk of exposure and promote overall food security.

5. Conclusion

The food system is increasingly globalized, which allows for buffering against local shocks, but exposes regions to external shocks. Evaluating exposure to such shocks helps assess vulnerability and risk within the global food system. Here we studied the response of the global seafood trade network to potential environmental and policy perturbations by modeling how negative local impacts propagate through the trade network and how trade flows are redistributed. Vulnerability to shocks in the network was assessed by comparing changes in national fish supplies to indices of each country's nutritional seafood dependency. The regions with higher imports, notably West Africa, Eastern Asia, and Southern and Western Europe tended to be most exposed within the network. As major exporters, Northern Europe, Eastern Asia, and Southeast Asia have the most significant influence initiating shocks in the network. Comparing exposure to sensitivity, revealed West and Central Africa to be relatively vulnerable to shocks within the network,

with West Africa becoming increasingly vulnerable when a GDP effect was included. The vulnerability of these regions is further emphasized by the low adaptive capacity previously reported in nearly all African countries. The methods developed in this study represent an approach to understanding how shocks are transmitted and where the highest risks are to external shocks in a food commodity trade network. Further development and extension of the analysis presented is an important step in building a more resilient food system.

Acknowledgments

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Appendix A

A.1. Derivation of closed formula for the exposure of each node

Assuming that shocks are passed on in proportion to the original trade flows and that shocks are sufficiently small so that the shock can always be passed on, it follows that the equilibrium result can be computed using the following linear equations. To see this, assume that of a shock $(1 - q)\mathbf{e}$ is absorbed locally and $Tq\mathbf{e}$ is transferred, where q is the proportion of the shock passed on, \mathbf{e} is the exports from each region, and T is the transfer matrix, consisting of the proportion of exports from each region being exported to each other region. At the next iteration, $(1 - q)Tq\mathbf{e}$ is absorbed and $Tq(Tq\mathbf{e})$ is transferred, and so on. The impact of the shock (\mathbf{c} , change in consumption) on each node is then the sum of the absorbed shock at each node:

$$\mathbf{c} = (1 - q)\mathbf{e} + (1 - q)Tq\mathbf{e} + (1 - q)T^2q^2\mathbf{e} + \dots$$

This is a geometric series which converges for $0 \leq q < 1$ as the eigenvalues of qT all have magnitude less than one. Thus, the impact at equilibrium is $\mathbf{c} = (1 - q)B\mathbf{e}$, where $B = [I - Tq]^{-1}$.

A.2. Robustness of uniform q assumption

The model presented in this paper assumes a uniform value for the propensity to pass on shocks, i.e., that parameter q among the regions. Here, we assess the robustness of this assumption by allowing q to vary among the regions. To investigate the impact of varying q by region on the model results, we independently draw a value for q from a beta distribution (shape parameters 2, 2), which provides high variability among q values between 0 and 1 for each region (coefficient of variation of 0.45 for q). All other parameters are held constant ($\alpha = 0$ and $s = 0.5$) to explore the variation due to allowing different q values for each region. We ran the model 10 000 times and plotted the mean and coefficient of variation for the percent of shock in each region due to a shock initiated in each other region (see supplementary figures A4(b) and A5). Our predictions of average shocks (see supplementary see supplementary figure A5(a)) show a very similar pattern to when q is held constant for all countries (see supplementary figure A5(b)) even with high variability in q . The difference between the average results when q varies by country versus when it is held constant for all countries were small, all less than 0.6 percent. Allowing different q values by region does produce variability in these results depending on how the selection of q for each region and the variability is approximately on the scale of the variability in the choice of q (see supplementary figure A4(b)). This demonstrates that our average predictions and general patterns we highlight in this manuscript are unaffected by the assumption of a fixed q , but that empirical estimates of q are necessary to model specific scenarios.

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