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Research Report

Global trade network patterns are coupled to fisheries sustainability

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Abstract

The rapid development of seafood trade networks alongside the decline in biomass of many marine populations raises important questions about the role of global trade in fisheries sustainability. Mounting empirical and theoretical evidence shows the importance of trade development on commercially exploited species. However, there is limited understanding of how the development of trade networks, such as differences in connectivity and duration, affects fisheries sustainability. In a global analysis of over 400,000 bilateral trade flows and stock status estimates for 876 exploited fish and marine invertebrates from 223 territories, we reveal patterns between seafood trade network indicators and fisheries sustainability using a dynamic panel regression analysis. We found that fragmented networks with strong connectivity within a group of countries and weaker links between those groups (modularity) are associated with higher relative biomass. From 1995 to 2015, modularity fluctuated, and the number of trade connections (degree) increased. Unlike previous studies, we found no relationship between the number or duration of trade connections and fisheries sustainability. Our results highlight the need to jointly investigate fisheries and trade. Improved coordination and partnerships between fisheries authorities and trade organizations present opportunities to foster more sustainable fisheries.

Keywords: marine fisheries, seafood trade, resilience, network analysis, serial exploitation, stock status assessment

Significance Statement

Can regulating local fisheries alone achieve fisheries sustainability? In an analysis of over 400,000 bilateral trade flows and stock status estimates for 876 fish and marine invertebrates from 223 countries, we found higher population relative biomass in trade networks with strong connectivity within a group of countries and weaker links between those groups (modularity). Modularity in networks has previously been associated with resilience as shocks are more easily contained within the group of strongly connected countries, rather than spreading between groups. Our findings highlight the value of regulating and jointly investigating fisheries, trade, and the networks connecting them. Thus, coordination and partnerships between international and national trade organizations and fisheries authorities present a powerful new pathway for fostering sustainable fisheries.

Introduction

Seafood trade has become globally connected and short term (1). In 2022, global seafood trade facilitated the exchange of almost 60 million metric tons of seafood, equivalent to 33% of global seafood production (reduced from 38% in 2018 due to covid-19 (2, 3)). Today, international seafood trade is primarily characterized by short-term trade connections lasting only a single year (4) with a high level of connectivity between trading countries—approximately 65% more trade partners for each country than in the early 1990s (1). Growth in the seafood sector has been accompanied by a

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Table 1. Network and trade duration indicators.

Indicator		Description
Connectivity indicators	Modularity	Measures the presence of strong connectivity within a subsystem and weaker connection between subsystems in a network (39, 40). It ranges from zero to one. A value of zero describes networks in which countries are equally connected. A value of one describes a network consisting of strongly connected subsystems without connections between the subsystems.
	Clustering	Represents the extent to which a set of trade partners also engages in trade with one another's other trade partners, i.e. if country X trades with country Y and country Z, while country Y also trades with country Z—these are called triangular connections. Clustering measures the existing ones relative to all possible triangular connections (25, 41). Clustering ranges from zero to one where a value of zero indicates exclusively bilateral and no triangular connections and a value of one indicates exclusively triangular connections.
	Degree	Represents the average number of trade partners (42–44). For example, if a country exports a commodity to two countries and imports a commodity from three countries, its node degree is five. The degree is large in highly connected trade networks.
Trade duration		Trade duration is defined as the percentage of trade connections lasting longer than 4 years. Trade duration is an essential indicator in trade economics and primarily measured in years (45, 46). We evaluated our hypothesis on trade duration by calculating a for- and backward-looking continuous indicator per year, exporter–importer pair, and species group. For an exporter with a trade connection lasting from 1995 to 1999, all years would be indicated with five.
Governance		A compound indicator representing the institutions by which authority in a country is exercised through different governance dimensions, including the rule of law, control of corruption, regulatory quality, and government effectiveness (47).

doubling of *per capita* seafood consumption since the 1960s (3). This growth is expected to continue, given the increasing reliance on seafood as a source of income, food, and nutrition (5). The harvest required to support this growing demand is increasing pressure on fished populations which are dwindling in many cases (3).

Trade network patterns can impact the sustainability of fish and invertebrate populations and vice versa. In many cases, fisheries have experienced rapid serial exploitation where an overexploited marine population of one species is substituted by another population from within the trade network at an accelerating pace (6–8). Theoretically, seafood exports can lead to overfishing or collapse in unregulated, open-access fisheries with governance gaps and prevailing illegal fishing if trade increases price sufficiently (9–14). This relationship is affected by subsidies that further lower costs (15). However, seafood exports and increasing prices are not expected to lead to overexploitation if fisheries are effectively regulated (16, 17).

We hypothesize that the connectivity of a seafood trade network negatively impacts sustainability. In highly connected trade networks, newly exploited populations with higher biomass can substitute overfished populations (11, 18). In this way, exploitation can spread by serial substitution of populations (19, 20). Serial substitution is associated with overexploitation, if overexploitation is more profitable than substitution. Furthermore, high connectivity allows multiple markets to drive up prices, increasing the incentive to exploit populations past their sustainable limits (21, 22). Finally, if a trade network features many strongly connected groups of countries (henceforth: subsystems), shifts in trade, for instance, caused by supply shocks, are more likely to be contained among a smaller number of trade partners (23, 24). Theoretically, such a network could have less potential for adverse effects on a species' global stock status (25).

We also hypothesize that the duration of trade connections can impact sustainability, but without specifying the direction. On the one hand, global empirical studies of marine invertebrates argue that short-term trade connections may be incongruent with the time frames in which fisheries assessments and management can be effective (26). For instance, in the United States, stock assessments are conducted every 2 to 5 years (27). In this way, trade-driven fishing pressure and overfishing may go unnoticed by fisheries managers, even in effectively regulated fisheries (18), and a large share of short-term trade connections could adversely affect species' stock status. On the other hand, trade duration is typically longer for high-value and volume trades (28, 29). High trade volumes could indicate exploitation levels that adversely affect species' stock status. Each impact direction holds under different conditions, yet it is unclear which prevails in global seafood trade.

Here, we tested the above hypotheses that highly connected trade networks and networks characterized by low trade duration are correlated to globally lower sustainability of marine fish and invertebrate population. We analyzed more than 400,000 international bilateral seafood trade flows between 1995 and 2015 (30) and stock status estimates for 876 exploited marine fish and invertebrates from 223 countries and territories (31). Fisheries sustainability, here defined as individual fishery's stock status, does not depend solely on fluctuations in the trade network over time, because specific environmental, social, and economic factors are of relevance to fish stocks (13, 17, 32–36). However, the purpose of this paper was to take a broad geographic and temporal scale approach to understand how trade networks may influence fisheries sustainability by testing the relationships between stock status and trade networks using dynamic panel regressions. We include a governance indicator in our analysis to represent some of the most important factors traditionally considered to maintain sustainability (37). Lagged-dependent variables were used as covariates and lags of the covariates to eliminate omitted variable biases and potential reverse causality (38). Our analysis focused on capture fisheries, where possible, excluding seafood from aquaculture. We characterized network connectivity using *modularity*, *degree*, and *clustering indicators* (Table 1; SI Appendix Table S1). Our analysis suggests exploring new hypotheses and regulatory approaches relating to international trade networks and connections.

Results

Trends in stock status, network, and governance indicators

Before evaluating the relationship between stock status and trade network structures, we characterized the trends of each indicator over the study time frame (1995–2015). Using an ensemble model that combines estimates from multiple models calibrated on a dataset with trusted properties (48), we estimated that, on average, the evaluated species groups have been overexploited ($B/B_{MSY} <$ 1.0) and that their stock status has declined (Fig. 1). Here, stock status represents the ratio of stock biomass (B) to biomass when fished at maximum sustainable yield (B_{MSY}), a common fisheries management benchmark (36).

The four trade network features we analyzed were modularity, degree, clustering, and trade duration. We found that *modularity*, which represents the degree of connectivity between subsystems, was low but increasing across the species groups' trade networks. Average values fluctuated and featured a low in 1996 (0.035) and a peak in 2003 (0.061). In comparison, the modularity of the global food trade network ranged between 0.065 and 0.095 (49).

Degree represents the average number of trade partners, and this measure peaked at a value of 61 in 2014, meaning each country or territory had an average of 61 trade partners per species group out of 222 possible trade partners. Overall, the average number of trade partners increased by 35% from 1995 to 2015. This agrees with the increasing number of trade connections in the international seafood trade network in recent decades (1).

Clustering represents the extent to which a set of trade partners also engage in trade with one another's other trade partners. We found *clustering* decreased slightly between 1995 and 2015. In the last year, there were 10% fewer triangular connections compared to the first year. The observed maximum value of average *clustering* was for 1995 (0.21) and decreased to its lowest value in 2011 (0.18).

Trade duration, represented by the percentage of trade connections lasting longer than 4 years, was hump shaped across all species groups and peaked at a value of 11 years in 2003. *Trade duration* was slightly higher in 1995 at a value of 9.6 years compared to 2015 at 9.3 years. Despite the high number of single-year trade connections reported in (1) for the entire seafood trade network, our data showed a median of 10.8 years.

Governance represents the institutions by which authority in a country is exercised. There has been a slight decrease in average governance of trading countries across species groups between 1995 and 2015.

Impact of network characteristics on stock status

Here, we present results from a generalized method of moments (GMM) analysis of UN Comtrade and FAO data across 28 taxonomic groups, including crab, mackerel, and sole (SI Appendix Table S2).

Higher levels of modularity were associated with higher stock status in our models (Table 2). This means if the degree of connectivity between subsystems was lower, stock status was higher. *Modularity* was positively associated with B/B_{MSY} in Model 1 ($P =$ 0.016), including governance, and Model 2 ($P = 0.026$), excluding governance. In addition, this result remained robust when using different sets of aquaculture thresholds and when including year dummies (SI Appendix Tables S3 and S5).

High trade duration value was consistently indicative of lower stock status (Table 2), but *P*-values were above 0.05. This means that, on average, trade relations lasting at least 4 years were associated with −0.002 lower stock status, but that there was substantial variation among species groups. These results were robust for different species group specifications and the inclusion of year dummies (SI Appendix Tables S3 and S5).

The models did not support the hypothesis that exporters with low *clustering* values would be associated with low stock status. This means that the extent to which a set of trade partners also engage in trade with one another's other trade partners was not significantly associated with stock status in any of the six tested model specifications.

The models did also not support the hypothesis that exporters with a high degree would be associated with low stock status. This means the average number of trade partners was not significantly associated with stock status in any of the six tested model specifications. Albeit the lack of a relationship with stock status, we detected a slightly negative correlation with modularity (−0.15 Pearson correlation coefficient; SI Appendix Fig. S1).

Finally, we found the control variable governance to be negatively associated with stock status in several model specifications (SI Appendix Tables S3 and S5). This result was in contrast to our hypothesis that stock status in high-governance countries would be higher due to more effective fisheries management (17).

Trade network development and stock status of species groups

We found a general association between modularity and stock status patterns in the GMM estimations. Yet, each species group features distinct characteristics. This section illustrates the characteristics observed in species groups with the maximum and minimum median values of *modularity* ($P < 0.05$; Table 2).

Hake and scallop exhibited the minimum and eel and coalfish the maximum median *modularity* values. The *modularity* value of the hake network (9.4×10^{-3}) is close to zero, meaning that in this network, countries are equally connected. The *modularity* values of the scallop network (1.8×10^{-2}) are also well below average (0.05). In 2005, the hake network consisted of a single strongly connected group of trade partners with a few smaller connections linked to the strongly connected group (Fig. 2). *Modularity* values of the coalfish network (0.12) are lower than that of eel (0.2) but still well above the average (0.05). The eel network in 2015 featured one of the highest *modularity* values (0.38). Compared to the hake network, the eel network had multiple dispersed trading groups (Fig. 3). In the eel trade network in 2015, there is a tightly connected trade network in Europe, while there are separate subsystems of exports from Canada and New Zealand to multiple countries (Fig. 3).

The *modularity* values of hake and scallop decreased alongside the stock status over time (Fig. 3). These findings are in line with the overall average findings of the GMM estimations that predict lower stock status with lower *modularity* (Table 2). *Modularity* values of the coalfish network are higher than of the eel network. In line with the findings of the GMM estimations, *modularity* and stock status of coalfish decreased, and *modularity* and stock status of eel increased during the time series (Fig. 3). The structure of the coalfish network is similar to that of the eel network, with a closely connected subsystem in Europe and an exporting subsystem in the US and Canada. Stock status of eel ($B/B_{MSY} = 0.77$) was below the average stock status ($B/B_{MSY} = 0.86$) but increased toward a maximum in 2015 (0.80). In 2009, *Anguilla* spp. were regulated under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (50). The regulation coincides with an increase in *modularity* and a subsequent increase in stock status.

As discussed in the previous section, we found a correlation between *modularity* and *degree*. The scallop network had the highest average *degree* (59) of the here compared species groups. The *degree* increased for the hake, scallop, and coalfish species groups which had decreasing stock status (SI Appendix Fig. S2).

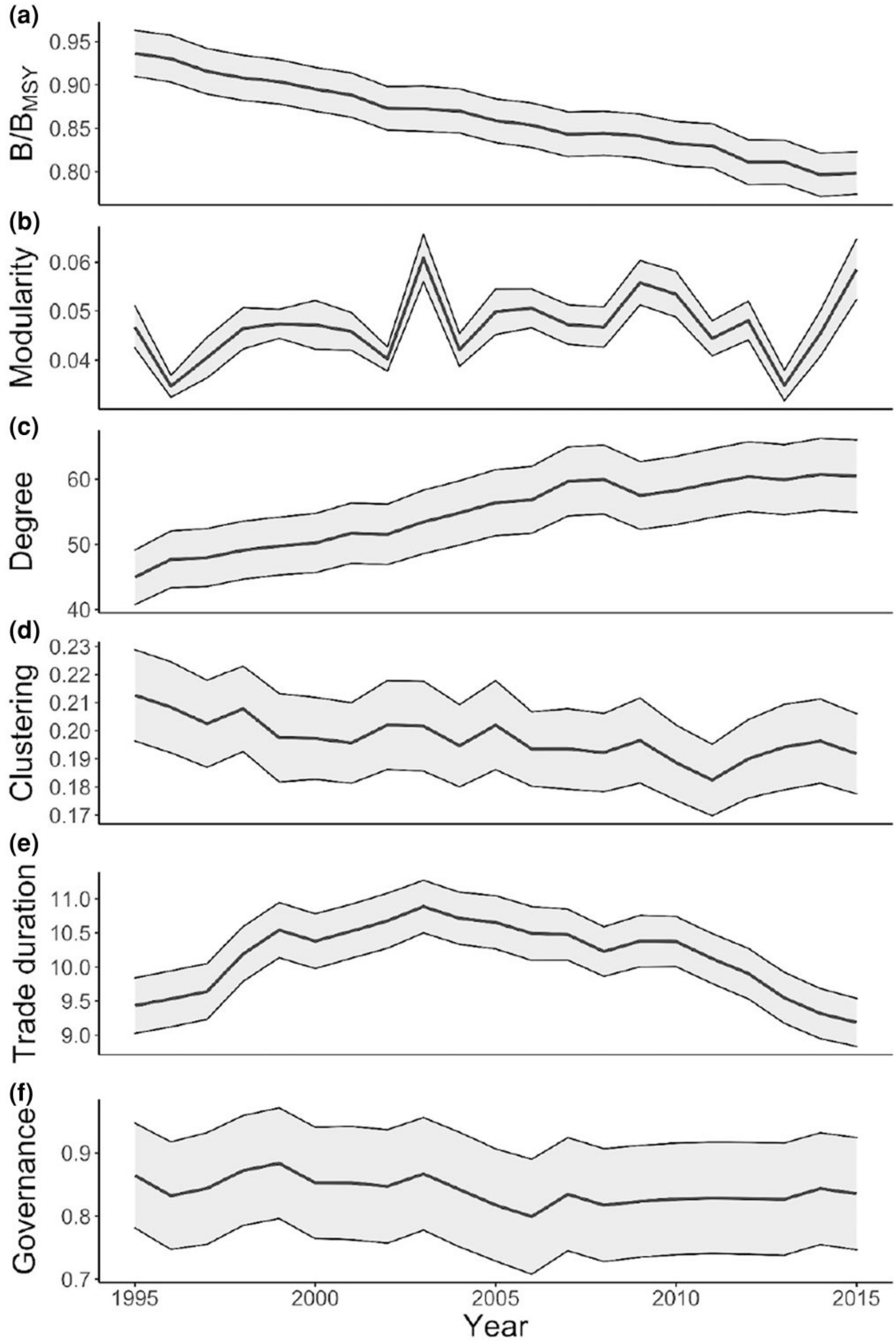

Fig. 1. From top to bottom: mean and 95% confidence intervals for a) biomass compared to biomass when fished at maximum sustainable yield (B/B_{MSY}), b) *modularity*, c) *degree*, d) *clustering*, e) *trade duration*, and f) *governance* of global seafood trade networks of all species groups between 1995 and 2015.

Discussion

This study empirically links indicators of global seafood trade networks to the sustainability of fish and invertebrate populations. Our findings show that theoretical frameworks of network characteristics (particularly *modularity*) are critical to understanding the resilience and sustainability of global food trade networks (e.g. (49, 51)) and more so with increasing seafood demand and trade (3, 11, 52). We found that more modular trade networks had higher average stock status, supporting the hypothesis that strongly connected subsystems with weak connections to other subsystems may have less adverse effects on species' global stock status (25). The two networks with the highest modularity (eel and coalfish) had a single strongly connected group of countries trading in Europe, with weaker connected trading subsystems in other countries.

Table 2. Dynamic panel GMM estimations with instrument variables using B/B_{MSY} as regressand. Model 1 includes the governance control variable. Windmeijer's finite-sample corrected standard errors in parentheses.

Network indicators	Model 1 B/B_{MSY}	Model 2 B/B_{MSY}
Modularity	0.190*	0.188*
	(0.0790)	(0.0844)
Degree	−0.00000475	−0.000249
	(0.000409)	(0.000477)
Clustering	−0.00508	0.0273
	(0.0416)	(0.0371)
Trade duration	−0.00268	−0.00195
	(0.00217)	(0.00219)
Governance	−0.0834*	
	(0.0418)	
Year	−0.00249***	−0.00172**
	(0.000664)	(0.000657)
(B/B_{MSY}) $t-1$	0.513***	0.530***
	(0.0280)	(0.0282)
(B/B_{MSY}) $t-2$	0.113***	−0.1310908***
	(0.0218)	(0.0213)
N	8397	8552
P-value AB test for AR(2)	0.868	0.964
P-value Hansen test	0.538	0.344

Significance levels reported as *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$. The P-value AB test for AR(2) and P-value Hansen test indicate that the first-differenced error term is not autocorrelated of order 2 and that the assumption of instrument exogeneity is not violated.

Multiple mechanisms could explain the relationship we found between *modularity* and fisheries sustainability. First, trade volumes between closer trade partners can be substituted before one population is overexploited. Thus, individual populations would not have to reach overexploited states (or worsening states) because other options through trade exist. Such substitution has been shown to occur between well-managed populations (53). For example, Japan was one of the biggest importers in the coalfish network and imported mainly from the United States of America (~80%), whose average stock status of coalfish was decreasing between 2000 and 2008 (from 0.8 to 0.6). In subsequent years, total coalfish imports in Japan decreased and came more from Norway (up to 100% in 2013), where stock status was higher (0.96). However, overall median modularity and stock status decreased over time in the coalfish network. Second, modular as opposed to highly interconnected networks are thought to diminish the propagation of supply shocks, as the shock is contained locally in a smaller subset of nodes in the network (54). For instance, shocks driven by declines in biomass or increases in demand create new demand across a network (23, 55). This means if a supply shock occurs in a seafood trade network, fewer trade connections and higher modularity would contain the spread of such a shock in a smaller set of countries.

Contrary to our hypotheses, trade duration, degree, and clustering were not significantly associated with marine fish and invertebrate stock status. There are several possible reasons for this. For instance, trade connections can be terminated for reasons unrelated to stock sustainability, such as changes to import regulations (50). *Degree* would exhibit a relationship to stock status if high levels of international trade increase demand and exploitation in fisheries (13). However, the nonsignificant finding for *degree* can also be a result of bidirectional causality (i.e. simultaneously decreasing stock status may decrease the number of trade connections), which our GMM estimations control for.

Our analysis highlights the need for a critical examination of the mechanisms that determine the seafood trade network structure and its relationship to fisheries sustainability. We found that between 1995 and 2015, modularity values fluctuated at a low level (i.e. observed values were half of that of the whole food [including seafood] network) (49). The number of trade connections was negatively correlated to modularity and increased over time. The increase in trade connections was likely due to increased trade liberalization (56–58). Therefore, international trade bodies that promote trade liberalization could consider trade agreements and policies' role in determining trade network structure. In parallel, such an investigation needs to consider the impacts of trade on livelihoods and the opportunity costs associated with retracting possible trade connections and terminating existing ones (59, 60). Specifically, our results suggest that agreements which promote the development of highly connected, nonmodular trade networks are not likely to benefit fisheries sustainability. Future research should further examine the mechanisms by which trade network patterns change fisheries' sustainability. This could be undertaken with higher resolution analyses, including cross-case study comparison to help differentiate trade impacts under different local policies and institutional settings (60).

Avenues of research departing from our analysis need to account for domestic trade and collect enhanced seafood trade and fisheries governance data. First, while international trade accounts for ~40% of global seafood production, domestic trade probably accounts for a similarly large share of seafood demand (61–63) indicating the importance of assessing domestic trade networks (64). For example, in Uganda, where seafood is increasingly consumed domestically (3), the impact of domestic trade networks will likely be more apparent than in China or Chile, where seafood is increasingly exported (65, 66). In domestic markets, there may be more incentives to prevent overharvesting compared to international markets (12). Increasing efforts to collect domestic trade data alongside international trade data (61, 67) could help differentiate between the influence of different types of markets.

Second, the sustainability of fish stocks is, in reality, a complex interplay of local (e.g. fishing practices, management, and consumption) and global factors (e.g. international trade and climate change). In light of our results, future analysis needs both improved and extended models, but also better data to determine the relative importance of local factors and trade network patterns under different context-specific conditions. For instance, we found a slight negative relationship between national governance indicators and fishery stock status in contrast to previous studies which found a positive relationship with fisheries management (17, 68). This could indicate governance could have arisen in response to overexploitation (15) or that national-scale governance indicators do not represent fisheries management.

Importers and exporters are recently experimenting with new types of trade relationships that could support the development of modules in trade networks. Aligning incentives between importers and exporters might be achieved if food supply and fisheries sustainability are codependent. Singapore, for example, has little autonomous food production, and negotiated trade contracts guarantee supply from a few countries (69). Co-dependence of importers and exporters incentivizes mutual collaboration for food supply and fisheries sustainability. Science-based development of trade policies requires an understanding under which conditions trade contracts support fisheries sustainability.

To achieve more sustainable fisheries globally, fisheries and ocean management cannot focus on regulating local fisheries

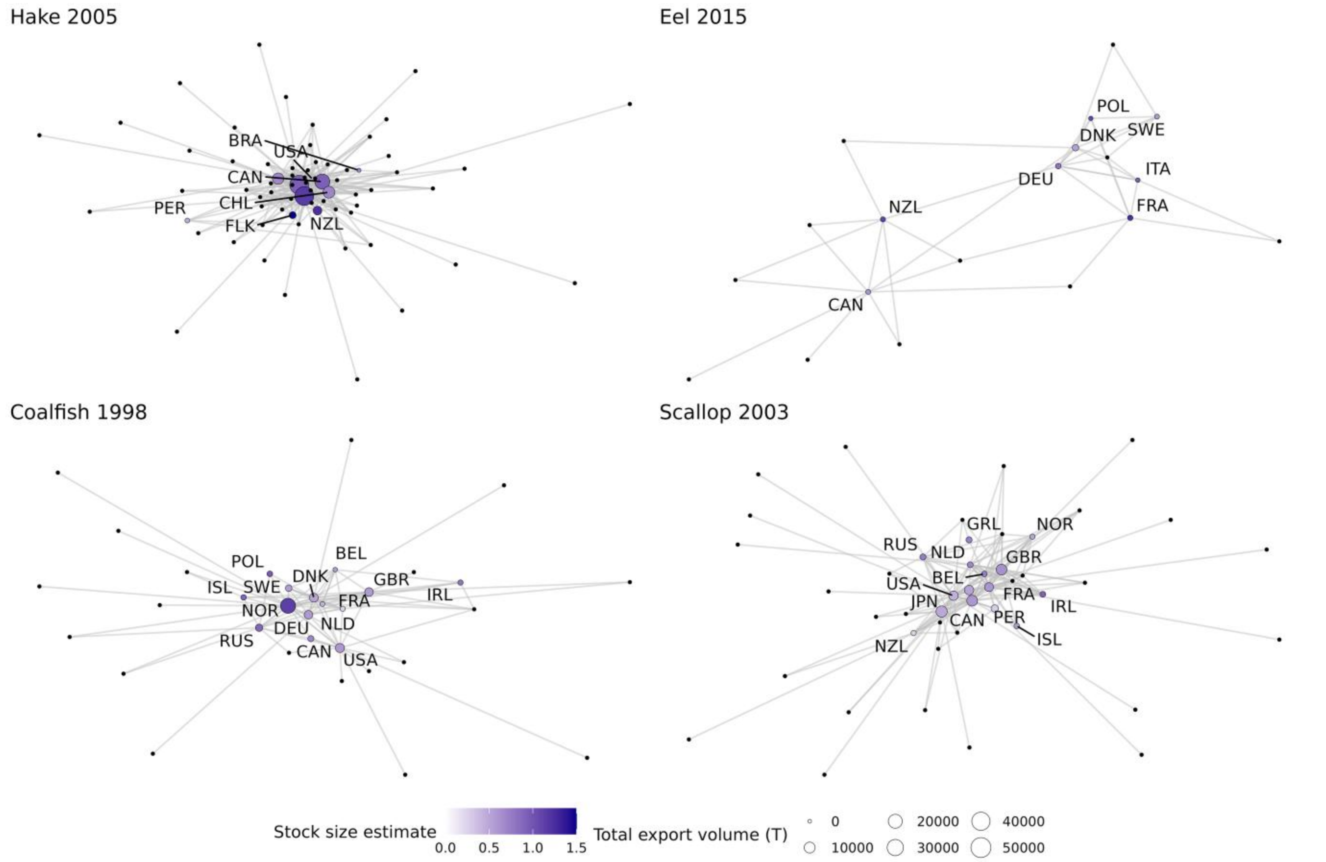

Fig. 2. The trade network figures illustrate the species groups and years corresponding to the minimum (hake and scallop) and the maximum median value (eel and coalfish) of modularity. Node shade indicates stock status. White is associated with low stock status, and darker shades with high stock status. Nodes representing individual countries are sized by export volumes in Tons. The smallest nodes, in black, only import and have no associated stock status. English country names corresponding to the illustrated ISO alpha-3 codes in Table S10.

alone. To date, the primary approach to prevent unsustainable exploitation is fisheries management, using measures such as quota allocation systems and spatial management measures (70). Such measures have had varying degrees of success to date (17, 68). Controlling seafood trade provides a second promising avenue to prevent conditions for unsustainable exploitation. However, the division of trade and fisheries in key institutions remains challenging. Trade and fisheries are frequently dealt with in separate national ministries. Also, the Food and Agriculture Organization's flagship report, "The State of World Fisheries and Aquaculture," lacks sufficient granular information to link trade to fisheries sustainability (3). Finally, despite the knowledge of trade impacts on plants and animals (71, 72), marine fish and invertebrate species are rarely regulated under global agreements such as CITES (73). The protection of Anguilla species under CITES in 2009, for instance, showed that trade authorities can simultaneously enhance modularity and protect population biomass.

This network approach poses the challenge for fisheries authorities and trade bodies to jointly investigate fisheries and trade and collaborate in new types of partnerships as a leading avenue to sustainable seafood trade. Investigating the effect of international and bilateral trade policies such as trade liberalization, multilateral agreements, and trade contracts on the structure of seafood trade networks and fisheries' sustainability requires mainstreaming existing trade and fisheries authorities' data collection and analysis by key institutions. Recent developments provide examples of improved coordination and partnerships. One strategy is that importers enhance trade partnerships through mutual collaboration. The European Union, for example, bans seafood imports that have been given a "red card" for inadequately addressing Illegal, Unreported, and Unregulated Fisheries (74, 75). In addition, the EU appointed a Chief Trade Enforcement Officer to help strengthen transparency and sustainability policies in seafood-exporting countries (76). Conservation measures such as CITES govern trade in the overexploitation of wild species and could be expanded to include the vast variety of marine fish and invertebrate species (73). This agenda represents a substantial departure from current policies for fisheries sustainability that focus on fisheries in isolation. It highlights the need for coordinating and forging partnerships between and among national and international trade institutions to drive global fisheries sustainability.

Materials and methods

Global seafood trade data, stock status estimates, and data matching

We used trade data from a processed version of the UN Comtrade International Trade Statistics Database (30, 77, 78). We estimated stock status from the FAO Fisheries Landings Database (31). The dataset we constructed from these two sources contains 401,027 bilateral trade transactions. It consists of a time series of (i) bilateral trade flows between import and export countries, (ii) the mean stock status of individual stocks contributing to each

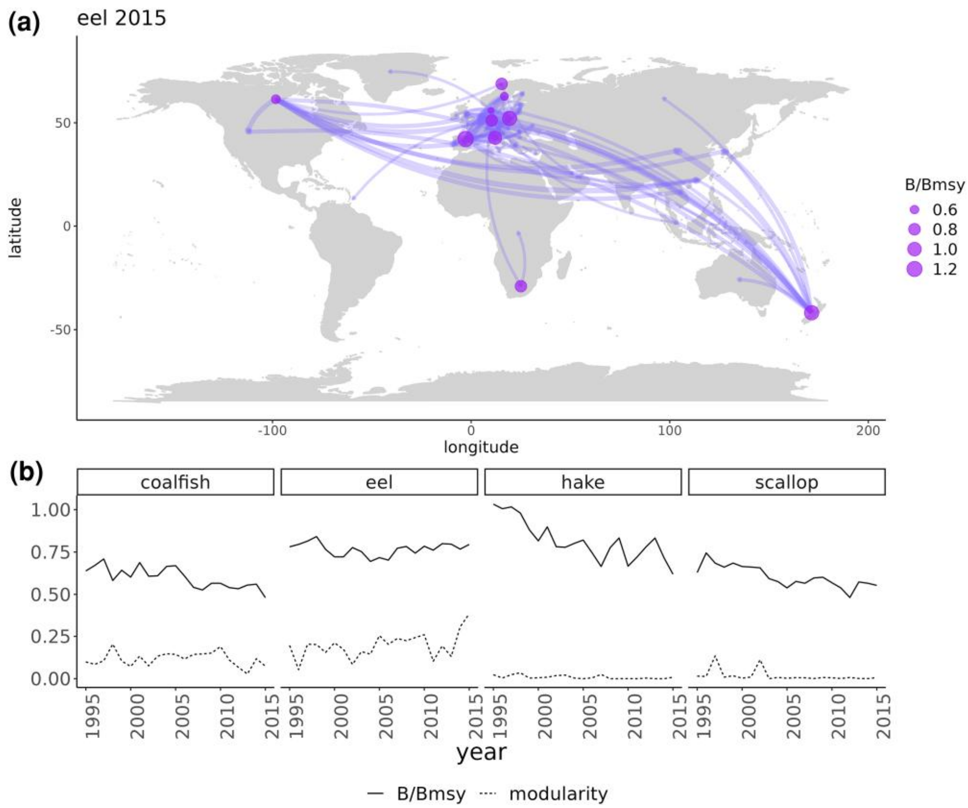

Fig. 3. a) Example map of trade flows and sock status (size of nodes) for eel in 2015. b) Time series of modularity and average stock status of species groups corresponding to lowest median modularity values (hake and scallop) and highest median modularity values (eel and coalfish).

species group, and (iii) network indicators of connectivity and duration of the trade networks for each species group.

First, we downloaded the FAO-reported annual, country-level catch time series of individual fish and marine invertebrates (31). From this data, we constructed a time series of stock status or B/B_{MSY} using an ensemble model of four individual catch-only stock assessment models (SI Appendix S1.1; SI Appendix Table S6, SI Figs. S3 and S4) and two spectral properties of the catch time series (48, 79). A B/B_{MSY} ratio of 1.0 indicates a fully exploited stock (which maintains maximum sustainable yield indefinitely), while ratios less than 1.0 indicate an overexploited fishery. We chose to use catch-only stock assessment estimates because stock assessment data are unavailable for many countries (e.g. (68)).

Second, we constructed trade networks from UN Comtrade International Trade Statistics, which provides self-reported, annual, bilateral flows (SI Appendix S1.2). From this database, we constructed global seafood trade networks for 28 species groups from 65 seafood HS codes (SI Appendix Table S2) following best practices identified by (1). These groups correspond to the Harmonized System (HS) codes from 1992 (World Customs Organization, 2020).

Finally, we had to match the data because stock status estimates use individual species, whereas the 1992 seafood HS codes in the UN Comtrade data vary in taxonomic resolution (SI Appendix S1.3). The commodity code descriptions contain common and scientific names of species, genus, family, order, class, and phylum. When a commodity code was not specified at the species level, we chose the next level of taxonomic resolution to match them to species-level stock status estimates. When commodity code descriptions were at a higher taxonomic resolution than class (e.g. "fish livers and roes, frozen"), we excluded the trade from the dataset. If multiple species were associated with a trade flow we averaged stock status estimates of those multiple species (on average, 1.5 stock status estimate per commodity-exporter combination). For example, while a total of six species are associated with the species group seabass, not all species are caught in all countries. *Centropristis striata* (L., 1758) is only caught in the USA, and its stock status is thus not averaged.

Network and trade duration indicators

We computed commonly used network connectivity indicators (80, 81): *modularity*, *clustering*, and *degree*, and a continuous variable for *trade duration* (Table 1; SI Appendix Table S1). We calculated *modularity*, *clustering*, and *degree* using the igraph R package (82). The indicators are accounted for regardless of their links' directionality, i.e. whether links are export or import links. All indicators except *modularity*, for which there is one value per year and species group, were computed at the node level, which means that there is one value for each indicator per country, year, and species group.

Dynamic panel regression analysis

We tested the relationships between fishery stock status and trade network indicators using GMM estimations. The following causal relationships are plausible: (i) stock status affects network indicators, (ii) network indicators affect stock status, or (iii) a combination of the two. The estimated coefficients using ordinary least squares or fixed effects estimators would reflect all three directions. The way to address this problem is to identify instrument variables that affect network properties and are not directly correlated with stock status. Therefore, we used a dynamic GMM estimation with 2- to 5-year lags of the covariates as instrument variables to assess the contemporaneous correlation between network patterns and stock status. GMMs can unveil causal relationships (by controlling for time effects, lag endogeneity, and reverse causality) (83). The causal inference approach is robust without other variables incorporated into the model because it avoids the potential bias in estimation caused by omitted variables, such as domestic trade and local consumption. The unexplained variation derives from omitted factors, such as different ecosystem variables, fishing practices, and socioeconomic conditions of fishing communities.

We included a composite governance index to control for different levels of fisheries management. The composite index comprises of the government effectiveness, regulatory quality, rule of law, and control of corruption indicators published by the World Bank (47). The parameters of the GMM estimations are interpreted as follows: suppose the estimated coefficient of covariate one is beta, then if covariate one increases by one unit, ceteris paribus, the response variable is expected to increase beta units. We evaluated model significance using the *P*-value with a ≤0.05 alpha value.

We ascertained the validity and robustness of our results using several approaches (SI Appendix S2). We tested for autocorrelation of the first-differenced error term using the Arellano–Bond test for AR(2) and overidentification of instruments using the Hansen test (84, 85). If *P*-values for the AR(2) test and the Hansen test are larger than 0.10, they indicate that the first-differenced error term is not autocorrelated of order 2 and that the assumption of instrument exogeneity is not violated. In addition, we assessed the robustness of our results by providing GMM estimations, including three different sets of species groups in the analysis based on their contribution to global aquaculture (SI Appendix Table S5). Finally, we provided additional GMM estimations with year dummies and a time covariate to control for time trends (SI Appendix Table S3).

Model specification

We employed three model specifications for the dynamic GMM estimations. The network effects on fishery stocks were assumed to be contemporaneous. We used 1- and 2-year lags of stock status to lessen dynamic endogeneity. We refer to this specification as the baseline model. It assumes the functional form described in equation 1 (Table 2, Model 1):

$$\frac{B}{B_{MSY\,git}} = \lambda + \beta_1\,(B/B_{MSY})_{\,git-1} + \beta_2\,(B/B_{MSY})_{\,git-2} + \beta_3\,\text{modularity}_{gt} + \beta_4\,\text{clustering}_{git} + \beta_5\,\text{degree}_{git} + \beta_6\,\text{trade duration}_{git} + \beta_7\,\text{governance}_{git} + \beta_8\,\text{year}_t + \varepsilon_{gt},$$

$$\text{where } \varepsilon_{gt} = u_{ig} + v_{igt}, \tag{1}$$

where continuous stock status (B/B_{MSY}) of species group g traded by exporter i in year t is predicted by the 1- and 2-year lags of stock status, the network indicators (modularity, *clustering*, and *degree*), *trade duration*, the control variable governance, and the time covariate in year t. The error term is composed of two terms: first, u_{ig} represents unobserved exporter-species time-invariant fixed effects. Second, v_{igt} represents a stochastic error term to introduce variation in other variables that could potentially affect stock status but are not included in our model.

Model 1 (Table 2), 5, and 6 (SI Table S5) specifications use the same GMM estimations. Table 2, Model 2 and SI Table S3, model 4 exclude the control variable governance, and SI Table S3, Model 3 and Model 4 exclude the time covariate but include year dummies.

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Supplementary material

Supplementary material is available at *PNAS Nexus* online.

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Conceptualization: L.G.E., M.O., J.A.G., C.M.F., E.T., and A.F.J.; analysis: L.G.E., M.O., J.A.G., C.M.F., J.Z., E.T., and E.M.B.; data curation: L.G.E., M.O., J.A.G., A.G.-N., and C.M.F.; visualization: L.G.E., M.O., J.A.G., and C.M.F.; writing: L.G.E., M.O., and A.F.J.; editing: all authors; supervision: J.A.G. and A.F.J.

Data availability

The following data and code are publicly available: [FAO data]*, FAO, "Global Capture Production 1950–2017 (v2019.1.0). Fisheries and Aquaculture Division [online]", published through FishStatJ (March 2019), 2019 (https://www.fao.org/fishery/en/collection/capture?lang=en). CEPII (bilateral trade) can be freely downloaded from the CEPII website http://www.cepii.fr/CEPII/en/bdd_modele/bdd_modele_item.asp?id=3. Data and Code "*Global trade network patterns are coupled to fisheries sustainability*". DOI: https://zenodo.org/badge/latestdoi/408461658.

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