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Modeling Atlantic herring fisheries as multiscalar human-natural systems

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ABSTRACT

Fisheries contribute to food and nutrition security, livelihoods, and poverty alleviation for billions of people globally. However, human-environmental interactions in fisheries are rarely assessed locally, regionally, and globally at the same time, limiting social-ecological resilience in fisheries management. We evaluated worldwide catches of a keystone forage fish (Atlantic herring, *Clupea harengus*) over 65 years (1950–2014); modeled local, regional, and global interactions among industrial, artisanal, subsistence, and recreational fishing sectors; and predicted future catches using a multifaceted and multilayered human-nature coupling framework for assessing social-ecological interactions within and across adjacent and distant fisheries (termed "metacouplings"). Across 17 exclusive economic zones (EEZs), catches by nations in their own EEZs (7.1×10^7 metric tons [MT]) outweighed those in adjacent EEZs (5.3×10^7 MT). However, adjacent-EEZ fishing was the largest-tonnage fishing type in more EEZs (53 %), reflecting the proximity of Northern/Western European fishing nations and regulations conducive to fishing in neighboring waters. Catches in distant (non-adjacent) EEZs were relatively small (1.2×10^7 MT). Fishing-sector interactions were generally positive but notably negative for artisanal fishing, which declined with increasing industrial and recreational catches in five EEZs (29 %). Combined with projected declines in artisanal and subsistence catches in parts of Germany, Norway, and Sweden, metacoupling interactions could elicit harmful financial, food-supply, and food/nutrition security outcomes for small-scale fishers if metacouplings remain absent from management programs. However, quantitative and conceptual tools developed herein enable fisheries managers to identify where, when, and how to maximize positive and minimize negative metacoupling interactions and thereby ensure continued ecological, economic, nutritional, and sociocultural benefits for fisheries stakeholders, locally to globally.

1. Introduction

Environmental challenges of the modern era, including climate change, species invasion, biodiversity loss, and food/nutrition insecurity, affect the depth and complexity of connections between humans and ecosystems (Vitousek et al., 1997; Parmesan and Yohe, 2003; Godfray et al., 2010; Blackburn et al., 2019). Amid the rapid pace of science and technology in our globalized world, it is increasingly feasible to understand how environmental challenges manifest locally, regionally, and globally. Global couplings—interactions between humans and nature over long distances—are the subject of a recently developed framework (telecoupling; Liu et al., 2013) for evaluating how people influence, and are influenced by, ecosystems far removed from where they reside. For example, biofuel mandates in the European Union and the United States elicit deforestation in the tropics, and fisheries harvest in Peru affects soybean and wheat supplies across the globe (Liu et al., 2015; Carlson et al., 2018a; Hull and Liu, 2018). The telecoupling framework has been recognized as a research priority by the Global Land Programme and the United Nations and applied to diverse social-ecological phenomena (e.g., agricultural trade, species invasion, ecotourism, water transfer; Liu et al., 2019). Despite its growing visibility and applications, the telecoupling framework captures merely one component of our globalized, hyperconnected world: distant social-ecological connections. People and ecosystems are also connected regionally and locally, demanding a conceptual and analytical framework akin to telecoupling but which explicitly accounts for human-nature couplings at smaller spatial scales.

A local-regional-global coupling framework termed "metacoupling" (Liu, 2017) is one such approach. Local-regional-global couplings (metacouplings) are human-nature interactions that occur within individual (local) coupled human and natural systems (Type 1 interactions) and between adjacent systems (Type 2) and distant systems (Type 3;

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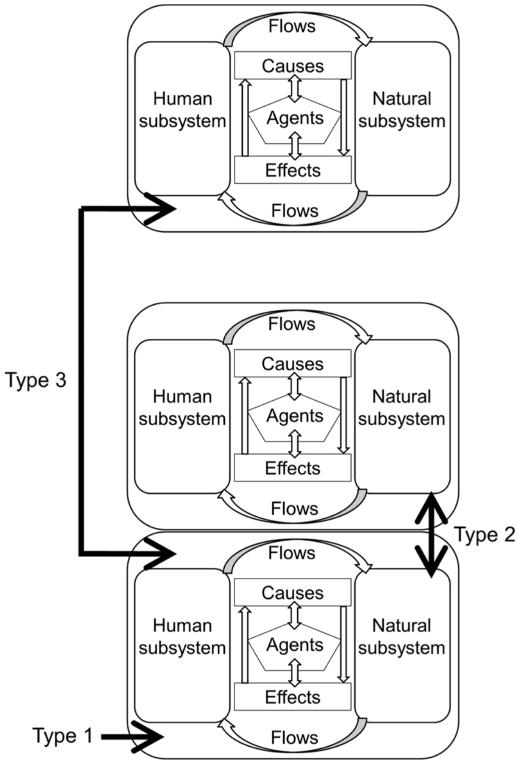

Fig. 1. Diagram of metacoupling. White arrows are local human-nature interactions within particular coupled human and natural systems (Type 1). Black arrows are human–nature interactions between adjacent systems (Type 2) and between distant systems (Type 3). Agents are human and organizational entities that create or impede flows (e.g., fish, money, information, people). Causes are reasons for human-nature couplings (e.g., economic, social, political, technological, cultural), whereas effects are outcomes and consequences of such couplings. Modified from Liu (2017).

Fig. 1). By juxtaposing these coupling levels and interactions, the metacoupling framework is useful for evaluating the relative importance of local, regional, and global human-nature interactions and thereby determining potential ecological or policy interventions. To date, the metacoupling framework has been applied to topics such as giant panda (*Ailuropoda melanoleuca*) conservation, agricultural trade, and marine and freshwater fisheries management (Liu, 2017; Schaffer-Smith et al., 2018; Herzberger et al., 2019; Carlson et al., 2020a, b,c). Studies have typically described local-regional-global interactions and policy implications rather than modeled or predicted these multiscalar connections. Hence, there is a need to connect theory and practice through quantitative local-regional-global coupling models that inform resource policy and management.

As coupled human and natural systems spanning individual locations, regions, and the globe, fisheries are ideal systems for operationalizing the metacoupling framework. Whether industrial (large-scale and commercial), artisanal (small-scale and commercial), subsistence (small-scale and non-commercial—primarily for consumption), or recreational (small-scale and non-commercial—primarily for pleasure; Pauly et al., 2020), fisheries are multiscalar systems encompassing human-nature interactions between people, fishes, and habitats. For example, site-specific catches and local market sales of artisanal fishers can be affected by local and regional distribution of industrial fishing vessels, which in turn reflect regional and global policies of fisheries agencies and fishing companies (Crona et al., 2015). Although international connections among fisheries ecosystems and human systems are increasingly investigated (Österblom and Folke, 2015; Tapia-Lewin et al., 2017), studies rarely assess fisheries catches at local, regional, and global scales over multidecadal time scales. There is a pressing need for such multiscalar fisheries catch information as billions of people throughout the world, including many in developing nations, depend on fisheries for food, income, livelihoods, and poverty alleviation. Fish are a relatively affordable source of omega-3 fatty acids and micronutrients and supply 4.5 billion people with $\geq$ 15 % of their animal-derived protein (Béné et al., 2015; Food and Agriculture Organization of the United Nations (FAO), 2020a). In addition, the diverse array of fishing sectors, locations, and fisher identities causes multiscalar connections between global policies and local conventions that affect fish stocks, habitats, and people in unique ways. For these reasons, it is imperative to develop quantitative approaches to operationalize fisheries metacoupling research, particularly at spatial scales relevant for contemporary fisheries management (e.g., exclusive economic zones [EEZs] in marine fisheries, states and provinces in freshwater fisheries).

As one of the world's most abundant and harvested fishes, Atlantic herring (*Clupea harengus*, hereafter "herring") is important nutritionally, culturally, and socioeconomically throughout its range in the North Atlantic Ocean from Canada to Northern/Western Europe and the Arctic (Tacon and Metian, 2009). In 1950–2014, herring was caught by 28 nations—86 % of which were from Europe—at a variety of scales (i.e., nations in their own waters, adjacent waters, and distant waters) by industrial, artisanal, subsistence, and recreational fishers using numerous gear types, including purse seines, bottom and pelagic trawls, longlines, gillnets, hand lines, small-scale encircling nets, and recreational fishing gear (Pauly et al., 2020). Herring is used primarily for fishmeal and fish oil production and direct human consumption, both intranationally and internationally (Cashion et al., 2016; Norwegian Seafood Council, 2020). In addition, herring is an important forage species for marine organisms such as Atlantic bluefin tuna (*Thunnus thynnus*), cods (Gadidae), killer whales (*Orcinus orca*), and Atlantic puffin (*Fratercula arctica*; Richard et al., 2017; Leo et al., 2018). Given the local, regional, and global importance of herring fisheries and the management significance of determining how catches interact across sectors and spatial scales, there is a need for metacoupling research specifically focused on herring.

The goal of this study was to use the local-regional-global metacoupling framework to understand past and present, and predict future, herring catches and fishing-sector interactions to better manage herring fisheries as multiscalar human and natural systems. Unless otherwise noted, "catches" are EEZ- and year-specific sums of: (1) catches reported to the United Nations Food and Agriculture Organization (FAO), and (2) catches unreported to the FAO and estimated using *Sea Around Us* (Pauly et al., 2020) catch reconstruction (see below). Our first objective was to assess herring catches over 65 years with available data (1950–2014) across multiple scales: local (catches by nations in their own EEZs), regional (in adjacent EEZs), and global (in distant EEZs). Our second objective was to generate models to quantitatively understand and predict how fishing sectors (industrial, artisanal, subsistence, recreational) interact locally, regionally, and globally. Our final objective was to compare local, regional, and global couplings in EEZs across the range of herring worldwide to yield insights for fisheries management that increases economic gains without destabilizing herring fisheries. We hypothesized that fishing-sector interactions would be largely positive and future catches stable to increasing given the expanding global population and sheer abundance of herring (IUCN, 2020). However, we also predicted that fishing-sector competition (e.g., artisanal-industrial, artisanal-recreational) would have management relevance because it can directly and indirectly affect income, employment, food supplies, and food/nutrition security of fishers across sectors (Crona et al., 2015; Prato et al., 2016). In light of the metacoupling framework's growing applications in natural resources (e.g., water, marine and freshwater fisheries, crops, soil; Liu, 2017; Schaffer-Smith et al., 2018; Herzberger et al., 2019; Carlson et al., 2020a, b,c), we anticipated that metacoupling models would yield useful insights for herring management and governance locally, regionally, and globally.

2. Methods

2.1. Metacoupling framework

Herring catches were subdivided into three broad classes. Type 1 catches result from fishing by nations within their own EEZs, including territories, collectivities, and other administrative divisions (Fig. 1). Type 2 catches represent fishing by nations in adjacent EEZs (shared land/maritime borders), whereas Type 3 catches denote fishing in distant (non-adjacent) EEZs (Fig. 1). The three classes encompassed six unique fishing types: Type 1 artisanal (small-scale commercial), subsistence (small-scale non-commercial), industrial (large-scale commercial), and recreational; Type 2 industrial; and Type 3 industrial. Importantly, in the context of the metacoupling framework, "global" does not necessarily mean "worldwide." As long as Type 1–3 boundaries separating local systems from adjacent and distant systems are clearly established (Fig. 1), the terms "local," "regional," and "global" are accurate descriptors of different coupling levels (Liu et al., 2013; Liu, 2017). Hence, although herring fisheries are not distributed worldwide, "global" is a useful descriptor for interactions between distant herring fisheries.

2.2. Data

Metacouplings, represented quantitatively as EEZ-level sums of Types 1, 2, and 3 catches (metric tons) across the six fishing sectors from 1950 to 2014, were assessed and modeled using herring catches from across the world (Fig. 2), with data obtained from the *Sea Around Us* (http://www.seaaroundus.org/; Pauly et al., 2020). Over this time span, herring were caught in 27 EEZs located primarily in Northern/Western Europe and northeastern North America. Of these, 17 EEZs had continuous 65-year catch data for at least three distinct fishing types—our criteria for including EEZs in metacoupling models in order to maximize reliability of historical catch assessment, future catch prediction, and fishing-sector interaction analysis.

The availability and quality of catch data are known to vary across EEZs and fisheries sectors. Generally, data are available only if countries regularly report catches to the FAO or produce fisheries research publications containing catch data. Even if catches are reported, underreporting and underestimation are recurrent issues with FAO data (Pauly and Zeller, 2016) that create a need for catch reconstruction, which varies methodologically across EEZs and sectors. Data on recreational and subsistence catches are often least available and most susceptible to biased estimation. Indeed, uncertainty is an important consideration in evaluating reconstructed catches, and there may be risks associated with incorporating reconstructions into models and using them to inform policies and management decisions. For instance, biases of reconstructed catches may range from slight differences in model parameters relative to reported catches, to larger differences in parameter magnitude or direction, to incorrect catch trends and misinformed conclusions and policy/management recommendations. Moreover, combining reported and unreported catches to generate total reconstructed catches could confound interpretation of type-specific trends or mask important methodological differences between types (Ye et al., 2017). As such, in the present study, amounts and temporal trends of reported, unreported, and total catches were distinguished in each EEZ to gauge the suitability of using total catches for metacoupling analysis.

Despite uncertainties associated with catch reconstruction, *Sea Around Us* attempts to improve upon FAO data by accounting for artisanal, subsistence, and recreational catches; discards (bycatch); and illegally-caught fish—all of which are routinely underreported or underestimated in FAO data (Pauly and Zeller, 2016). Rather than treating these poorly quantified catches as "zeroes," it is important to estimate them using the best available information (e.g., FAO catches in combination with peer-reviewed research, fisheries agency documents, independent research reports for individual EEZs; Pauly et al., 2020). Therein lies the purpose of *Sea Around Us*, which estimates catches using data from an average of 35 publications per reconstruction (Pauly and Zeller, 2016). *Sea Around Us* accounts for catch reconstruction uncertainty using the approach employed by the Intergovernmental Panel on Climate Change to evaluate climate prediction uncertainty (Funtowicz and Ravetz, 1990; Mastrandrea et al., 2010). Developers of catch reconstructions are asked to rate the quality of EEZ-specific time series for each fishing sector (industrial, artisanal, subsistence, recreational) across three time periods (1950–1969, 1970–1989, 1990–2010; Pauly et al., 2020). Ratings include "very high" (± 10 % uncertainty), "high" (± 20 %), "low" (± 30 %), and "very low" (± 50 %), with percent ranges

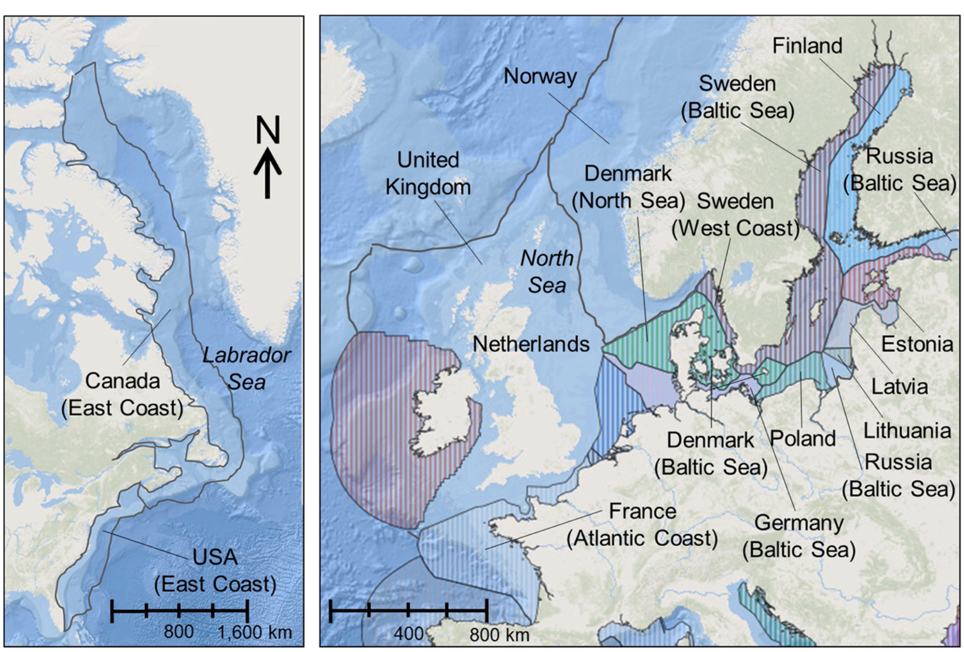

Fig. 2. Map of exclusive economic zones (EEZs) where Atlantic herring catches were assessed. The map was created using the publically accessible European Atlas of the Seas interface.

adapted from Monte Carlo simulations in Ainsworth and Pitcher (2005) and Tesfamichael and Pitcher (2007). Proponents and critics of catch reconstruction (Pauly and Zeller, 2017, Ye et al., 2017) recognize its potential for assessing trends in minimally-quantified fisheries subsectors (e.g., recreational fisheries), evaluating the success of management actions and fisheries' contributions to food/nutrition security, and improving countries' catch submissions to the FAO. Overall, although reconstructed catches are imperfect and prone to limitations described above, they represent a potentially viable option for quantifying and modeling catches and improving catch assessments amid widely-known limitations of typical marine fisheries data.

Herring data were downloaded from *Sea Around Us* and rearranged by EEZ to determine fishing nation identity, type (1–3), sector, and catch magnitude every year in 1950–2014. Data for more recent years were not available at the time of this writing. It is important to note that individual nations ratified the United Nations Convention on the Law of the Sea (UNCLOS) at different times, causing declaration years for the world's 280 EEZs to be quite variable, ranging from 1950 to 2011 (Pauly et al., 2020). However, *Sea Around Us* contains fisheries catch data for EEZ-equivalent waters (same waters as present-day EEZs) in years prior to EEZ declaration. As such, Types 1, 2, and 3 fishing were defined consistently in 1950–2014 according to the geographic proximity between fishing nations and waters fished (i.e., nations' own EEZs or EEZ-equivalent waters [Type 1], adjacent waters [Type 2], distant waters [Type 3]). This approach is reasonable because fishing occurred both intranationally and internationally prior to the year each EEZ was declared (Pauly et al., 2020), causing flows of fish within and beyond nations and creating metacouplings that are largely unassessed and unaccounted for in fisheries management programs. From a metacoupling perspective, fishing known to have occurred and which is numerically supported in databases like *Sea Around Us* needs to be accounted for—rather than treated as a "zero" (Pauly and Zeller, 2016) until EEZ declaration—to comprehensively understand formation and evolution of human-nature interactions in fisheries in 1950–2014, and thereby yield insights for fisheries management and governance. In addition, rather than adhering to particular geographic designation systems, the metacoupling framework is designed to accommodate different systems for defining spatial boundaries and assessing Type 1–3 interactions; catches in EEZs and EEZ-equivalent waters were thus sufficient for evaluating fisheries metacouplings in a consistent, standardized manner in 1950–2014 (Liu, 2017).

2.3. Analyses

The percentage contribution of unreported catches to total catches was calculated across EEZs and years as an index of the relative magnitude of catch reconstruction and the relative uncertainty associated with drawing conclusions from partially-reconstructed data, as in Gibson et al. (2014). In addition, reported herring catches were statistically compared to total reconstructed catches (reported + unreported) during three time periods (1950–1969, 1970–1989, 1990–2014) corresponding to those used in previous analyses of reconstructed catches (Zeller et al., 2015; Pauly and Zeller, 2016; Pauly et al., 2020). In particular, linear regressions were created between year (x) and natural-log-transformed catch (y) with reporting status (reported, total reconstructed) included as a categorical factor. Regressions were produced for all EEZ-time period combinations (n = 51) and evaluated using slope and intercept comparison techniques developed in previous fisheries catch research (Zeller et al., 2015) to determine if and when EEZ-specific catch trends differed between reporting statuses.

Metacouplings associated with herring fishing were assessed by graphing total (reported + unreported) catches and their Type 1–3 components over 65 years in each of the 17 EEZs. Flows of herring within and between nations were depicted using Sankey diagrams, which display flows in proportion to tonnage (line width). In addition to graphical techniques, total herring catches and fishing-sector interactions were evaluated using autoregressive integrated moving average (ARIMA) modeling. This approach is a reliable, regularly used tool to understand time-series patterns (Hyndman and Athanasopoulos, 2018) and predict future phenomena, including fisheries catches (Tsitsika et al., 2007), wind speed (Kavasseri and Seetharaman, 2009), and vehicular traffic flow (Williams and Hoel, 2003). ARIMA modeling is also an emerging tool in the metacoupling literature, recognized for its ability to quantify and predict metacouplings in a manner relevant for decision-makers such as natural resource policy makers, managers, and biologists (Herzberger et al., 2019). Although ARIMA modeling was used herein, it should be noted that fisheries metacouplings can be investigated using a variety of approaches that warrant further research (e.g., agent-based modeling, network analyses, harmonic regression, dynamic regression, state space modeling; Liu, 2017; Schaffer-Smith et al., 2018; Dou et al., 2019; Carlson et al., 2020b, c).

ARIMA models use time-series properties (i.e., lagged values and prediction errors of dependent variables) as predictors to forecast how time series will develop in the future. By including autoregressive (AR (p)) and moving average (MA(q)) parameters, ARIMA models tend to improve model fit compared to either technique in isolation (Hamilton, 1994; Hyndman and Athanasopoulos, 2018). ARIMA models also contain integrated (I(d)) terms that stationarize time series by subtracting current values of dependent variables from previous values d times. While not explicitly accounting for external independent variables, standard ARIMA models (those with only AR, I, and MA parameters) endogenize effects of major drivers by accounting for non-stationarity, seasonality, and auto-correlation in time series. In addition, ARIMA models can be modified to include external independent variables if appropriate time-series data exist (Hamilton, 1994; Hyndman and Athanasopoulos, 2018).

Across the 17 EEZs, ARIMA models were generated for each fishing type using 65-year herring catch data (1950–2014), and resultant equations were used to predict catches for 16 additional years (2015–2030). For purposes of clarity and continuity with previous metacoupling research (Herzberger et al., 2019; Carlson et al., 2020b), below we include preliminary Eqs. (1–4) to illustrate the mathematical progression from autoregressive models to full ARIMA models (Eqs. 5 and 6) that we ultimately used to evaluate and predict herring catches. First, natural-log-transformed herring catches were modeled as a function of AR(p) terms representing lagged catch values:

$$Y_{tef}(1) = \delta + \sum_{i=1}^{p} \phi_i y_{(t-i)ef} + \varepsilon_{tef} \quad (1)$$

where $Y_{tef}(1)$ is catch at time t for EEZ e and fishing type f (Type 1 industrial, artisanal, subsistence, and recreational; Type 2 industrial; Type 3 industrial), δ is a constant, p is the AR polynomial order, ϕ_i terms are AR parameters, $y_{(t-i)ef}$ terms are lagged values of catch for EEZ e and type f, and ε_{tef} is an error term for EEZ e and type f. Catch time series were stationarized via the I(d) term by subtracting current from previous catches d times:

$$y_{d,tef} = Y_{tef} - Y_{(t-1)ef} \quad (2)$$

$$Y_{tef}(2) = \delta + \sum_{i=1}^{p} \phi_i y_{d,(t-i)ef} + \varepsilon_{tef} \quad (3)$$

where $Y_{tef}(2)$ is catch at time t for EEZ e and fishing type f, $y_{d,tef}$ is y_{tef} differenced d times, and other terms are the same as above. Errors between predicted and observed catches were treated as predictors via the MA(q) term:

$$Y_{tef}(3) = \delta + \sum_{i=1}^{q} \theta_i \varepsilon_{(t-i)ef} + \varepsilon_{tef} \quad (4)$$

where $Y_{tef}(3)$ is catch at time t for EEZ e and fishing type f, δ is a constant, q is the MA polynomial order, θ_i terms are MA parameters, $\varepsilon_{(t-i)ef}$ terms are prediction errors for EEZ *e* and type *f*, and ε_{tef} is an error term for EEZ *e* and type *f*. Collectively, AR(*p*), I(*d*), and MA(*q*) terms constitute ARIMA models of the form:

$$Y_{tef}(4) = \delta + \sum_{i=1}^{p} \phi_i y_{d,(t-i)ef} + \sum_{i=1}^{q} \theta_i \varepsilon_{(t-i)ef} + \varepsilon_{tef} \quad (5)$$

where $Y_{tef}(4)$ is catch at time *t* for EEZ *e* and fishing type *f* and other terms are the same as above Finally, ARIMA models were updated to account for interactions among fishing types by adding a matrix of external regressors (**A**):

$$Y_{tef}(5) = \mathbf{A} + \sum_{i=1}^{p} \phi_i y_{d,(t-i)ef} + \sum_{i=1}^{q} \theta_i \varepsilon_{(t-i)ef} + \varepsilon_{tef} \quad (6)$$

where $Y_{tef}(5)$is catch at time *t* for EEZ *e* and fishing type *f*, **A** is a matrix containing 65-year catch data for fishing types other than *f* operating in EEZ *e*, and other terms are the same as above. Eqs. 5 and 6 were used to evaluate interactions among fishing sectors and predict future catches across all EEZs and fishing types; Eq. 5 was used if most-parsimonious models (see below) did not include external regressors, whereas Eq. 6 was used if most-parsimonious models included external regressors.

Assumptions of ARIMA modeling such as stationarity and lack of autocorrelation were evaluated using Dickey-Fuller and Box-Ljung tests, respectively. In addition, autocorrelation and partial autocorrelation functions were employed to ensure reliable parameter estimation through maximum-likelihood methods and information-theoretic model selection (Tsitsika et al., 2007). For each EEZ and fishing type, unique combinations of AR(*p*), I(*d*), MA(*q*), and external regressors (i.e., Eqs. 5 and 6) were compared using Akaike's Information Criterion (AIC). To ensure that final, most-parsimonious models only included informative parameters (those that reduce model deviance) while receiving substantial AIC support, models with ΔAIC < 2 and one additional parameter relative to top-performing models were excluded from further consideration (Burnham and Anderson, 2002).

ARIMA models with the lowest AIC score and random, independent residuals as inferred from Box-Ljung tests were treated as final, most-parsimonious models for each EEZ and fishing type. Models were validated by comparing model-predicted and observed herring catches using standard ARIMA model evaluation metrics (i.e., mean absolute scaled error [MASE], normalized root mean squared error [NRMSE], RMSE/standard deviation), where values between 0 and 1 (as opposed to >1) indicated good to great performance (Hyndman and Athanasopoulos, 2018). Most-parsimonious models were used to assess metacoupling interactions among fishing types within EEZs, and predict future catches in 2015–2030 for all fishing types. Fishing-type interactions were assessed by referring to external regressor *p* values and coefficients derived from the **A** matrix in Eq. 6. A regressor was only treated as having a significant effect on herring catches if $p < 0.05$. Within EEZs, fishing-type interactions were depicted in conceptual diagrams where arrows connecting types signify significant catch relationships, and arrow width and color are proportional to interaction magnitude and direction (positive, negative). All graphs were produced and analyses performed in RStudio Desktop version 1.2.5019 (RStudio, 2019).

3. Results

3.1. Catches by reporting status

Unreported catches represented a small percentage of total reconstructed catches, averaging 9.3 ± 0.3 % (SEM) across the study area in 1950–2014 (Figure S1). Over this time span, unreported catches were proportionally smallest in Norway (5.8 ± 0.3 %) and less than 15 % of total reconstructed catches in all EEZs except Poland (16.7 ± 2.2 %), Denmark (Baltic Sea, 17.6 ± 1.3 %), and the Netherlands (23.6 ± 1.3 %; Table 1, Figure S2, S3). Reported and total reconstructed catches exhibited equivalent temporal trends (equal slopes, $p > 0.05$) for 98 % of EEZ-time period combinations ($n = 50$; Table S1). Germany (Baltic Sea, 1950–1969) was the only EEZ-time period for which reported and total reconstructed catches had different slopes ($p = 0.03$). For 35 % of EEZ-time periods ($n = 18$), model y-intercepts differed between reported and total reconstructed catches ($p < 0.05$, Table S1) due to inclusion of unreported catches in reconstructions.

Table 1
Mean percentage contribution of unreported Atlantic herring catches to total catches (reported + unreported) over 65 years (1950–2014) for 17 exclusive economic zones (EEZs). Standard deviation (SD), sample size (N) in years, and standard error of the mean (SEM) are also included.

EEZ	Mean %	SD	N	SEM
Canada (East Coast)	9.2	1.3	65	0.2
Denmark (Baltic Sea)	17.6	10.2	65	1.3
Denmark (North Sea)	9.4	6.5	65	0.8
Estonia	7.9	6.7	65	0.8
Finland	10.4	5.7	65	0.7
France (Atlantic Coast)	7.6	3.6	65	0.5
Germany (Baltic Sea)	14.4	10.5	65	1.3
Latvia	8.8	10.7	65	1.3
Lithuania	14.5	18.1	65	2.2
Netherlands	23.6	10.5	65	1.3
Norway	5.8	2.3	65	0.3
Poland	16.7	17.5	65	2.2
Russia (Baltic Sea)	10.7	12.6	65	1.6
Sweden (Baltic Sea)	13.1	7.5	65	0.9
Sweden (West Coast)	8.3	4.5	65	0.6
United Kingdom	13.6	7.3	65	0.9
USA (East Coast)	7.7	4.9	65	0.6

3.2. Catches by metacoupling type

Temporal trends in total herring catches varied among EEZs. Total catches increased over 65 years in 23 % of EEZs ($n = 4$), decreased in 12 % of EEZs ($n = 2$), and remained relatively stable in 65 % of EEZs ($n = 11$; Figs. 3, 4). Types 1, 2, and 3 catches—by nations in their own, adjacent, and distant EEZs, respectively—also exhibited temporal variability (Fig. 5a). However, they generally changed in the same direction such that overall percentage contributions to total catches were relatively stable in 1950–2014 (Fig. 5b). Type 1 catches averaged 51 % of total catches across EEZs over time (SEM 0.4, range 44–59 %), compared to 41 % for Type 2 catches (SEM 0.2, range 38–47 %) and 8% for Type 3 catches (SEM 0.4, range 3–15 %; Fig. 5b).

Across EEZs, Type 1 herring catches averaged 4.0×10^6 MT (SEM 1.7×10^6 MT, range 2.9×10^4–2.7×10^7 MT) in 1950–2014 (Table 2). Type 2/3 catches averaged 3.3×10^6 MT (SEM 1.4×10^6 MT, range 4.1×10^5–1.9×10^7 MT). There was spatial heterogeneity in the predominance of different fishing types, as 78 % of nations bordering the Baltic Sea were Type-2-dominant (22 % Type-1-dominant), compared to 25 % of countries bordering the Atlantic Ocean/North Sea (75 % Type-1-dominant).

Type 2 industrial fishing was the largest-tonnage fishing type in 53 % of EEZs studied ($n = 9$), where it averaged 59 % of total herring catches across years in 1950–2014 (Table 2). Type 1 industrial fishing predominated in the remaining 47 % of EEZs ($n = 8$), where it annually averaged 56 % of total catches. Overall, Types 1, 2, and 3 industrial fishing (1.2×10^8 MT) accounted for 91 % of total catches across EEZs in 1950–2014 (1.4×10^8 MT; Table S2). Tonnages were considerably smaller for artisanal (1.2×10^7 MT), subsistence (7.5×10^4 MT), and recreational (2.5×10^5 MT) fishing.

3.3. Type 2/3 fishing nations

Denmark was the largest-tonnage fishing nation in 18 % of EEZs ($n = 3$), where it annually averaged 54 % of Type 2/3 catches in 1950–2014 (Table 2, Fig. 6, Figure S4–S20). Likewise, Russia and Sweden were each

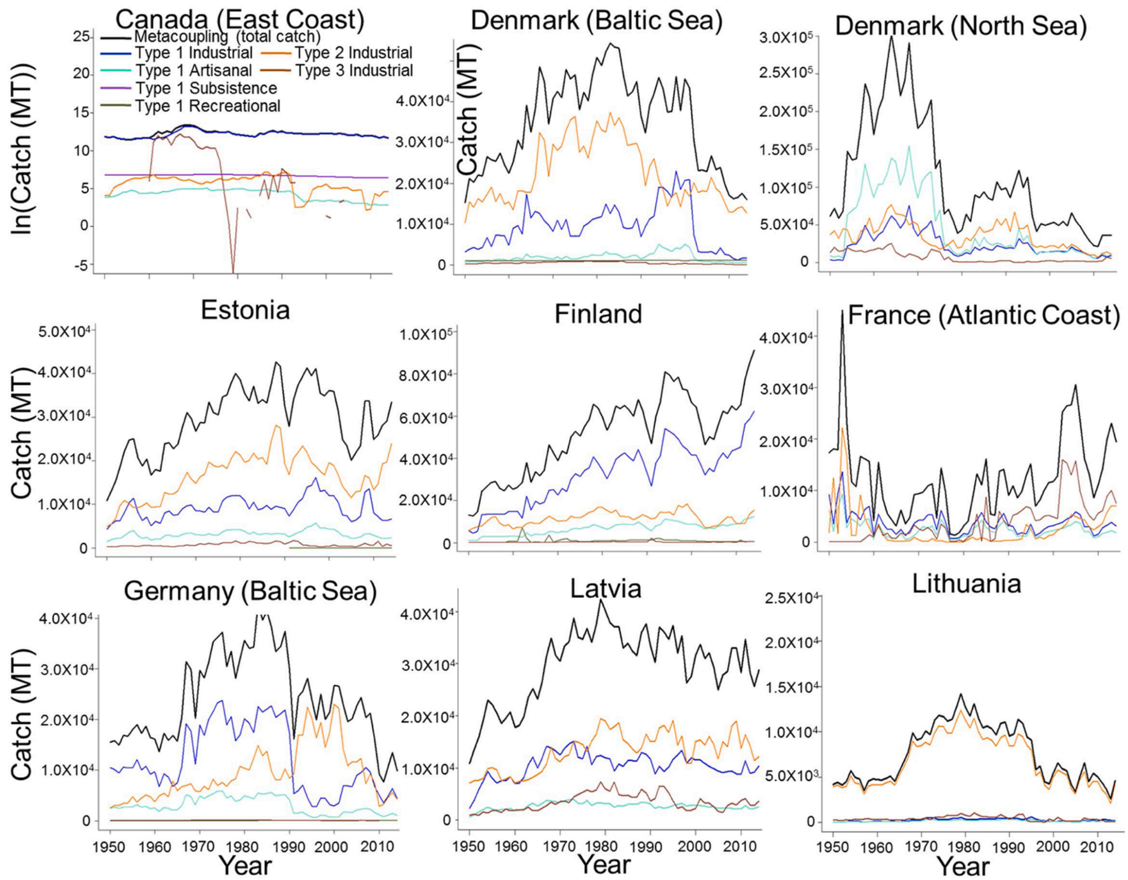

Fig. 3. Atlantic herring catches (metric tons, MT) in 1950–2014 within nine exclusive economic zones. Catch types are metacoupling (total catch), Type 1 (industrial, artisanal, subsistence, and recreational catches by nations in their own EEZs), Type 2 (industrial catches in adjacent EEZs), and Type 3 (industrial catches in distant EEZs). Note that some catch types are depicted using natural-log-transformed y-axes (for clarity) or have noncontinuous data in 1950–2014.

the primary Type 2/3 fisher in 18 % of EEZs, where they annually averaged 45 % and 41 % of total catches, respectively. Estonia (mean 49 % of catches across years), Germany (45 %), and Finland (38 %) were each the primary Type 2/3 fisher in 12 % of EEZs (n = 2; Table 2, Fig. 6, Figure S4–S20).

3.4. Relationships among fishing sectors

The most common fishing-sector relationship revealed by ARIMA models was a bidirectional positive interaction between artisanal and Type 1 industrial fishing, which occurred in 76 % of EEZs (n = 13; Tables 2, 3, Figs. 7, 8, Table S3–S19). Bidirectional positive relationships also existed for Type 2 and Type 1 industrial fishing (18 % of EEZs, n = 3), Type 3 and Type 2 industrial fishing (12 %, n = 2), Type 3 and Type 1 industrial fishing (12 %, n = 2), and artisanal and Type 2 industrial fishing (12 %, n = 2).

The most common unidirectional relationship was a positive effect of Type 1 industrial herring catches on Type 2 industrial catches (+I1–I2, Tables 2, 3, Figs. 7, 8), which occurred in 18 % of EEZs studied (Table S3–S19). Other relatively prevalent unidirectional positive relationships (+I3–I1, +I2–I3) and negative relationships (–I3-A, –I2-A) occurred in 12 % of EEZs (n = 2).

3.5. Catch projections

Across the 17 EEZs and six fishing types studied, there were 70 unique EEZ-fishing type combinations. Of these combinations, ARIMA models projected herring catches to increase for 19 % (n = 13), decrease for 11 % (n = 8), and remain stable for 70 % (n = 49) in 2015–2030 compared to 2014 tonnages (Table 2, Figure S21–S37).

Fishing types with the largest percentage of EEZs having projected catch increases were subsistence fishing (33 %, n = 1) and Type 1 industrial fishing (23 %, n = 4; Table 2, Figure S21–S37). By comparison, predicted catch decreases were most prevalent again for subsistence fishing (33 %, n = 1) and for artisanal fishing (19 %, n = 3). The percentage of EEZs with stable projected catches was largest for recreational fishing (86 %, n = 6) and Type 2 industrial fishing (75 %, n = 12; Table 2, Figure S21–S37).

4. Discussion

Our study illustrates how metacouplings are widespread, spatially and temporally variable phenomena affecting Atlantic herring fisheries throughout the world. Although research on fisheries as coupled human and natural systems is growing (Crona et al., 2015; Österblom and Folke, 2015; Tapia-Lewin et al., 2017), few studies have explicitly considered local, regional, and global scales and associated interactions among fishing sectors, leaving considerable knowledge gaps regarding the structure, magnitude, and extent of fisheries metacouplings. We helped ameliorate these information deficiencies by quantifying, modeling, and predicting metacouplings for a globally important fish species.

Type 2 industrial fishing was the predominant component of metacouplings by tonnage in the majority of EEZs studied, followed by Type 1 industrial fishing, suggesting that fishing in neighboring nations is comparatively important for herring. This finding reflects the nearness of herring-fishing nations, most of which are in Northern/Western Europe, alongside regulations that allow fishing in neighboring waters while protecting aquatic ecosystems in the North-East Atlantic through

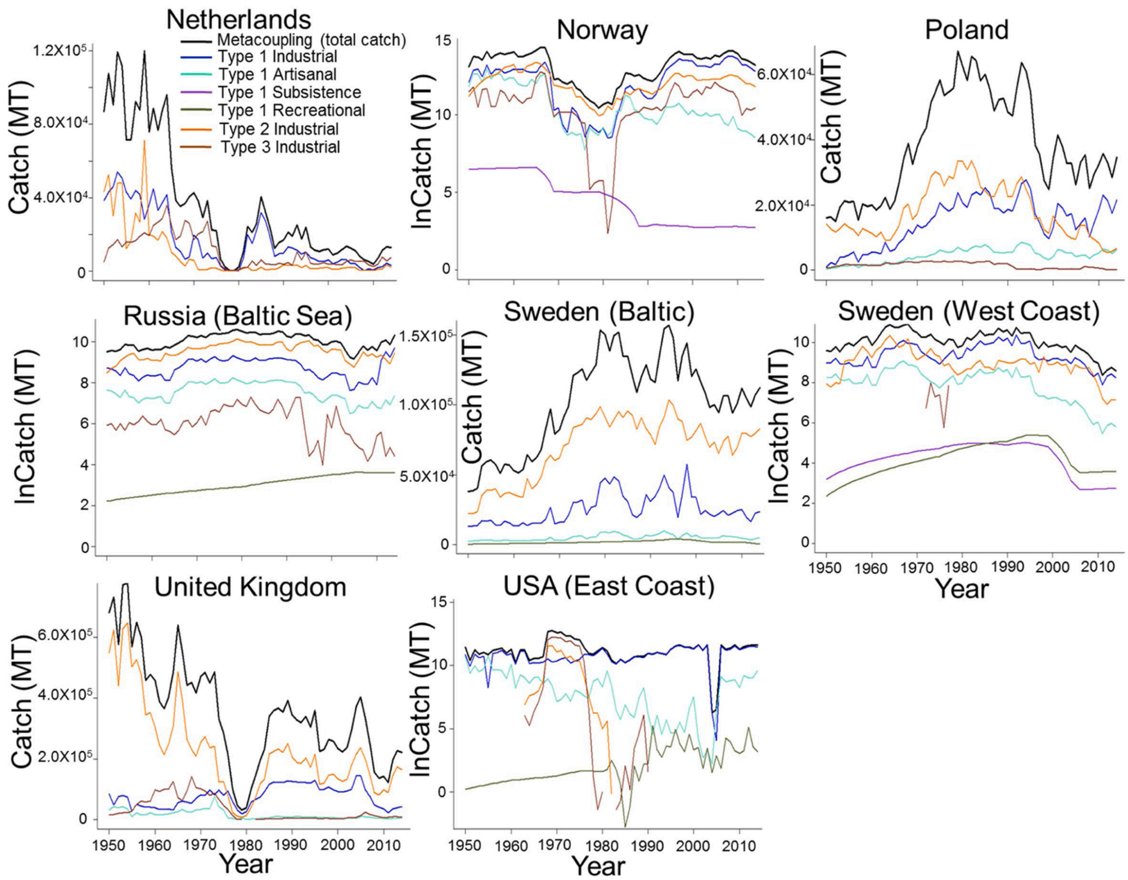

Fig. 4. Atlantic herring catches (metric tons, MT) in 1950–2014 within eight exclusive economic zones. Catch types are metacoupling (total catch), Type 1 (industrial, artisanal, subsistence, and recreational catches by nations in their own EEZs), Type 2 (industrial catches in adjacent EEZs), and Type 3 (industrial catches in distant EEZs). Note that some catch types are depicted using natural-log-transformed y-axes (for clarity) or have noncontinuous data in 1950–2014.

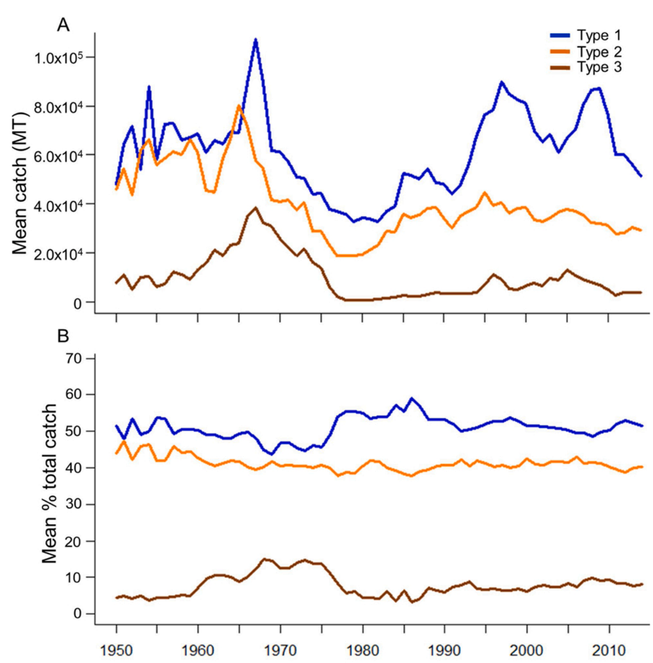

Fig. 5. Changes in Atlantic herring metacouplings in 1950–2014. (A) Mean catch (metric tons, MT) across EEZs by fishing type and year. (B) Mean percentage of total catch across EEZs by fishing type and year.

robust fisheries monitoring and enforcement (e.g., Convention for the Protection of the Marine Environment of the North-East Atlantic [OSPAR Convention], EU Common Fisheries Policy; de La Fayette, 1999; Churchill and Owen, 2010; European Commission, 2020). The prevalence of Type 2 herring fishing stands in contrast to the predominance of Type 1 fishing for marine fishes collectively (Carlson et al., 2020a) and Peruvian anchoveta (*Engraulis ringens*), Mahi Mahi (*Coryphaena hippurus*), Atlantic Bluefin Tuna, and cods (Gadidae) in particular (Carlson et al., 2018a, 2020b). Compared to these species, herring are highly abundant in a somewhat smaller area with a greater density of developed, high-capacity fishing nations (World Bank, 2020)—conditions conducive to Type 2 fishing. This trend is also evidenced within regions studied herein, as 78 % of nations bordering the Baltic Sea were Type-2-dominant, compared to only 25 % of countries bordering the much-larger Atlantic Ocean/North Sea—an asymmetry in fishing behavior mirroring that of animals (e.g., fish, horses) in competition and territoriality research (Rubenstein, 1981a, b, c).

Across EEZs, Type 3 industrial fishing was never the most prevalent fishing type in 1950–2014, and in only two EEZs (France [Atlantic Coast], Netherlands) was it the second-most predominant (mean 35 % by tonnage). This finding suggests that herring fisheries are relatively resilient to exploitative Type 3 fishing—including illegal distant-water fishing—that predominates in regions like Western Africa that face fisheries management and governance limitations (Alder and Sumaila, 2004; Agnew et al., 2009; Belhabib et al., 2014). In contrast, Northern/Western European and North American nations typically have necessary resources to protect fisheries and enforce regulations that discourage exploitative Type 3, as opposed to Types 1 and 2, fishing. For instance, European Union regulations on sustainable management of

Table 2

Summary of Atlantic herring catches, fishing-sector relationships, and catch projections for 17 exclusive economic zones (EEZs). Type 1, 2/3 (MT) is the total tonnage (metric tons, MT) of Type 1 and Type 2/3 catches over 65 years (1950–2014). Dominant (%) is the largest-tonnage fishing type and its percentage of total catches averaged across 1950–2014. Nation (% 2/3) is the largest-tonnage Type 2/3 fishing nation and its percentage of Type 2/3 catches in 1950–2014. Relationships are the bidirectional positive (++), unidirectional positive (+), and unidirectional negative (–) relationships between fishing types (artisanal [A], recreational [R], subsistence [S], Type 1 industrial [I1], Type 2 industrial [I2], Type 3 industrial [I3]). ++ indicates a positive effect of the first fishing type on the second, and vice versa, whereas + and – indicate a positive/negative effect of the first type on the second (not the opposite). Catch projections are predicted changes in catch (increase ↑, decrease ↓, stable ↔) for fishing types in 2015–2030 derived from ARIMA models (see Table S1–S17).

EEZ	Type 1, 2/3 (MT)	Dominant (%)	Nation (% 2/3)	Relationships	Catch projections
Canada (East Coast)	1.4×10^7, 1.4×10^6	I1 (93)	Russia (47)	++ (A–S, A–I2)	↑(A), ↔ (I1, I2, S)
Denmark (Baltic Sea)	7.8×10^5, 1.5×10^6	I2 (66)	Germany (56)	++ (A–I1, I3–I1), + (I1–R), – (A–R)	↔ (A, I1, I2, I3, R)
Denmark (North Sea)	4.5×10^6, 2.7×10^6	I2 (37)	Sweden (64)	++ (A–I1), + (I3–A, I2–I1), – (I2–A, I3–I1)	↑(I1), ↔ (A, I2, I3)
Estonia	8.0×10^5, 1.1×10^6	I2 (55)	Finland (36)	++ (A–I1), + (I3–I1, I1–I2, I2–I3), – (I3–A)	↑(I2), ↔ (A, I1, I3)
Finland	2.6×10^6, 7.7×10^5	I1 (60)	Estonia (63)	++ (A–I1), + (I3–I2)	↑(A, I1), ↔ (I2, I3, R)
France (Atlantic Coast)	4.0×10^5, 4.1×10^5	I1 (34)	Netherlands (60)	++ (A–I1), + (A–I3, I1–I2), – (I2–A)	↑(I3), ↔ (A, I1, I2)
Germany (Baltic Sea)	9.7×10^5, 6.0×10^5	I1 (48)	Denmark (47)	++ (A–I1)	↓(A, I1), ↔ (I2, R)
Latvia	8.5×10^5, 1.1×10^6	I2 (44)	Sweden (29)	++ (A–I1, I3–I2)	↔ (A, I1, I2, I3)
Lithuania	2.9×10^4, 4.6×10^5	I2 (89)	Russia (42)	++ (A–I1, I3–I2)	↑(I3), ↔ (A, I1, I2)
Netherlands	1.1×10^6, 1.3×10^6	I1 (44)	Denmark (26)	++ (I3–I1, I2–I1)	↓(I2, I3), ↔ (I1)
Norway	2.7×10^7, 1.9×10^7	I1 (41)	Russia (46)	++ (A–I1, I2–I1), + (I2–I3, I1–I3, I1–S, S–A)	↑(I1), ↓(A, S), ↔ (I2, I3)
Poland	1.2×10^6, 1.2×10^6	I2 (48)	Sweden (31)	++ (A–I1), + (I3–I1, I2–A), – (I3–A, I2–I1)	↔ (A, I1, I2, I3)
Russia (Baltic Sea)	5.7×10^5, 9.8×10^5	I2 (61)	Estonia (35)	++ (A–I1), + (I1–I2)	↑(I1), ↓(I3), ↔ (A, I2, R)
Sweden (Baltic Sea)	2.1×10^6, 4.5×10^6	I2 (68)	Finland (39)	++ (A–I1)	↑(I2), ↔ (A, I1, R)
Sweden (West Coast)	1.1×10^6, 6.1×10^5	I1 (51)	Denmark (89)	++ (A–I1, R–S)	↑(I2, R, S), ↓(A, I1)
United Kingdom	6.0×10^6, 1.7×10^7	I2 (60)	Norway (34)	++ (A–I2, I2–I1)	↔ (A, I1, I2)
USA (East Coast)	4.0×10^6, 1.8×10^6	I1 (77)	Germany (34)	+ (R–I1), – (R–A)	↔ (A, I1, R)

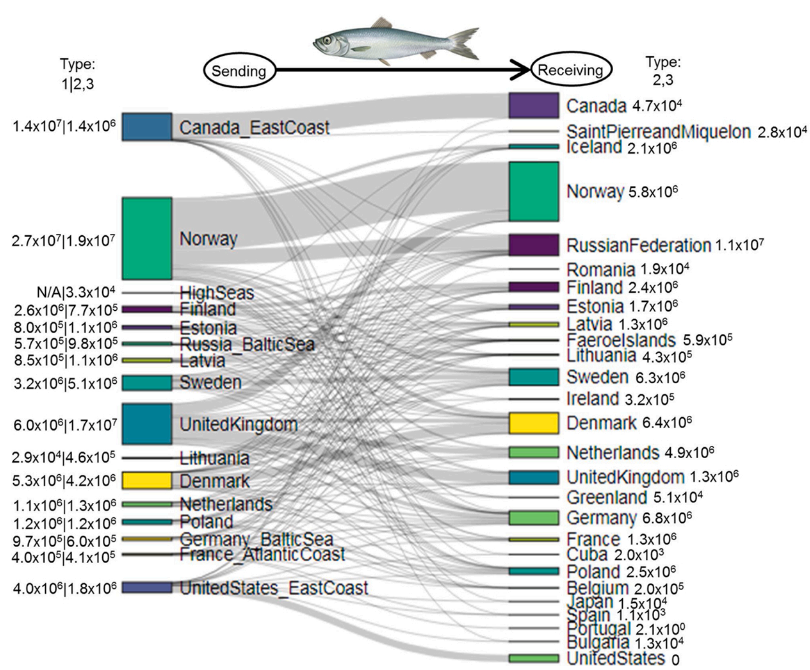

Fig. 6. Flows of Atlantic herring (metric tons) within and between exclusive economic zones (EEZs) in 1950–2014. In the left margin, numbers to the left of the divider represent Type 1 fishing—catches by nations in their own EEZs. Numbers to the right of the divider represent Type 2/3 fishing—catches in adjacent/distant EEZs. Numbers in the right margin are Type 2/3 catches by each nation in other EEZs. Sweden EEZs (2) and Demark EEZs (2) are combined within nations to save space.

external fishing fleets, approved in December 2017, updated historical international fishing rules to better protect stocks against exploitative distant-water fishing (Guggisberg, 2019). The low prevalence of Type 3 fishing may also be partly attributable to movement and migration patterns of herring in relation to their fisheries (e.g., coastal movements causing greater susceptibility to Types 1 and 2 fishing; Ruzzante et al., 2006; Kanwit and Libby, 2009).

Across EEZs in 1950–2014, the lowest-tonnage fishing types were artisanal, subsistence, and recreational (Table S2). This is to be expected given vessel and gear limitations and the relatively small size and spatial distribution of these sectors compared to industrial fisheries (Cooke and Cowx, 2004; Smith and Basurto, 2019). However, small-scale herring fisheries are socioeconomically vital and make direct and indirect contributions to human health and well-being (Devold, 1955; Lorentzen and Hannesson, 2004; Rorke, 2005). For instance, subsistence catch trends and metacoupling interactions with other fishing sectors in 1950–2014 have important implications for food supply and food/nutrition security in the three EEZs that exhibited subsistence fishing: Canada (East Coast), Sweden (West Coast), and Norway. In Canada, where subsistence herring fisheries have existed for centuries (Perley, 1852; Stephenson et al., 1993), notably stable subsistence catches (annual mean 8.3×10^2 MT, SEM 1.4×10^1 MT) and a positive, mutualistic 65-year relationship with

Table 3
Summary of Atlantic herring ARIMA models across exclusive economic zones (EEZs). Models include AR, I, and MA parameters in parentheses, along with fishing types (artisanal [A], recreational [R], subsistence [S], Type 1 industrial [I1], Type 2 industrial [I2], Type 3 industrial [I3]). Model statistics include log likelihood values (LL), Akaike's Information Criterion (AIC) scores, mean absolute scaled error (MASE), normalized root mean squared error (NRMSE; RMSE/standard deviation), and p values from Box-Ljung tests (B-L). Low MASE and NRMSE values indicate high-performing models; values greater than 1 indicate low-performing models. Box-Ljung p values were used to determine if residuals were autocorrelated (p values > 0.05 indicate no autocorrelation).

EEZ	Model	LL	AIC	MASE	NRMSE	B-L
Canada (East Coast)	A ~ (1,1,3)+ I2+S	34.43	−54.87	0.52	0.38	0.84
	S ~ (4,1,1)+A	266.50	−518.99	0.26	0.13	0.66
	I1 ~ (2,1,3)	41.90	−71.81	0.53	0.52	0.94
	I2 ~ (3,1,3)+A	−59.80	135.60	0.44	0.54	0.79
Denmark (Baltic Sea)	A ~ (1,1,1)+I1	74.24	−128.48	0.19	0.20	0.71
	I1 ~ (1,1,2)+A + I3	63.60	−113.21	0.10	0.09	0.88
	I2 ~ (2,1,3)	30.96	−49.92	0.62	0.46	0.93
	I3 ~ (2,1,5)+I1	−28.96	71.92	0.49	0.35	0.88
	R ~ (0,1,3)+A + I1	246.98	−479.96	0.88	0.54	0.93
Denmark (North Sea)	A ~ (0,1,4)+ I1+I2+I3	59.09	−102.17	0.03	0.03	0.37
	I1 ~ (0,1,4)+A + I2+I3	69.74	−121.49	0.05	0.04	0.73
	I2 ~ (1,0,0)	−2.40	12.80	0.74	0.60	0.41
	I3 ~ (0,1,4)	−91.49	192.98	0.62	0.50	0.86
Estonia	A ~ (2,1,0)+ I1+I3	103.14	−196.28	0.26	0.20	0.70
	I1 ~ (4,1,1)+A + I3	102.07	−188.15	0.03	0.02	0.96
	I2 ~ (3,1,0)+I1	52.84	−93.68	0.44	0.31	0.82
	I3 ~ (5,1,0)+I2	−18.35	50.71	0.16	0.27	0.92
Finland	A ~ (0,1,3)+I1	203.38	−396.77	0.03	0.02	0.61
	I1 ~ (0,1,3)+A	203.50	−397.01	0.04	0.02	0.59
	I2 ~ (1,1,3)+I3	37.41	−62.82	0.39	0.29	0.81
	I3 ~ (4,1,1)	−39.54	91.08	0.41	0.74	0.91
	R ~ (4,1,4)	−63.28	144.56	0.56	0.57	0.92
France (Atlantic Coast)	A ~ (5,1,0)+ I1+I2	45.55	−75.10	0.01	0.03	0.28
	I1 ~ (4,0,0)+A	44.50	−75.00	0.02	0.02	0.87
	I2 ~ (2,1,4)+I1	−85.67	187.34	0.41	0.32	0.62
	I3 ~ (4,1,3)+A	−79.33	178.66	0.05	0.05	0.96
Germany (Baltic Sea)	A ~ (0,2,2)+I1	121.12	−234.23	0.02	0.02	0.38
	I1 ~ (0,2,2)+A	117.57	−227.14	0.02	0.02	0.34
		2.60	4.80	0.76	0.62	0.79

Table 3 (*continued*)

EEZ	Model	LL	AIC	MASE	NRMSE	B-L
	I2 ~ (2,1,2)					
	R ~ (3,2,2)	122.25	−232.50	0.49	0.29	0.71
Latvia	A ~ (0,1,1)+I1	214.71	−423.42	0.02	0.02	0.83
	I1 ~ (0,1,1)+A	215.26	−424.52	0.02	0.02	0.81
	I2 ~ (2,1,2)+I3	45.03	−78.06	0.47	0.56	0.47
	I3 ~ (3,1,3)+I2	9.33	−2.66	0.33	0.30	0.93
Lithuania	A ~ (1,1,1)+I1	610.12	−1211.56	0.00	0.00	0.89
	I1 ~ (1,1,1)+A	612.21	−1212.24	0.00	0.00	0.89
	I2 ~ (0,1,1)+I3	19.20	−32.41	0.53	0.76	0.92
	I3 ~ (3,1,3)+I2	−45.28	106.56	0.56	0.44	0.81
Netherlands	I1 ~ (3,1,2)+ I2+I3	−73.98	163.96	0.16	0.17	0.70
	I2 ~ (3,1,3)+I1	−66.04	148.07	0.14	0.11	0.93
	I3 ~ (3,1,1)+I1	−31.61	75.22	0.62	0.65	0.92
Norway	A ~ (2,1,3)+ I1+S	−12.56	41.12	0.51	0.40	0.78
	I1 ~ (4,1,2)+A + I2	−15.09	50.18	0.01	0.01	0.86
	I2 ~ (2,1,2)+I1	5.98	1.52	0.44	0.33	0.63
	I3 ~ (4,1,3)+ I1+I2	−69.50	159.01	0.03	0.02	0.98
	S ~ (2,1,1)+I1	46.38	−80.75	0.29	0.20	0.94
Poland	A ~ (1,1,2)+ I1+I2+I3	128.52	−243.03	0.06	0.06	0.84
	I1 ~ (1,1,3)+A + I2+I3	127.13	−238.27	0.07	0.07	0.97
	I2 ~ (0,1,1)	27.12	−48.24	0.70	0.43	0.85
	I3 ~ (2,1,3)	−44.84	101.68	0.51	0.40	0.90
Russia (Baltic Sea)	A ~ (2,1,3)+I1	46.29	−78.59	0.36	0.47	0.74
	I1 ~ (0,2,1)+A	24.67	−43.33	0.49	0.48	0.30
	I2 ~ (3,1,4)+I1	29.68	−41.36	0.36	0.55	0.89
	I3 ~ (3,1,2)	−50.11	112.23	0.47	0.62	0.98
	R ~ (1,1,0)	262.34	−520.67	0.44	0.26	0.90
Sweden (Baltic Sea)	A ~ (1,1,2)+I1	92.91	−175.81	0.45	0.40	0.79
	I1 ~ (1,1,2)+A	89.01	−168.01	0.41	0.55	0.84
	I2 ~ (0,1,1)	52.49	−98.99	0.63	0.68	0.99
	R ~ (0,1,3)	97.95	−187.91	0.40	0.22	0.80
Sweden (West Coast)	A ~ (1,1,0)+I1	218.86	−429.72	0.04	0.03	0.34
	I1 ~ (1,1,1)+A	218.56	−429.13	0.04	0.04	0.36
	I2 ~ (1,0,1)	−18.94	45.87	0.64	0.28	0.94
	R ~ (1,1,0)+S	240.27	−472.54	0.01	0.01	0.77
	S ~ (1,1,0)+R	237.22	−466.43	0.01	0.01	0.71

(*continued on next page*)

Table 3 (*continued*)

EEZ	Model	LL	AIC	MASE	NRMSE	B-L
United Kingdom	A ~ (2,1,3)+I2	−33.66	81.32	0.29	0.29	0.79
	I1 ~ (4,1,0)+I2	7.50	−3.00	0.46	0.26	0.99
	I2 ~ (1,1,3)+A + I1	−3.37	20.74	0.22	0.16	0.89
United States (East Coast)	A ~ (4,1,3)+R	−92.30	202.61	0.24	0.25	0.96
	I1 ~ (4,1,4)+R	−92.54	205.08	0.84	0.47	0.95
	R ~ (2,1,4)	−83.24	180.47	0.39	0.57	0.75

artisanal fishing suggest that subsistence fisheries may persist in the future, as predicted in 2015–2030 (Table 2, Figure S21). Subsistence and artisanal catches are also supported through the Canadian government's active protection of small-scale herring fisheries, the nutritional, social, and ceremonial benefits of which are explicit objectives in the Southwest Nova Scotia/Bay of Fundy herring management plan, which allocates 20 % of the Total Allowable Catch to small-scale fisheries (Fisheries and Oceans Canada (DFO), 2014).

Similar to Canada, accounts of herring contributing to food supply and food/nutrition security in Sweden and Norway date back hundreds of years (Devold, 1955; Piriz, 2004; Rorke, 2005), with many Norwegians reportedly consuming herring on a daily basis in the years during and shortly after World War II (Norwegian Seafood Council, 2020). In Sweden (West Coast), subsistence herring catches were projected to increase in 2015–2030 (Table 2, Figure S35) due to generally increasing or stable catches in 1950–2014 and a mutually positive relationship with recreational fishing, suggesting that Swedish subsistence fishers may continue to derive food provisioning and food/nutrition security benefits from fishing. However, declines in Norway's subsistence catches in the late 1960s and 1980s, alongside an absence of mutually positive associations with other fishing types, resulted in a predicted catch decline in 2015–2030 (Table 2, Figure S31) with negative effects on subsistence fishers' food supply and food/nutrition security.

Unlike subsistence herring fishing, artisanal fishing occurred in all EEZs except the Netherlands in 1950–2014. Artisanal catches generally represented less than 10 % of metacouplings across EEZs, although mean annual percentages were relatively high in Denmark (North Sea, 35 %), Sweden (West Coast, 13 %), and Norway, Poland, and USA (East Coast, 11 %). Denmark has a long history and cultural tradition of herring fishing, including artisanal and industrial catches for direct human consumption and reduction to fishmeal and fish oil (Vestergaard, 1990; Gibson et al., 2014). In 1950, a full 50 % of herring caught in Denmark for human consumption was artisanally harvested, but catch declines in the 1970s (in the North Sea EEZ) and again in the 2000s (North and Baltic Seas) reduced this figure to 20 % by 2010 (Gibson et al., 2014). As such, models developed herein predicted artisanal catches to remain relatively small and consistent, by historical standards, in both Danish EEZs until 2030 (Table 2, Figure S22, S23). Empirically, artisanal catches accounted for < 30 % of herring tonnage in 2016 despite representing 79 % of fishing boats—compared to >70 % tonnage and 3% of boats for large commercial vessels (Eurofish, 2016)—providing context for negative metacoupling interactions between artisanal and Type 2 industrial fishing observed herein. Artisanal herring fisheries are considered economically vulnerable in Denmark, exhibiting a negative profit margin (-19 %) in recent years (Scientific, Technical and Economic Committee for Fisheries (STECF), 2017). However, artisanal fishers are important for the socio-cultural lifeblood of the Danish fishing industry (Hubbard and Carpenter, 2017); projected stability in catches—as in Poland, the USA (East Coast), and most other EEZs (Table 2)—suggests that artisanal livelihoods may be sustainable for some fishers in the future.

Artisanal catches in Norway decreased 96 % between 1950 and 2014, reflecting an historic stock collapse and recent ecological and socioeconomic stressors. In the 1960s and 1970s, Norwegian herring stocks collapsed due to reduced fish productivity and overfishing driven by a rapid increase in fishing vessel size, power, and technological capabilities (e.g., sonar; Lorentzen and Hannesson, 2004). The collapse

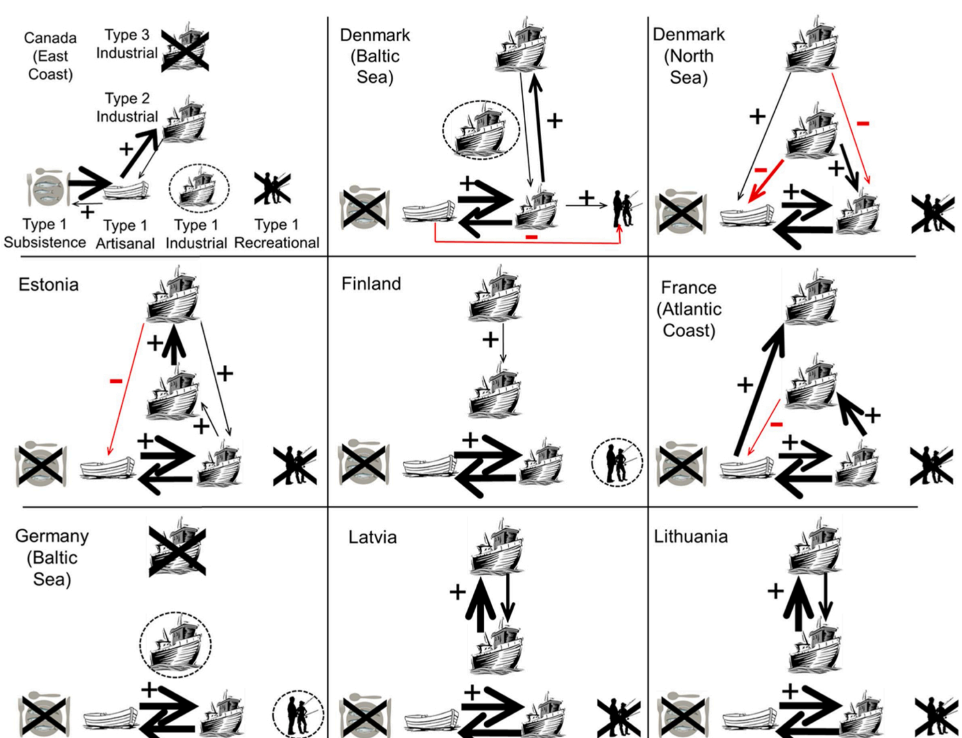

Fig. 7. Metacoupling relationships among fishing types in nine exclusive economic zones. Positive interactions are depicted in black and negative interactions in red, with arrow width proportional to effect size (Tables S1–17). Dotted ovals indicate that a particular fishing type was unaffected by, and did not affect, catches of other fishing types. "X" symbols indicate that a particular fishing type did not meet the requirement of continuous 65-year data and thus was not included in models. . *(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)*

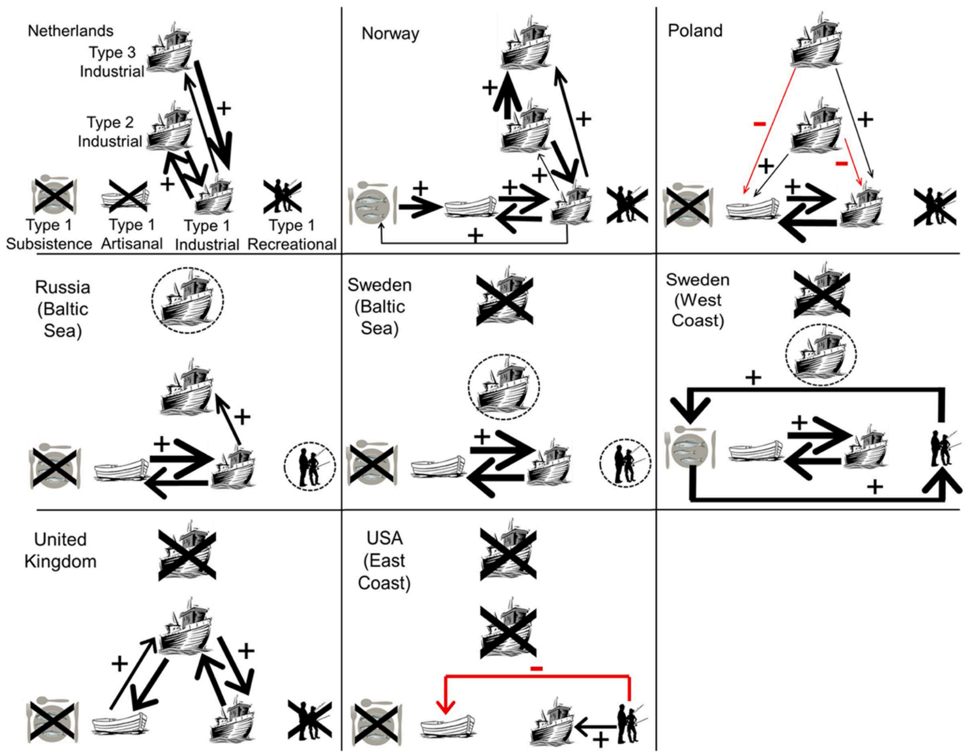

Fig. 8. Metacoupling relationships among fishing types in eight exclusive economic zones. Positive interactions are depicted in black and negative interactions in red, with arrow width proportional to effect size (Tables S1–17). Dotted ovals indicate that a particular fishing type was unaffected by, and did not affect, catches of other fishing types. "X" symbols indicate that a particular fishing type did not meet the requirement of continuous 65-year data and thus was not included in models. *(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)*

caused catch declines across fishing sectors and induced socioeconomic consequences: reduced artisanal and industrial revenue and employment, displacement of fishers within and beyond Norway, decreased real estate values, and increased herring demand in Canada (Stephenson et al., 1993; Sigurdsson, 2006). Employment relief funds were disbursed to fishers, but many were eventually forced to switch to fish-farming or petroleum occupations, which were growing in the 1970s and helped ameliorate the stock collapse's impact on fishers. In recent years, Norwegian artisanal herring catches have continued to decline due to competition with industrial purse seine fisheries and population growth of helmet jellyfish (*Periphylla periphylla*), which consume herring larvae and prey (Tiller et al., 2015). Mirroring recent catch trends, artisanal harvest in 2015–2030 was projected to decrease in Norway, much like Sweden (West Coast) and Germany (Baltic Sea; Table 2). Overall, historic and projected future declines in Norwegian artisanal herring catches illustrate the powerful impacts of external pressures (e.g., environmental, ecological, socioeconomic) on fisheries. In many cases, these effects cannot be predicted using ARIMA models, highlighting the importance of carefully evaluating catch projections to avoid over-interpreting model results.

A global herring fishery dominated by Type 2 and Type 1 industrial catches is relatively well-protected against exploitative and illegal Type 3 fishing. However, metacoupling relationships between industrial fishing types—and their interactions with artisanal, subsistence, and recreational sectors—need to be comprehensively accounted for in management and governance programs to build social-ecological resilience across scales. For instance, in 1950–2014, artisanal herring catches were positively associated with Type 1 industrial catches in 13 of 17 EEZs studied, suggesting that nations tend to fish industrially in ways that do not impair their other fisheries, although exceptions exist (Carlson et al., 2018a). However, artisanal catches declined with increasing Type 2 industrial catches in Denmark (North Sea) and France (Atlantic Coast) and Type 3 industrial catches in Estonia and Poland, mirroring negative impacts of large-scale industrial fishing on artisanal catches observed for other species (e.g., Atlantic bluefin tuna, cods; Belhabib et al., 2013; Divovich et al., 2015; Carlson et al., 2020b).

Such metacoupling interactions and potential competition for fish and market sales (Leroy et al., 2016; Prato et al., 2016; Babali et al., 2018) could have negative outcomes for artisanal fishers' income, employment, and food supply. Negative effects on artisanal fishers are especially pronounced when their opinions and concerns are not actively identified by fisheries management agencies, as evidenced in the decline of Norway's artisanal herring fisheries (Tiller et al., 2015). Given that small-scale fisheries provide income and support food/nutrition security and poverty alleviation for 37 million fishers globally—in addition to employment for 100 million people in fish processing, distribution, and marketing (Food and Agriculture Organization of the United Nations (FAO), 2020b)—metacouplings and their effects on artisanal and subsistence fisheries need to be incorporated into fisheries policies. Such metacoupling-informed fisheries management should include stakeholder engagement programs that promote bottom-up information flow from fishers to managers and policy makers, particularly the perspectives of artisanal fishers whose catches are negatively affected by Types 2 and 3 industrial fishing in some nations. Moreover, legislative instruments and bodies (e.g., European Union regulations on sustainable management of external fishing fleets, OSPAR Convention) need to consider metacouplings to achieve their mission to protect herring and additional species and habitats against overfishing, pollution, and other stressors both locally and regionally (de La Fayette, 1999; Guggisberg, 2019).

Metacoupling-informed herring management involves explicit consideration and integration of multiscalar interactions among fishing sectors, which can take many forms. For instance, the metacoupling framework can be used to incorporate multiscalar interactions among fishing sectors into herring harvest strategies and control rules (Cleary et al., 2010). By revealing the magnitude and direction (i.e., positive, negative) of sector interactions, metacoupling models can be used to set appropriate harvest levels for each sector that minimize negative effects on potentially vulnerable stakeholders (e.g., artisanal and subsistence fishers), markets, and value chains. The metacoupling framework can also be used to update herring data collection systems to ensure that catches are analyzed using approaches that incorporate local to global fishing-sector interactions, including metacoupling models developed herein. Multiscalar catch monitoring would enable managers to assess how metacouplings change over time and how they are affected by variable environmental, ecological, and socioeconomic conditions (e.g., emergent climate events, policy and management changes, economic crises), anomalies that can have unexpected effects on herring catches in ways that ARIMA-based predictions do not capture. More broadly, by providing a systematic, quantitative tool for understanding fishing-sector interactions across scales, the metacoupling framework can be used to inform management strategy evaluation (Feeney et al., 2019), decision support tools (Lam et al., 2019), and other methods for determining effective approaches for balancing ecological and socioeconomic objectives across multiple herring fisheries and stakeholder groups. Finally, as an instrument for illustrating human-nature couplings, the metacoupling framework is a useful communication tool for broadening and deepening dialogue between fisheries managers and their many stakeholders (Carlson et al., 2020b, c), a critical component of metacoupling-informed herring management. For example, fisheries managers can use bottom-up stakeholder engagement programs to understand how fish harvesters, processors, consumers, and other groups perceive fisheries metacouplings and resultant social-ecological challenges (e.g., fishing-sector competition, species invasion). In turn, managers can integrate stakeholder perceptions with results of metacoupling models and harvest strategies to develop robust approaches for communicating with diverse resource users.

Reconstructed catches have uncertainties and biases, as described above, that must be taken into consideration when using reconstructions in models and applying them to inform policies and management decisions. However, for Atlantic Herring in this study, there was a high degree of statistical similarity in temporal trends of reported and total reconstructed catches, and numerical differences between these catch types were small in most EEZs in 1950–2014. As such, any uncertainties introduced by reconstruction had little effect on catch trends, metacoupling interactions, or associated implications for fisheries policy and management. EEZs that deviated from this pattern—and for which model outputs should be interpreted more cautiously and evaluated in future research—included Germany (Baltic Sea), the Netherlands, and Denmark (Baltic Sea). Overall, the main difference between reported and total reconstructed catches was that the latter incorporated unreported fishing that is known to occur—an important contribution—explaining why y-intercepts were statistically different between reported and total-reconstructed catch models for 35 % of EEZ-time period combinations. Catch uncertainty is highly important to consider, particularly for reported catches, which have a degree of uncertainty that is rarely quantified and scarcely thought to require quantification despite the fact that uncertainty is a common criticism of reconstructed catches (Pauly and Zeller, 2017; Ye et al., 2017; Pauly et al., 2020). Ultimately, both reconstructed and reported catches are influenced by uncertainty, data limitations, and incomplete nation-specific reporting procedures, reaffirming the need for development and broader adoption of transparent, accurate catch reporting systems. It is our hope that the metacoupling framework, as explored in the present study, can contribute to improvement of catch reporting by facilitating quantification of local, regional, and global catches; linking these catches in predictive models; and generating assessment, policy, and outreach tools to manage fisheries as multiscalar human and natural systems.

Despite growth in research on fisheries as coupled human and natural systems (Crona et al., 2015, 2016; Österblom and Folke, 2015), few studies have considered, much less quantified, fisheries metacouplings spanning local, regional, and global scales. In addition, fisheries metacoupling research has been largely descriptive, focused less on modeling metacouplings than on identifying metacoupling flows, causes, and effects (Tapia-Lewin et al., 2017; Carlson et al., 2017, 2018a, 2020c). Both approaches are valuable, but advancing quantitative metacoupling research has the unique potential to reveal management-relevant applications that purely qualitative studies do not. For instance, metacoupling models developed herein represent new tools for understanding and predicting catches across scales, within and beyond herring fisheries. Likewise, metacoupling models were useful for quantifying relationships among fishing sectors and comparing them across 17 EEZs, which demonstrated rich metacoupling diversity in predominant fishing types, herring catches and intra/international flows, and fishing-sector interactions. Moreover, our analysis indicates the importance of carefully considering metacoupling interactions among industrial, artisanal, subsistence, and recreational fishing sectors, as underlying mechanisms vary due to the manifold ecological, socioeconomic, political, and cultural conditions that generate positive cross-sector catch relationships in some locations and negative relationships in others (Pauly and Zeller, 2016; Pauly et al., 2020). For instance, the take-home portion of artisanal catches—used by fishers to feed themselves and their families—is defined as subsistence-derived fish in many EEZs throughout the world (Coll et al., 2015; Khalfallah et al., 2015; Lindop et al., 2015; Pauly et al., 2020). This procedure contributes to positive artisanal-subsistence relationships, particularly when subsistence data are scarce and catch estimation is necessary. In contrast, negative artisanal-subsistence relationships can occur when economic developments within nations over time make it possible for subsistence fishers to transition to artisanal fishing (Krumme et al., 2013; Ramdeen et al., 2014; Pauly and Le Manach, 2015). Overall, relationships among fishing sectors are driven by complex, often EEZ-specific factors (e.g., environmental, ecological, socioeconomic) that must be considered when interpreting metacoupling models and sector interactions.

Importantly, generalities and specificities revealed in our analysis imply that metacoupling-informed herring management requires a mixture of top-down and bottom-up governance across nations with unique socioeconomic and political conditions. Such an approach will ensure that policies are well-coordinated within and across EEZs to maximize positive and minimize negative metacoupling interactions and thereby provide continued ecological, economic, nutritional, and sociocultural benefits for fisheries stakeholders. Overall, the metacoupling framework adds qualitative and quantitative rigor to analysis of fisheries as coupled human and natural systems. Whereas fisheries flows, causes, and effects have often been studied in isolation at specific spatial scales, the metacoupling framework integrates these elements locally, regionally, and globally, allowing researchers and managers to address the many multiscalar complexities that fisheries encompass. Future advances in metacoupling research, including network analyses, agent-based models, time-series assessments, and state space models (Carlson et al., 2018b; Schaffer-Smith et al., 2018; Dou et al., 2019), will help broaden and deepen analytical insights and facilitate actionable strategies for metacoupling-informed management of fisheries and other social-ecological phenomena within and beyond marine environments, including infectious disease, species invasion, and international trade.

Data availability statement

Datasets analyzed in this study can be found at the Sea Around Us (http://www.seaaroundus.org/) and are available on request to the corresponding author.

CRediT authorship contribution statement

Andrew K. Carlson: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Daniel I. Rubenstein:** Conceptualization, Methodology, Investigation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Simon A. Levin:** Conceptualization, Methodology, Investigation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2020.105855.

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