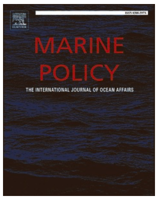
Marine Policy 157 (2023) 105818

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol



Telecouplings in Atlantic cod—The role of global trade and climate change

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ARTICLE INFO

Keywords:
Fisheries trade
Atlantic cod
Correlation network
Prices
Resilience
Structural equation modelling

ABSTRACT

Seafood trade is a global business, where catches, processing, and consumption are increasingly separated. An increasingly integrated global market creates telecouplings, i.e. connections between fish stocks that are ecologically separated. These telecouplings may spread the impact of vulnerabilities, such as climate change, between unconnected fisheries. The effect of climate change on fisheries is often analyzed on a fish stock basis, which may overlook the spread of these vulnerabilities. Atlantic cod (*Gadus morhua*) stocks, an iconic fish species, are no exception. Depending on the geographical location, stocks have been impacted differently by climate change, with North-East Arctic (NEA) cod, the stock in the Barents Sea, reaching record high biomass levels and other stocks being extremely depleted. Here, we investigate how these dynamics occurring in the ecological system affect global trade of cod. We find that the global export is fully dominated by NEA cod catches. Applying Structural Equation Modelling, we discover that the high biomass level of NEA cod has positive effects on catches and exports and leads to lower global market prices. However, zooming in on individual stocks and the countries exploiting them using correlation networks, we find heterogeneous responses of other countries, where catches for some stocks increase and others decrease in response to lower global prices. Our results highlight how changes on one fishery may have important repercussion on stocks in different ecosystems, as well as on societies reliant on them.

1. Introduction

Fish trade, like most other trades, has become increasingly complex and global in nature. In 2018, approximately 38% (67 million tons) of all fish caught or farmed were traded internationally, with an estimated value of $168 billion USD [16]. Seafood trade is characterized by large and complex global supply chains, at times spanning multiple countries. It is common for a fish to be caught in one country, exported for processing to another and reimported in different forms by the original country or further distributed across the world [4,19,20]. These types of dynamics can create connections among fish stocks far away from each other, that are not connected via their ecosystems. This is commonly referred to as telecoupling. In this paper, we examine the presence of a telecoupling relationship among stocks of Atlantic cod (*Gadus morhua*), mediated via global trade. We also explore the interaction between trade and climate change and its impacts on the recoveries and exploitation of cod stocks.

Telecoupling is the interactions of coupled natural and human systems over physical distance [25]. Social-ecological systems may seem to be isolated as each of them are located in a specific location within a specific context and are affected by many different environmental and socioeconomic factors. Yet they might still be connected via factors

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https://doi.org/10.1016/j.marpol.2023.105818
Received 14 March 2023; Received in revised form 7 August 2023; Accepted 27 August 2023

beyond their local area, such as tourism or trade [35]. Even though telecouplings have been predominantly described in terrestrial systems, they can be important also for fisheries systems [8,35]. In the case of fisheries, the social-ecological systems are geographically apart but can be connected via factors such as trade, where economic dynamics connect fisheries that are physically unconnected [8,21,25]. Fishing is becoming an increasingly global industry implying that telecoupling connections between distant social-ecological fisheries systems are expected to become more pronounced. The presence of telecouplings and the connection of distant fisheries poses challenges to fisheries management, as harvest size is usually based on the health of the stock and the local environment, while the relevant drivers may be global. Trade-induced telecouplings may also mediate wider shocks, such as climatic changes that affect catches in some fisheries which in turns could affect profitability of exploitation in other parts of the world [8,21,25]. In some cases, however, the presence of telecouplings can also mitigate and dissipate the effect of wider shocks through the network [10,19].

Cod holds a prominent position within global fisheries and their trade. FAO [16] estimates suggest that Atlantic cod (*Gadus morhua*) alone featured amongst the top ten species worldwide by landings between 1950 and 2017. This makes cod (including Atlantic cod, Pacific cod (*Gadus macrocephalus*) and Greenland cod (*Gadus ogac*)) one of the largest marine sources of seafood products in the whitefish markets [3]. Cod's significance extends beyond its local harbors and well into international trade. FAO [14] estimates that cod along with hake and haddock combined account for nearly 10% of the total value of seafood traded globally and nearly 15% of global seafood trade by live weight. The biggest trade volume of all cod is frozen cod for which China is the biggest importer, followed by the Netherlands, and South Korea [40]. Globally, Atlantic cod is one of the most landed species and it has a higher-than-average proportion of stocks that have been overfished [16].

Atlantic cod is distributed across the North Atlantic and, like many other fish populations, its stocks have also been impacted by climate change and overfishing [26,38]. Indeed, around the end of the 1980s and the beginning of 1990s, 19 out of 20 stocks distributed across the North Atlantic abruptly collapsed [18,39]. At the moment, Northeast Arctic (NEA) cod is the only stock that is doing very well amongst the Atlantic cod stocks (apart from Iceland that is also at sustainable levels but not as good as the NEA cod [23]). It has reached record-high biomass levels and is predominantly harvested by Norway and Russia [30,48]. In contrast, all the other Atlantic cod stocks are depleted and below management reference points making them unsuitable for increased exploitation [48].

The imbalance between cod stocks that do well and stocks that are in critical states can have implications for fishing and trade. Climate change impact on stocks is likely to widen those inequalities. The increase of temperature has opposite influences on the stocks, depending on where they are located in relation to their northern and southern distribution limits [48]. Temperature increase has a negative impact on cod stocks at the south or middle latitudes — areas in which cod is already close to the maximum metabolic growth — and a positive effect on stocks at the northern distribution limit of the species such as NEA cod [7,12,30,31,43,48].

Our study aims at finding evidence of telecoupling relationships in the global cod fishery mediated via global trade. The presence of telecouplings can have wider implications for the management of Atlantic cod, and fisheries management more generally. A major challenge for stock recovery is that management has control over fishing pressure (at best), but no control over global drivers, such as climatic change or economic dynamics external to the fishery. While previous research has investigated how climatic and ecosystem changes affect cod sustainability [41,48,52] we still have a very limited understanding of how economic dynamics in the global cod market can affect local fisheries. The impact of telecouplings on fisheries is likely to be dependent on the management structure of the fisheries in question. In our study, we focus on cod which is managed via a variety of quota systems. This is likely to limit the impacts of telecouplings as the fishers' ability to respond to any changes in market conditions are restricted by quotas. As an example, if global prices rise quickly, fishers in an open access fishery may be able to respond with higher catches while those in managed fisheries will be limited by the quota that they hold. In such a scenario, the outcomes of the price rise are likely to be felt more on an open access fishery than a managed fishery.

Here, we investigate how the increase in biomass of the NEA cod stock in the Barents Sea, due to a combination of good management and favorable environmental conditions, has affected the global price of cod and how this in turn affects fishers in different areas of the world; thus, telecouplings effects. We combine a Structural Equation Modelling (SEM) approach with correlation networks to explore how this increase has affected global export volume and prices. We see that NEA cod stock dominates the international trade and has gained a significant market share of the global cod trade. The increase of export has led to a decline of Norwegian and global export prices. We use a correlation network to explore possible repercussions on all stocks. Further, we demonstrate how trade can mediate environmental drivers, such as climate change, creating telecouplings between fish stocks apparently disconnected from each other, opening up new avenues for fisheries management.

2. Materials and methods

2.1. Investigate global trade dynamics

To understand the dynamics of global cod trade, we explored the export changes by producing countries from 1976 until 2015 using trade data from [15] (to know more about data processing see SI Appendix A). To analyze changes in global export dynamics, we calculated the percentage of cod exported by all the countries in two different periods: from 1980 to 1990 and between 2010 and 2015. By comparing the biggest exporters and their fishing areas, we constructed a map representing the stocks from which the cod biomass was mainly extracted from during these two periods.

2.2. Conceptual model

We used a conceptual model to describe how changes in NEA cod stocks could affect global trade dynamics and the other stocks locally. We divided the conceptual model in three parts (Fig. 1). First, at a Norwegian level, we conceptualized how an increase of NEA cod biomass could affect the global export prices. We hypothesized that an increase in biomass of NEA cod should lead to an increase in Norwegian catches. As a consequence, we would expect a decline of Norwegian local landing prices [2]. An increase in catches would also lead to a bigger Norwegian export quantity, and thus to a decline of Norwegian export prices [42,49] (Fig. 1a). We then focused on global trade (Fig. 1b), and we hypothesized that global prices would decline in response to lower Norwegian export prices [1]. Finally, we looked at effects on local stocks from countries other than Norway (Fig. 1c). We expected that if global export prices would decrease, cod fishers outside Norway have lower incentives to catch cod since they could earn less. However, cod stocks are generally managed with quotas (Total Allowable Catches (TACs)), which are typically based on the local biomass of the stock. This would weaken any effects of changes in cod prices on total landings (Fig. 1c). To incorporate the effect of climate change on biomass of the stocks, we included Sea Surface Temperature (SST) as a control variable for the different stocks.

2.3. Structural equation modelling (SEM)

We used a SEM (package "piecewiseSEM" in R) to test the relationships proposed in the conceptual model. We used a variety of data to fit

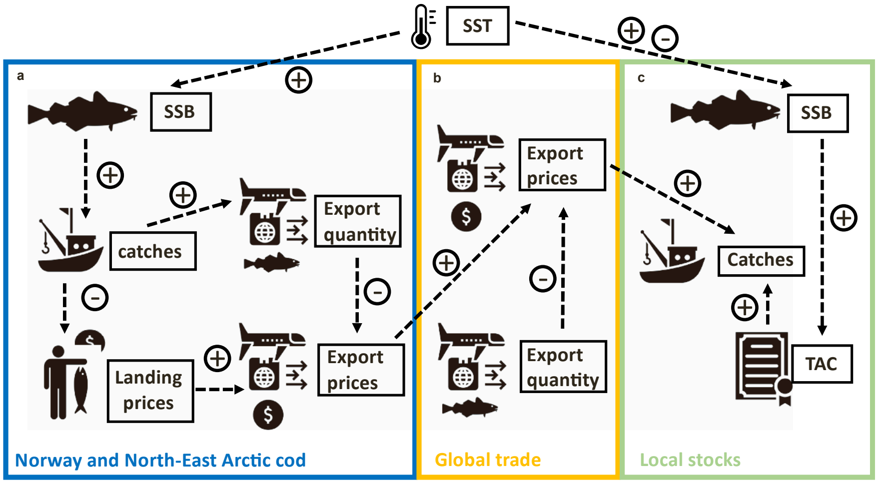

Fig. 1. Conceptual model of Atlantic cod trade. a) Hypothesised link among different components of the Norwegian cod trade, from stock biomass (SSB) to Norwegian export prices. b) Hypothesised relationship among components of the global trade, in particular global export quantity and prices. c) Hypothesised effect of global export prices on local management components (TAC= Total Allowable Catch, SSB= Spawning Stock Biomass). Temperature (SST) affects the stock of Norway and also the local stocks. The symbol + indicate a positive relationship, while the – a negative one.

the conceptual model to the SEM: biomass (coming from the stock assessment), catches (coming from FAO dataset), landing prices (from Statistics Norway) and export prices and quantity (from the FAO data). The latter were divided in commodities such as “frozen”, “fresh”, “fillets” cod. To standardize the analyses we used just “frozen” cod as a commodity, after testing that it was better than the others (See SI Appendix A). SEM is a statistical framework that can test the assumed causal relations among multiple predictors and response variables in a single network and is thus suitable for analysing complex systems [22,33,34]. A typical regression model tests the relationship between a single dependent and several independent variables. SEMs help to investigate whether a proposed model with interrelated variables with assumed causal effects has a close fit to the sample data [6,11,22]. Hence the SEM model allows us to examine whether our hypothesized conceptual model, where multiple relationships are proposed, is a fit with the data that we have collected. Firstly, we built a network of cause-effect relationship based on our conceptual model on how the coupled Norwegian-global trade system should work. The assumed cause-effect relation networks between the variables were established in a set of regression models. We used linear models using generalized least squares estimation to fit each regression model under the SEM. Autoregressive moving average (ARMA) processes could be included in the model to address potential temporal autocorrelation of the data [17]. The detail of model fitting procedures and fitting results can be found in the SI Appendix B. At the end, we tested the regression model sets by estimating the coefficients of the cause-effect relations, the significance of the estimated cause-effect coefficients, and the goodness-of-fit of the model. The estimated goodness-of-fit of the model as well as the direction and significance of the estimated cause-effect coefficients gave the directions of model revision and were used to decide the final model (see SI Appendix B). The data sources of each variable mentioned in the conceptual model used for SEM can be found in SI Appendix A and SI Appendix A Table1.

2.4. *Correlation network*

Lastly, we wanted to understand the effect of global prices on catches on individual stocks. As previously mentioned, the effect of the change in price would be determined also by the condition of the stock (SSB) and the management (TAC). To reveal relationships between these components, we used a simple explorative correlation network. The local stocks we investigated were European stocks, in particular Eastern Baltic, Western Baltic, Kattegat, Irish Sea, Celtic Sea, West of Scotland, Faroe, Iceland, Coastal, and North Sea cod. We constructed correlation networks, using Pearson correlations for the different components within each of the subsystems as illustrated by the conceptual model (see Fig. 1c). We also analysed the direct relationship between SSB and catches to account for the role of management. Lastly, we tested the influence of SST on SSB to see which effect climate change has on the individual stocks. We use SST as a broad proxy for climate change to understand whether stocks differ in their exposure to climate change effects by geographical areas and in particular at different latitude as in previous studies [48]. Where data were available, we ran the analyses between 2001 and 2015 (SI Appendix A Table2). The data sources of SSB, TAC, and SST can be found in SI Appendix A Table 3 as well as Appendix A Table1.

3. Results

3.1. *Global trade dynamics*

Inflation adjusted global export prices show a decreasing trend in the long-term, with an increase around the end of 2000. From 1977 until 2015, the total global export increased from 350 to 700 thousand tons. A remarkable growth can be observed in the last six years, from 2009 to 2015 (Fig. 2, grey line). This increase of export corresponds to an evident decline of prices. The prices declined by 61% for the period 1977–2016, and by 42% if we look just from 2007 to 2016. When Norway and Russia, the two main countries fishing NEA cod, are removed from the total export, a clear and steady declining trend since the 1990s is observable, with exports falling below 200 thousand tons (Fig. 2, black line). This highlights the dominance that countries fishing NEA cod have on the global market. The increase in cod exports is purely driven by Norway and Russia since they are able to increase exports at a rate that surpasses the decline of all the other cod exporting countries combined.

The relative importance of countries on the global market has changed between the 1980s and today. In particular, countries such as Canada, Denmark, Iceland, Norway, but also Germany and Sweden, were key exporters of cod in the 1980s (Fig. 3a), while just three countries, Norway, Russia, and Iceland, are responsible for nearly all the export since 2010 (Fig. 3b). Particularly interesting is that while in 1980s the main exporting countries fished on 20 stocks (Fig. 3c), in recent years, the exported commodities come from mainly one stock, the NEA cod, and partially from the Icelandic cod stock (Fig. 3d). This indicates a fragility of the global trade that basically depends solely on one fish stock, the NEA cod, and is thus tied to its health status.

3.2. *Structural equation modelling*

We used the SEM in order to understand how the increase in NEA cod affected global trade. The final SEM results (p-value of Fisher’s C

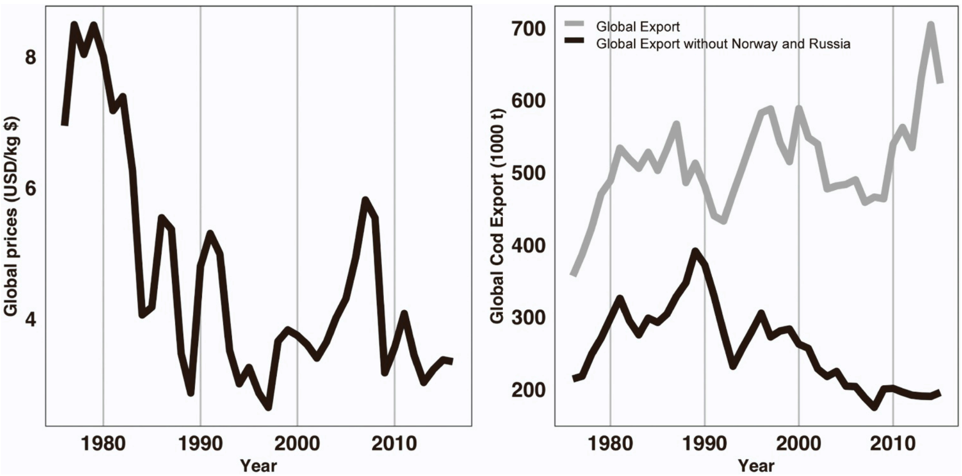

Fig. 2. Time series of Atlantic cod trade. a) Time series of global prices of frozen cod [15] corrected by inflation, using consumer price index (CPI) (OECD, 2022). b) Time series of global export [15] and global export without accounting.

statistic test = 0.78, Fig. 4 and SI Appendix B) can explain the variance of global cod export prices, global cod export quantity, and Norwegian cod export prices rather well (between 38% and 91%, shown as R^2 in Fig. 4). The model explains less of the variance of Norwegian cod catches (15%) and Norwegian cod landing prices (19%) and that of Norwegian cod exports (1%). In general, the SEM results confirm the relationships hypothesized in the conceptual model: increasing NEA cod biomass positively influences Norwegian local catches, which are negatively related to local price. Thus, an increase of local catches will lead to a decline of local prices. The change of local price then transmits to the Norwegian cod export price and the export price in the global market, confirming that the increased catches of cod in Norway are leading to a decline of global market price (shown in Fig. 2). The SEM results also show that global cod export quantity is significantly influenced by the export amount from Norway. In addition, Norwegian and global cod exports have a negative impact on the Norwegian export price and also the global export price, respectively.

However, a few minor relations are not as expected as those in the conceptual model. Fig. 4 reveals a strong link between NEA cod SSB and global export quantity (including Norwegian cod export). This is most likely due to the relationship between Norwegian cod catches - which are depending upon NEA cod SSB - and Norwegian export quantity, which is not significant in the model. The not significant relation between Norwegian cod catches and Norwegian export quantity is probably due to the data used to perform the SEM. We only use “frozen cod” as it is the most exported cod commodity over the last decades. However, there are also other commodities traded that could have an effect on the results of our model. We fitted an alternative model performed with aggregated data of frozen cod plus frozen cod fillets (SI Appendix C), which shows the significant relations between Norwegian cod catches and export quantity. Moreover, an alternative conceptual model with the opposite assumption that global market had influences on the Norwegian local market was also tested, but no final model derived from this candidate model passed the model evaluation (see SI Appendix C. Fig.8), meaning that the model(s) with the opposite assumption did not fit the data.

3.3. Correlation network

We use correlations between global prices, management measures (TAC) and ecological conditions (SSB) to explain catches of cod regionally, hypothesising that a decline of global price should reduce the incentive of fishers to catch cod in telecoupled areas. The correlation network shows that global export prices, depending mainly on changes in NEA cod, only have significant relationships with catches of three stocks (Fig. 5). We find that only the catches of Western Baltic cod decrease as global export prices decline [44,51]. This corresponds with a TAC that is not fully fished in the Western Baltic (SI Appendix A Fig. 7), which is a symptom of the unprofitable nature of that fishery, resulting in an de facto open access condition (European Market Observatory for Fisheries and Aquaculture Products, 2021; [44,51]) Interestingly, we find that catches from Coastal as well as North Sea cod increase. Here, we observe that catches are higher than the TAC for both stocks, even when the condition of both stocks is poor (SI Appendix A Fig. 7). One potential explanation could be that fishers try to compensate for the decreased prices by increasing the quantity to keep the revenue stable. Given that both stocks are negatively affected by SST, this is increasing the pressure on the stocks even further. For the majority of the stocks, we find no significant correlation either way.

Given our short time periods of data we cannot be certain we pick up all the effects between local catches and global prices. Hence, we also plot the insignificant correlations (hollow arrows in Fig. 5) to give an indication of what might be going on. We find that there is no clear response mechanism to decreasing global prices. While stocks like Celtic, Iceland, Eastern Baltic, and Kattegat have the tendency to increase catches with decreasing prices, the catches for Faroe, Irish Sea, and West of Scotland are decreasing with declining prices. These patterns are not determined by the TAC since we see that Celtic and Eastern Baltic are fishing less than the TAC, whilst Iceland, Kattegat, and West of Scotland report catches that are higher than the TAC and for Irish Sea the TAC is more or less equal to catch (SI Appendix A Fig. 7). Theoretically, it would be plausible that countries that have high exports of cod are also the ones reacting strongly to the changes in prices. Yet, the cod market is dominated by Russian and Norwegian exports who are both fishing mainly NEA cod. All other exporters have similar export quantities thus this would not necessarily explain different reactions to global price changes (SI Appendix A Fig. 3).

Regarding sustainability, a decrease in catches would be beneficial, especially if the stock is negatively affected by climate change which is the case for all stocks for which we see decreases in catches. For the stocks where we see an increase in catches, we can distinguish them into two groups: those that are positively impacted by SST and those that are negatively affected. Responding with increased catches to decreasing prices can have severe effects on stocks if SST is negatively impacting SSB (Eastern Baltic and Kattegat), especially if the management system might be able to avoid these effects through a strict TAC setting based on SSB. For the stocks that have a positive correlation between SST and SSB (Celtic Sea and Iceland), the effect on sustainability of an increase of catches is less clear. These stocks show also positive correlations between TAC and SSB.

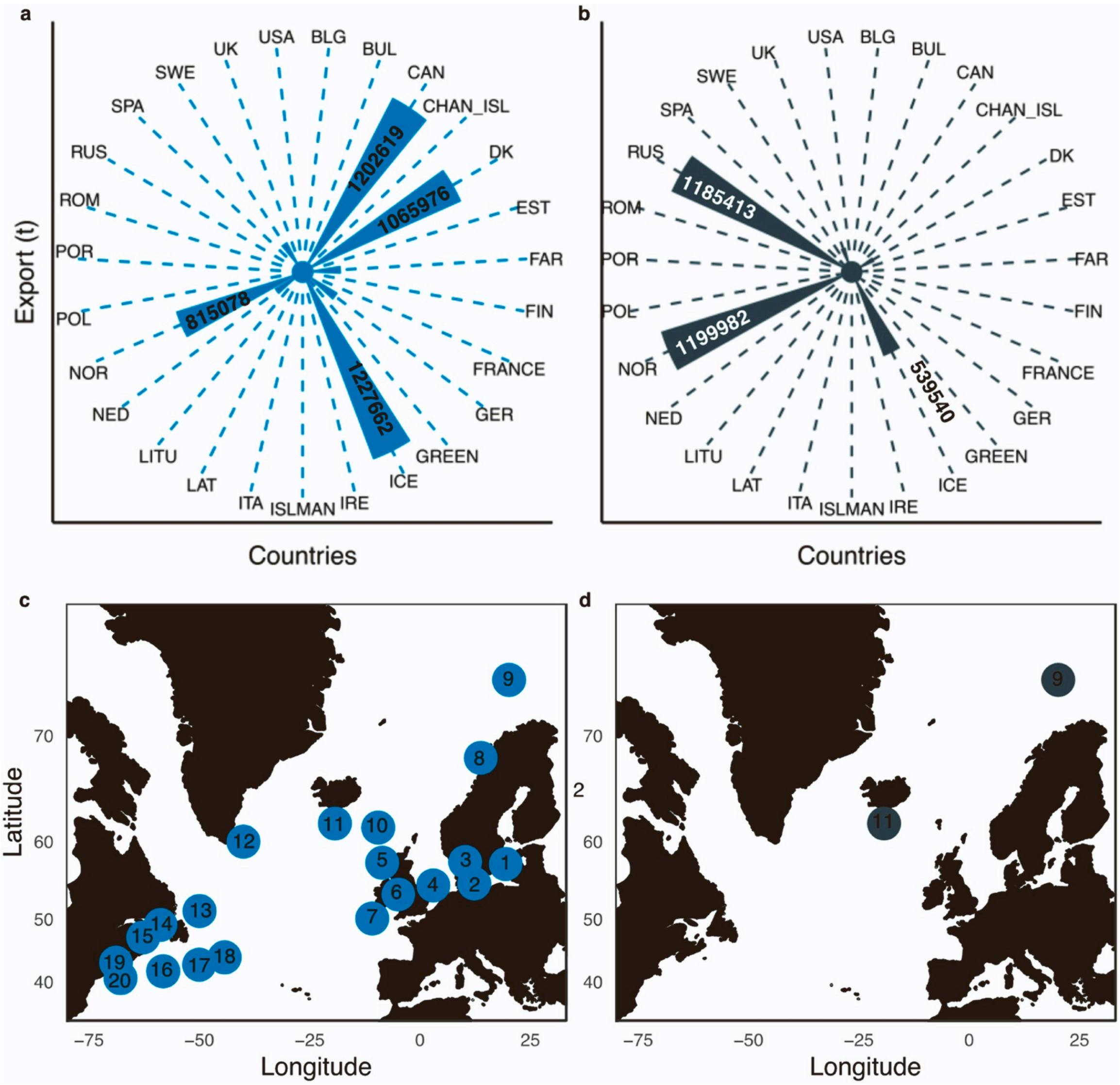

Fig. 3. Changes in the Atlantic cod market and the origin of cod traded over time. Main exporting countries with their total export in tons, from 1980 to 1990 (a) and 2010 to 2015 (b). Cod stocks from where the main exporting countries fished from 1980 to 1990 (c) and from 2010 to 2015 (d). Code exporting countries: BLG= Belgium, BUL= Bulgaria, CAN=Canada, CHAN_ISL= Channel Island, DK= Denmark, EST= Estonia, FAR=Faroe, FIN=Finland, FRANCE= France, GER= Germany, GREEN= Greenland, ICE= Iceland, IRE=Ireland, ISLAMAN= Island of Man, ITA0 Italy, LAT= Latvia, LITU= Lithuania, NED= Netherlands, NOR= Norway, POL=Poland, ROM= Romania, RUS= Russia, SPA= Spain, SWE= Sweden, UK= United Kingdom, USA= United State of America. Data source: FAO (2017). Code cod stocks: 1) Eastern Baltic, 2) Western Baltic, 3) Kattegat, 4) North Sea, 5) West of Scotland, 6) Irish Sea, 7) Celtic Sea, 8) Coastal cod, 9) North-East Arctic, 10) Faroe, 11) Iceland, 12) Greenland, 13) Northern, 14) North Gulf of St. Lawrence, 15) South Gulf of St. Lawrence, 16) Eastern Scotian Shelf, 17)Grand Banks, 18) Flemish Cap, 19) Georges Bank, 20) Gulf of Maine.

To sum it up, the correlation networks identify different groups:

1) Stocks that decrease local catches due to a decrease in global export prices (Western Baltic, West of Scotland, Faroe, Irish Sea).
2) Stocks that report an increase of catches and are positively affected by SST and changes in TAC correlate strongly with SSB (Iceland and Celtic Sea).
3) Stocks that report an increase of catches are negatively affected by SST, and changes in TAC do not necessarily reflect changes in SSB (North Sea, Coastal Cod, Kattegat, Eastern Baltic).

4. Discussion

Cod fisheries are some of the most important fisheries in the world with a long history of engaging in global trade [16,27]. The global nature of the trade, coupled with environmental drivers such as climate change, have created strong telecouplings among cod stocks distributed all over the Atlantic. Climate change is having an impact on cod stocks and their trade in the global markets in an uneven manner, creating winners and losers among cod fishing communities and nations. Climate change has benefitted the North-East Arctic (NEA) cod stock while hampering the recovery of other cod stocks around the world [12,48]. Here we have investigated the presence of telecouplings among cod stocks and in particular the effect of an increased biomass of NEA cod on global prices and on the rest on the stocks.

The Structural Equation Modelling (SEM) results show that as the biomass of NEA cod increases, we see an increase in Norwegian catches, which leads to lower local Norwegian prices. This decrease in local prices subsequently decreases Norwegian cod export prices, which in turn reduces the global export prices. This allows the impact of Norway's cod catches to reverberate across the entire local and global cod market. NEA cod catches themselves are strongly dependent on the health of the

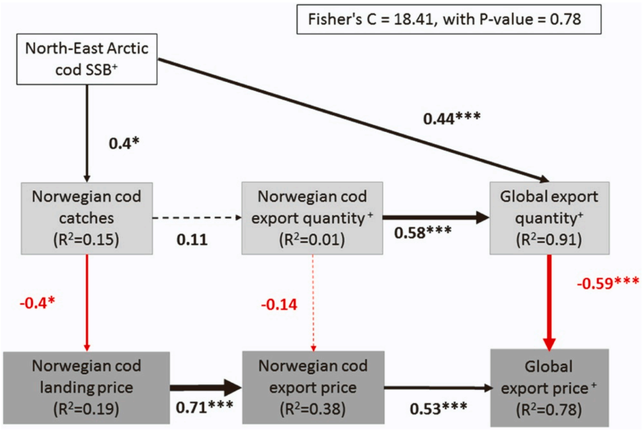

Fig. 4. SEM results. $^+$ means that the variables were log-transformed. Black arrows indicate the positive cause-effect relations and red arrows indicate the negative cause-effect relations. Dotted-line arrows imply that the estimated coefficients of the cause-effect relations have p-value> 0.05 and solid line arrows imply that the estimated coefficient of the cause-effect relations are significant (*p-value<0.05, ** 0.001 <p-value<0.05, *** p-value<0.001).

fishery which is sensitive to climate change impacts. Our results show a strong positive relationship between SSB – our proxy for cod stocks' health – and Norwegian cod catches. Therefore, the impacts of climate change on the NEA cod fishery can directly and significantly affect the global cod supply and global cod prices.

In general, the correlation network shows that reactions to a decrease in price differ between stocks. Whilst a decrease in catches is favorable for the sustainability of the stocks that are already under pressure, the fishers are going to be severely impacted. While they can sell less fish, they also get a lower price. Increased catches, in spite of lower prices, might indicate that fishers are trying to compensate for the lower prices. For those stocks that are under increased fishing pressure and are negatively affected by SST, the risk of a collapse becomes more imminent. So, whilst fishers might be able to adjust to the global market prices in the short term, this severely endangers their long-term income. The effect on those stocks that display increased catches and also are positively impacted by SST the effects are less clear since it depends on whether the positive impacts of climate change can compensate for the increased catches.

Our study has two limitations that could be addressed by future research. First, we show that even if local prices are shaped by a global market, and ultimately the NEA cod fishery, the ability of fishers to adapt to changing prices is limited. All the Atlantic cod stocks are regulated and managed via total quotas, since after the 1990s [30], putting constraints on fishers to simply increase catches in years when prices are high. These quotas are based on the spawning stock biomass (SSB) in a pre-defined geographic region (management unit). For shared stocks, countries obtain quotas for stocks based on historical fishing rights that are rather inflexible [24,29,50]. Thus, if one of the stocks is low in biomass the system prohibits fleets from simply changing their fishing grounds because their quota is specified for a given management unit [46]. As an example, North Sea cod fishers cannot switch their fishing grounds to fish the NEA stock. Fishers may also be incentivized to maintain their catches at a certain level to hold on to their fishing rights. As a result, due to the management structure of cod across the world, the effects observed in our study may not translate directly to fisheries which are either entirely or partially open access. Thus, the cod management structure may dampen the effects of telecoupling – as it would be reduced by the ecological and management limits – which would otherwise have been greater in an open access fishery where fishers may respond more freely. Thus, it is fundamental to explore telecoupling in fisheries in order to find ways in which it could be considered in management practices. Still, other stock specific measures such as the

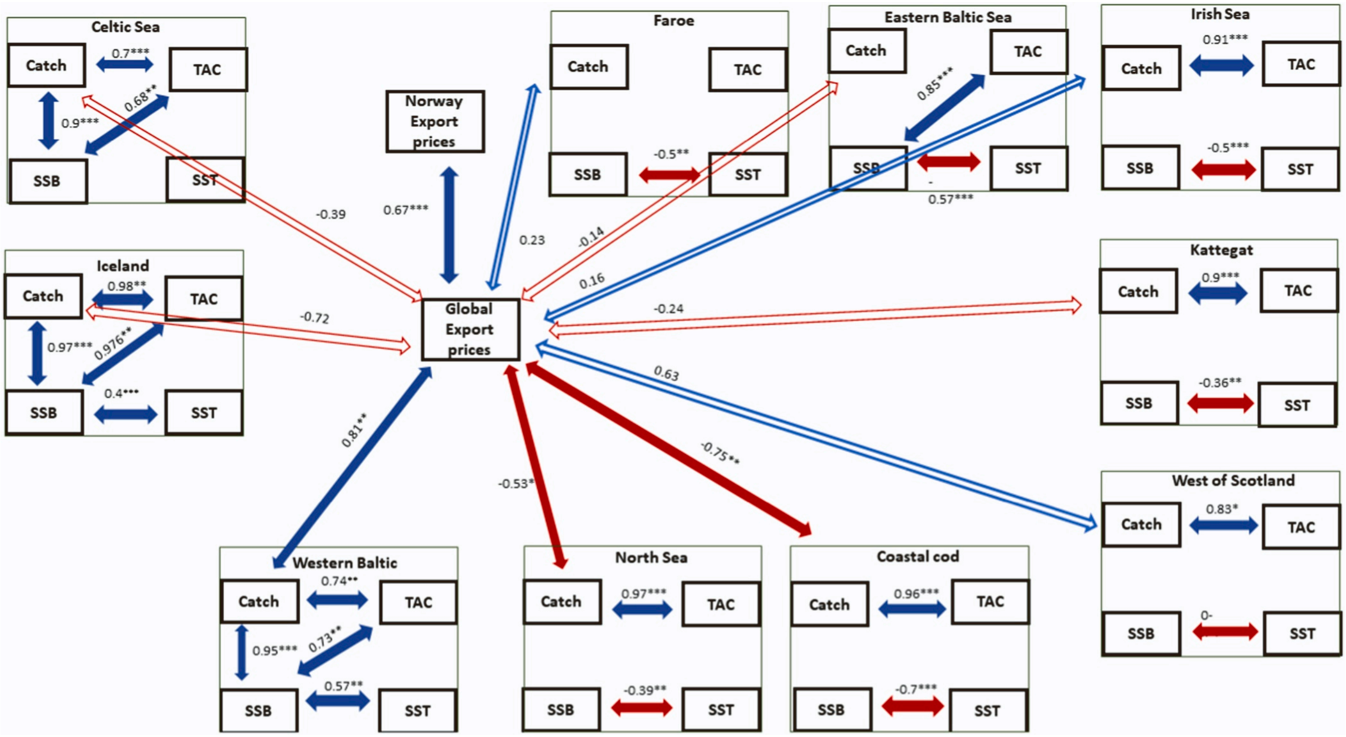

Fig. 5. Correlation network for Atlantic cod stocks. Correlation network for the different stocks. All correlations are reported for the relationship between catch and global export prices. Significant correlations are represented in bold arrows and non-significant correlations with hollow arrows. Only significant correlations for the subsystems are reported. Red indicates negative correlations and blue positive correlations. While we hypothesized that a decrease of global prices would lead to a decrease in local catches, we can see here that the response to decreasing global prices differ. The correlation network provides some insights into the functioning of the management as well as the impact of the SST on the biomass of the stocks.

presence of government subsidies to fish cod, the cultural value of cod fisheries in some area, the price of the fuel, the presence of direct substitute species, can also have a strong influence on cod fisheries and have a fundamental impact on the willingness to fish and export cod by the fishers [5,37,49].

Second, given the outsized quantity and value of Atlantic cod in international trade relative to other cod species, we choose to focus solely on Atlantic cod stocks in our analysis. However, an obvious question is to what extent such telecouplings may occur across species. Given the recent shift in fish trade that focusses more on large groups of species that share similar characteristics, i.e. whitefish, instead of single species such as Atlantic cod [1], it stands to reason that telecouplings via price occur also across species. Thus, a potential drop in the supply of NEA cod is likely to have severe repercussions in substitute fisheries as well. While all the cod stocks around the world are managed through quotas and unlikely to see a surge in fishing, countries which have weaker regulations are likely to see increased exploitation of substitute fisheries, potentially leading to their collapse [13,28]. Substitute species are also likely to see an increase in the price on the global market in a negative cod supply shock environment. Countries where those substitute species play an important role in promoting local food security face pressure to export these substitutes. Future research could investigate how trade may create telecouplings in fisheries that are imperfect substitutes for consumers by looking at all whitefish stocks or seafood more generally.

Global cod supply is vulnerable to negative ecosystem shocks to NEA cod stock. Even though NEA cod is thriving under a warmer climate, projections show that near-future temperature fluctuations may also involve cooler periods leading to a decline of NEA even if a sustainable management system is put in place [32]. A sudden decline in NEA cod would further increase pressures on other stocks that lack capabilities to increase catches, which is mainly due to the current state of their biomass status and unfavorable environmental conditions [18,36,48]. We cannot predict how fishery managers of other cod stocks may respond to any decline of the NEA cod, but their choice set is likely to be limited by the health of their respective stocks. As a result, while the current supply of cod in the global market is healthy, it is entirely dependent on the health of a single stock, which may indicate a lack of resilience in the global supply. This vulnerability of the global cod supply is masked by the nature of international trade. As long as there is a constant supply of affordable cod, prices lose their signaling power on the dire state of most of the cod stocks [9].

5. Conclusions

Overall, while climate change is advantageous to a few stocks, it has made it difficult for the vast majority of cod stocks to recover [36,48]. With the global cod market being so heavily reliant on the NEA cod, climate change has eroded the resilience of the cod market as a whole. Were there to be a negative shock to the NEA stock, its effects are likely to be catastrophic to the global supply of cod in the short term and may lead to the overexploitation of poorly regulated whitefish substitutes in the medium to long term. By creating winners and losers among cod fishing countries, climate change has also led to socio-economic changes. As most stocks are unable to recover, fishers from countries reliant on the respective stocks are unable to earn a livelihood from them ([26,45]). Cod has historically been one of the largest fisheries for those countries and a lack of robust recovery of their cod stocks is a significant loss of potential incomes, livelihoods, and culture for their fishing communities as well as those further down in the value chain of cod products [45,47]. Finally, as the effects of climate change become increasingly severe, we believe such a situation is likely to occur in other fisheries in the future. In order to maintain the livelihood of fishers across the world as well as to aid global food security via seafood production, we believe more research is needed to understand telecoupling effects in fish trade such as the impact of climate change on the market structure and dynamics of fish stocks, as well as the consequent impact of a shock to a single stock on local fishing communities and global trade of the respective species.

Data availability

The Data are available on the internet and a link has been shared.

Acknowledgements

This study was initiated and supported through MARmaED (MARine MAnagement and Ecosystem Dynamics under climate change). The MARmaED project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 675997. The results of this publication reflect only the authors’ view and the commission is not responsible for any use that may be made of the information it contains.

Authoŕs contribution

CS, AR, and CM designed the study; CS, ES, SG and TYL collected and analysed the data and produced the figures. All the authors contributed to the writing of the manuscript.

Conflict of interest

There was no conflict of Interest.

Data Accessibility

All the data are open access and were collected from different repositories, indicated in the supplementary information.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105818.

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