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Mahi-mahi metacouplings: quantifying human–nature interactions in dolphinfish (*Coryphaena hippurus*) fisheries

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Abstract

Non-Technical Summary (99 words)

Fisheries encompass humans and fish, but fisheries researchers rarely model human–nature interactions over space and time. I filled this information gap for dolphinfish (*Coryphaena hippurus*), a popular, widely distributed species that supports industrial, artisanal, recreational, and subsistence fisheries. Dolphinfish human–nature interactions showed a long-term up-and-down pattern in 1950–2019. Recent declines in catch mirror decreases in abundance and size that have been observed in parts of the species' range. This research provides a robust perspective on the recreational, economic, cultural, and nutritional significance of dolphinfish while creating an approach for evaluating human–nature interactions in fisheries worldwide.

Technical Summary (200 words)

Fisheries are coupled human and natural systems, but rarely does research examine metacouplings: human–nature interactions within and between adjacent and distant fisheries. I used the metacoupling framework to compare dolphinfish (*Coryphaena hippurus*) catches in exclusive economic zones (EEZs) in 1950–2019; model interactions and forecast catches of dolphinfish across sectors; and examine management implications of metacouplings. Dolphinfish catches increased in 1950–1998, decreased in 1998–2000, and increased in 2000–2012 before declining in 2012–2019, mirroring recent declines in abundance and size that have been observed in parts of the species' range. The most common fishing-sector interactions were bidirectional positive relationships between small-scale industrial and artisanal fishing, although large-scale industrial fishing negatively affected artisanal catches in some EEZs. Despite the economic and cultural importance of recreational dolphinfish fisheries, industrial fishing accounted for 49% of metacouplings in 1950–2019, followed by artisanal (29%) and recreational (20%) fishing.

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Subsistence catches—a small but nutritionally significant portion of dolphinfish fisheries—were predicted to decline in four EEZs in 2020–2035. This research provides a holistic perspective on the recreational, economic, cultural, and nutritional importance of dolphinfish while generating a template for social–ecological synthesis to inform fisheries management and conservation worldwide.

Social Media Summary (120 characters with spaces): Dolphinfish metacouplings (multiscalar human–nature interactions) are common, diverse, and management relevant worldwide

Introduction

As systems of fish, habitats, and people (Scalet *et al.*, 1996; Krueger and Decker, 1999), fisheries are coupled human and natural systems (Liu, 2007). Indeed, modern fisheries research stems from human and natural disciplines such as economics, human dimensions, ichthyology, ecology, and quantitative fisheries science (Magnuson, 1991; Hunt *et al.*, 2013). Although many aspects of fish, habitats, and people are investigated by fisheries scientists—with research published in journals spanning the spectrum from human to natural systems—the simultaneous local, regional, and global dimensions and dynamics of fisheries have scarcely been investigated. For example, the Peruvian anchoveta *Engraulis ringens* fishery has been locally to globally important to humans for decades, yet only recently has harvest of anchoveta been examined in terms of simultaneous local effects on artisanal fishers, regional effects on fisheries managers and policymakers, and global effects on consumers of fish oil, soybeans, and wheat (Carlson *et al.*, 2018).

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Effects of distant phenomena on local conditions can be studied using various frameworks. For instance, the concept of teleconnections encompasses climatic connections among distant regions of the world, and the telecoupling framework captures economic, political, social, cultural, and ecological interactions among coupled human and natural systems over distances (Liu *et al.*, 2013; Carlson *et al.*, 2018). The telecoupling framework allows users to systematically analyze the systems, flows, agents, causes, and effects associated with long-distance human–nature interactions, particularly in terrestrial ecosystems (Liu *et al.*, 2015; Hulina *et al.*, 2017). However, there are important knowledge gaps concerning the structure, function, and dynamics of local, regional, and global social–ecological linkages in terrestrial and aquatic environments. For example, inland fisheries support livelihoods, food supply, and nutrition for hundreds of millions of people worldwide, but they were not mentioned in the United Nations Sustainability Development Goals despite their sustainability significance (Cooke *et al.*, 2016). Even marine fisheries, which are comparatively well researched and receive primary attention in global sustainability dialogues concerning aquatic resources, have scarcely been investigated from a simultaneous local–regional–global perspective (Carlson *et al.*, 2020). These knowledge gaps are problematic because they mask the multiscalar importance of fisheries and induce management and governance decision-making with incomplete information about how fisheries influence, and are influenced by, a constellation of social–ecological linkages.

A paucity of research on multiscalar human–nature interactions, their causes, and their effects prompted development of an integrated local–regional–global approach, the metacoupling framework (Liu, 2017). Allowing researchers to study social–ecological linkages at multiple scales across the world, the metacoupling framework illuminates human–nature interactions that occur within a specific coupled human and natural system (intracouplings) and between adjacent

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systems (pericouplings) and distant systems (telecouplings). Collectively, these interactions are termed metacouplings (Figure 1). The metacoupling framework is useful and advances related frameworks (e.g., teleconnections, telecouplings) because it provides a flexible, adaptable approach that researchers and managers can use to quantify and compare social–ecological linkages not only over long distances (i.e., telecouplings), but also at local and regional levels. Such a framework may be helpful for understanding connections between humans and nature in fisheries and other systems involving biota, habitats, and humans that have traditionally been studied in a monothematic (i.e., human- or nature-focused) manner. Although it was originally used to investigate human–nature interactions in terrestrial systems (e.g., giant pandas *Ailuropoda melanoleuca* within and beyond Wolong Nature Reserve, China), the metacoupling framework has shown promise as an aquatic approach (Carlson *et al.*, 2020, 2021, 2022).

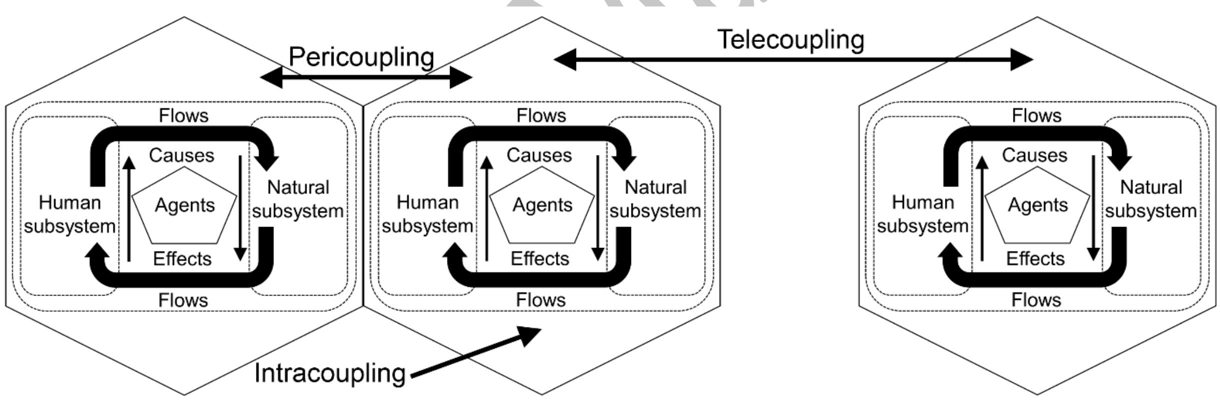

Figure 1. Illustration of metacoupling: human–nature interactions within a coupled human and natural system (intracoupling) and between adjacent (pericoupling) and distant (telecoupling) systems.

Common dolphinfish (*Coryphaena hippurus*) are migratory marine predators that have a broad, circumtropical and circumsubtropical distribution (Fishbase, 2024). As prized sport fish that support high-value industrial and artisanal fisheries (Merten *et al.*, 2022a), dolphinfish are recreationally, economically, culturally, and nutritionally important. Characterized by rapid maturation, short generation time, fast growth, and large size (Fishbase, 2024), dolphinfish life

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history is believed to impart relatively high biological resilience to exploitation. However, there has been a documented decrease in dolphinfish abundance in the western Atlantic Ocean (Lynch *et al.*, 2018; Damiano *et al.*, 2024), and there is a shortage of information on the species and its fisheries (e.g., ecology, stock assessment, governance; Moltó *et al.*, 2020; Merten *et al.*, 2022b). Given these basic knowledge gaps, it is not surprising that broader investigations of multiscalar social–ecological linkages are scarce for dolphinfish (Carlson *et al.*, 2020). For instance, there is little information on interactions, synergies, and tradeoffs between and among industrial, artisanal, subsistence, and recreational dolphinfish fisheries at local, regional, and global scales. Likewise, although dolphinfish are important for human nutrition and livelihoods, particularly in smaller, less developed countries (e.g., Cape Verde, Niue, Saint Vincent and the Grenadines; Pauly *et al.*, 2020), little is known about the nutritional and livelihood effects of local to global human–nature interactions involving dolphinfish fisheries. Such knowledge gaps hinder the development of multiscalar management and governance approaches that encompass the full recreational, cultural, and nutritional value of dolphinfish, not to mention their economic importance in trade markets (Fishbase, 2024; NOAA, 2024).

The purpose of this study is to use the metacoupling framework to explore multiscalar human–nature interactions in—and inform management and governance of—dolphinfish fisheries across the world. My first objective is to quantify and compare dolphinfish catches as metacouplings, intracouplings, pericouplings, and telecouplings over 70 years (1950–2019). My second objective is to use time-series analysis to model different fishing sectors (i.e., industrial, artisanal, subsistence, recreational), characterize their multiscalar interactions, and predict future catches. Finally, my third objective is to evaluate the dynamics and variability of dolphinfish

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metacouplings across different parts of the world to yield insights for multiscalar management and governance of dolphinfish fisheries in coupled human and natural systems.

Methods

Metacoupling framework

I defined metacouplings as multiscalar human–nature interactions that occur within a particular exclusive economic zone (EEZ), between adjacent EEZs, and between distant EEZs or in the high seas (Figure 1). In practice, metacouplings can be quantitatively represented as total dolphinfish catches, which can be subdivided into intracouplings (fish caught within a nation's own EEZ), pericouplings (fish caught in adjacent EEZs), and telecouplings (fish caught in distant EEZs or the high seas).

Data

The United Nations Food and Agriculture Organization (FAO) collects fish catch data that can provide insights into fisheries metacouplings worldwide. However, FAO data are known to underreport actual fish catches in particular places and times (Pauly and Zeller, 2016). Reconstructing catches using both FAO data and non-FAO information from sources such as peer-reviewed journal articles, research reports, and fisheries agency documents is one way to reduce underreporting bias. Hence, fish catch data (metric tons) were obtained from the *Sea Around Us* database (Pauly *et al.*, 2020), which integrates FAO data with reliable non-FAO information to reconstruct legal and illegal catches and quantify discards (bycatch) of numerous fish species in the world's 280 EEZs in 1950–2019. Despite the potential shortcomings of building catch models with reconstructed data (e.g., slight to substantial differences in model

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parameters relative to reported data), it is important for fisheries scientists, managers, and policymakers to account for fishing that is known to occur but is not captured by FAO data. Rather than treat these fishing activities as "zeroes," the *Sea Around Us* integrates FAO and non-FAO data to holistically reconstruct catches using 35 publications per reconstruction, on average (Pauly and Zeller, 2016). In reconstructing fish catches, experts consider data quality by rating the certainty of industrial, artisanal, subsistence, and recreational time series as very high (± 10% uncertainty), high (± 20%), low (± 30%), or very low (± 50%). Overall, reconstructions are useful because they allow researchers to account for known unreported and underreported catches and thereby better represent fisheries for science, management, and policy evaluations.

Dolphinfish data were obtained from the *Sea Around Us* and organized to identify fish catches, fishing nations, scales (intracoupling, pericoupling, telecoupling), and sectors (industrial, artisanal, subsistence, recreational) in 19 EEZs (Table 1, Figure 2) and the high seas in 1950–2019. These 19 EEZs were selected because they encompassed relatively large catches from three or more fishing sectors, a requirement for representing the various types of dolphinfish metacoupling interactions across the world. The high seas were included because they inherently involve distant-water fishing (i.e., telecouplings), an important component of the analysis.

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Table 1. Summary of dolphinfish fishing-type relationships, catches in 1950–2019, and catch predictions in 2020–2035. “Intra” and “Peri/tele” are total tonnage (metric tons) of dolphinfish intracouplings, and pericouplings plus telecouplings, in 1950–2019. Dominant (%) is the largest-tonnage fishing type (artisanal [A], intracoupled industrial [I1], pericoupled industrial [I2], recreational [R], subsistence [S], telecoupled industrial [I3]) and its percentage of metacouplings in 1950–2019. Fisher (% peri/tele) is the largest-tonnage pericoupling or telecoupling fishing nation and its percentage of metacouplings in 1950–2019. Catch projections are -forecasted changes in dolphinfish catches in 2020–2035 (increase ↑, decrease ↓, stable ↔) as predicted by autoregressive integrated moving average models. EEZ = exclusive economic zone, n/a = not applicable.

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EEZ	Relationships	Intra	Peri/tele	Dominant (%)	Fisher (% peri/tele)	Catch projections
Cape Verde	– (I1–A, A–I3)	2.7E+03	3.8E+01	A (92)	France (0.7)	↑(I3), ↔(A, I1)
China	– (I2–S), + (A–S, A–I2), ++ (I1–A, I1–S)	1.2E+06	7.1E+04	I1 (54)	Taiwan (6)	↓(I2, S), ↔(A, I1)
Hawaii (Main Islands)	– – (I3–I1), + (I3–R), ++ (I1–R)	3.2E+05	2.6E+02	R (94)	Japan (0.1)	↓(I1, R), ↔(I3)
Italy (Mainland)	– (I1–R, S–I1), + (S–R), ++ (I1–A, A–S)	5.2E+05	2.1E+03	A (52)	Malta (0.4)	↑(R), ↓(I1, S), ↔(A)
Libya	– – (I2–I1), ++ (I1–A)	7.4E+03	2.9E+03	A (58)	Malta (28)	↑(A, I1, I2)
Malta	– – (R–S), – (R–A), ++ (I1–A, I1–R, I1–S)	3.3E+04	4.7E+02	A (49)	Tunisia (1.4)	↑(I1, S), ↓(A, R)
Mexico (Pacific)	+ (I1–R), ++ (A–R)	4.4E+05	2.0E+04	A (80)	USA (4)	↑(A, I1, R), ↔(I3)
Niue	– – (A–S), + (A–I3)	2.5E+02	1.3E+02	S (62)	Taiwan (13)	↓(A, S), ↔(I3)
Northern Marianas	– (I2–A), + (R–A, A–S), ++ (I3–I2, I1–R)	1.1E+03	3.6E+03	I3 (74)	Taiwan (74)	↑(R), ↓(A), ↔(I1, I2, I3, S)
Pakistan	++ (I1–A)	9.5E+05	4.1E+03	I1 (81)	Taiwan (0.4)	↑(A, I1), ↔(I3, S)
Philippines	– (I2–A, R–I2), ++ (I1–A)	3.1E+04	1.9E+04	A (50)	Taiwan (33)	↑(A), ↓(I1, I2), ↔(I3, R)
Samoa	n/a	2.5E+03	3.7E+02	A (59)	USA (4)	↑(I3), ↓(A), ↔(I2, S)
Sicily	– (R–I2), + (A–I1, A–R), ++ (A–S)	1.6E+05	6.2E+03	A (57)	Malta (4)	↑(I2), ↓(A), ↔(I1, R, S)
St. Lucia	+ (I2–R), ++ (I3–I2, I1–A)	1.5E+04	2.6E+03	A (62)	Venezuela (5)	↑(A), ↔(I1, I2, I3, R)
St. Vincent & the Grenadines	– (I1–I2), + (A–I2), ++ (I1–A)	3.9E+03	1.5E+02	A (80)	Grenada (3)	↑(A, I1), ↓(I2, R), ↔(I3)
USA (East Coast)	+ (R–A, R–I2), ++ (I1–R)	5.3E+05	2.1E+03	R (94)	Malta (0.4)	↑(A, I1, R), ↔(I2, I3)
USA (Gulf of Mexico)	+ (R–I3), ++ (R–A)	1.2E+05	1.3E+02	R (90)	Martinique (0.1)	↔(A, I1, I3, R)
USA (West Coast)	– (I3–I1), ++ (R–A)	1.8E+04	5.9E+01	I1 (83)	Japan (0.3)	↑(I1), ↓(I3), ↔(A, R)
Wallis & Futuna	n/a	3.0E+01	3.9E+02	I3 (93)	USA (36)	↑(A, I3), ↓(S)

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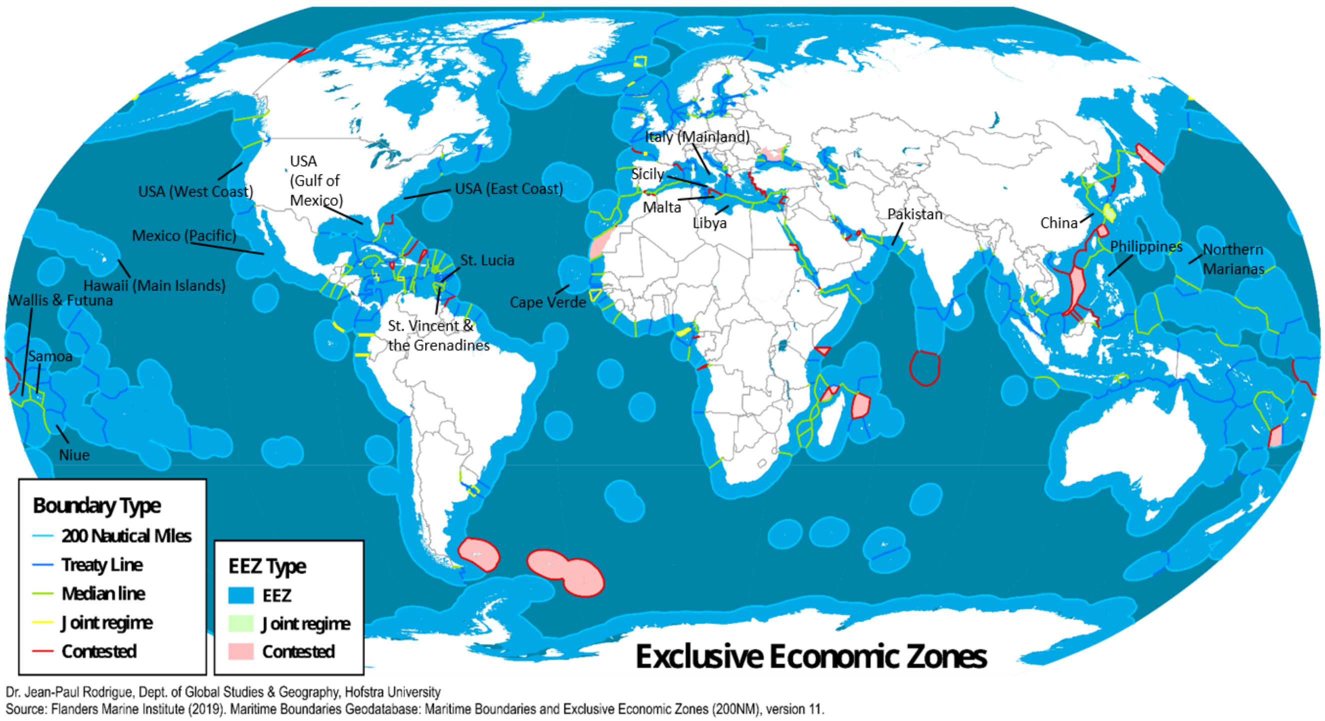

Figure 2. Map of the world's exclusive economic zones (EEZs). The 19 EEZs included in this dolphinfish study are labeled. The map was created by Dr. Jean-Paul Rodrigue and is freely available at https://transportgeography.org/wp-content/uploads/Map_Exclusive-Economic-Zones.pdf.

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Analysis

Dolphinfish data were first evaluated by plotting total and sector-specific catches in each EEZ in 1950–2019 and visualizing local, regional, and global flows of fish using Sankey diagrams. Then, dolphinfish catches and fishing-sector interactions were modeled using autoregressive integrated moving average (ARIMA) models. From fish populations to climate patterns and electricity demand to large-scale human health interventions (Lai and Dzombak, 2020; Schaffer *et al.*, 2021; Luzia *et al.*, 2023; Yesuf *et al.*, 2023), ARIMA models are used to investigate time-series trends and predict future outcomes. Moreover, ARIMA models are increasingly used in metacoupling research because they are helpful for analyzing time series and metacoupling interactions in various natural and human systems (e.g., crop trade, species invasion, animal and human migration, tourism; Herzberger *et al.*, 2019).

Time series have underlying properties such as lagged values and prediction errors that can be used to understand and project how dependent variables may behave in the future. Mathematically, ARIMA models employ this logic through a series of autoregressive parameters (AR(p)), moving averages (MA(q)), and integrated, stationarizing terms (I(d)) that generally improve model accuracy relative to autoregressive or moving-average approaches alone (Hamilton, 1994; Hyndman and Athanasopoulos, 2018). These models also accommodate external regressors of interest to metacoupling researchers (e.g., effects of telecoupled industrial fishing on intracoupled artisanal fishing). Hence, ARIMA models were informative for the purposes of this study.

ARIMA models were used to assess past, present, and future trends in all six dolphinfish fishing types represented in the *Sea Around Us*: intracoupled artisanal, intracoupled industrial,

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intracoupled subsistence, intracoupled recreational, pericoupled industrial, and telecoupled industrial. Models were developed to represent catches of each fishing type in each of 19 EEZs in 1950–2019. Model equations provided information for addressing study objectives such as quantifying interactions between fishing types and predicting future dolphinfish catches. First, ARIMA models required dolphinfish catches to be natural-log transformed and modeled as a function of lagged catch values (i.e., AR(p) terms):

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

In this equation, $Y_{tzf}(1)$ is catch at time t for EEZ z and fishing type f, δ is a constant, p is the AR polynomial order, ϕ_i terms are AR parameters, $y_{(t-i)zf}$ terms are lagged values of catch for EEZ z and fishing type f, and ε_{tzf} is an error term for EEZ z and fishing type f. Adding the I(d) term served to stationarize the time series:

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

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

where $y_{d,tzf}$ is catch at time t for EEZ z and fishing type f differenced d times, and other terms are defined above. The MA(q) represented errors between predicted and observed dolphinfish catches:

$$Y_{tzf}(3) = \delta + \sum_{i=1}^{q} \theta_i \varepsilon_{(t-i)zf} + \varepsilon_{tzf}$$

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(4),

where δ is a constant, q is the MA polynomial order, θ_i terms are MA parameters, $\varepsilon_{(t-i)zf}$ terms are prediction errors for EEZ z and fishing type f, and ε_{tzf} is an error term for EEZ z and fishing type f, and other terms are defined above. Combining information from equations (1) through (4), ARIMA models included AR(p), I(d), and MA(q) terms:

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

(5).

Final ARIMA models incorporated interactions among fishing types:

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

(6),

where **A** is a matrix of external regressors containing catch data for fishing types other than f within EEZ z, and other terms are defined above.

Various approaches were used to evaluate model quality. For example, augmented Dickey–Fuller tests were used to evaluate the ARIMA assumption of stationarity, and Box–Ljung tests were used to assess the assumption of lack of autocorrelation. Autocorrelation and partial autocorrelation functions were also useful in verifying the accuracy of parameter estimates using maximum-likelihood methods and information-theoretic model selection. Different combinations of ARIMA parameters and external regressors were compared using Akaike Information Criterion (AIC); models with the lowest AIC scores and random, independent residuals were considered the most parsimonious for evaluating interactions among fishing types and forecasting future catches. Standard ARIMA assessment methods (i.e., normalized root mean square error [NRMSE], mean absolute scaled error [MASE]) were used to

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validate models by comparing model-projected and observed dolphinfish catches. Values of these metrics between 0 and 1 indicate great to good performance, whereas values >1 indicate poor performance (Hyndman and Athanasopoulos, 2018). The most parsimonious models for all EEZ–fishing type combinations were used to assess interactions among fishing types and predict future dolphinfish catches in 2020–2035. Fishing-type interactions were quantified by evaluating external regressor (i.e., Equation 6) coefficients for significant ($P \leq 0.05$) regressors and visualized using arrow diagrams. Arrows indicate a significant effect of one fishing type on another, with arrow width and color representing the magnitude and direction of the effect, respectively. Analyses were performed in RStudio version 3.6.1 (R Development Core Team, 2019).

Results

Dolphinfish catches: a metacoupling perspective

Dolphinfish metacouplings totaled 4.86 x 10^6 MT in 1950–2019, including 4.45 x 10^6 MT in EEZs and 4.05 x 10^5 MT in the high seas. Metacouplings increased from 1950 to 1998, decreased from 1998 to 2000, and again increased in 2000–2012 before declining in more recent years (2012–2019; Figure 3a). Intracouplings in 1950–2019 (4.32 x 10^6 MT) exhibited the same general trend as metacouplings, whereas pericouplings (1.22 x 10^5 MT) were relatively small and stable in 1950–2019. Telecouplings (4.18 x 10^5 MT) peaked in 1987 before declining in more recent years (Figure 3a). Intracouplings represented the largest percentage of metacouplings overall (mean: 89.6% in 1950–2019), although their contribution reached a low point in 1987, when telecouplings accounted for 35.5% of metacouplings (Figure 3b). Pericouplings averaged 2.5% of metacouplings in 1950–2019.

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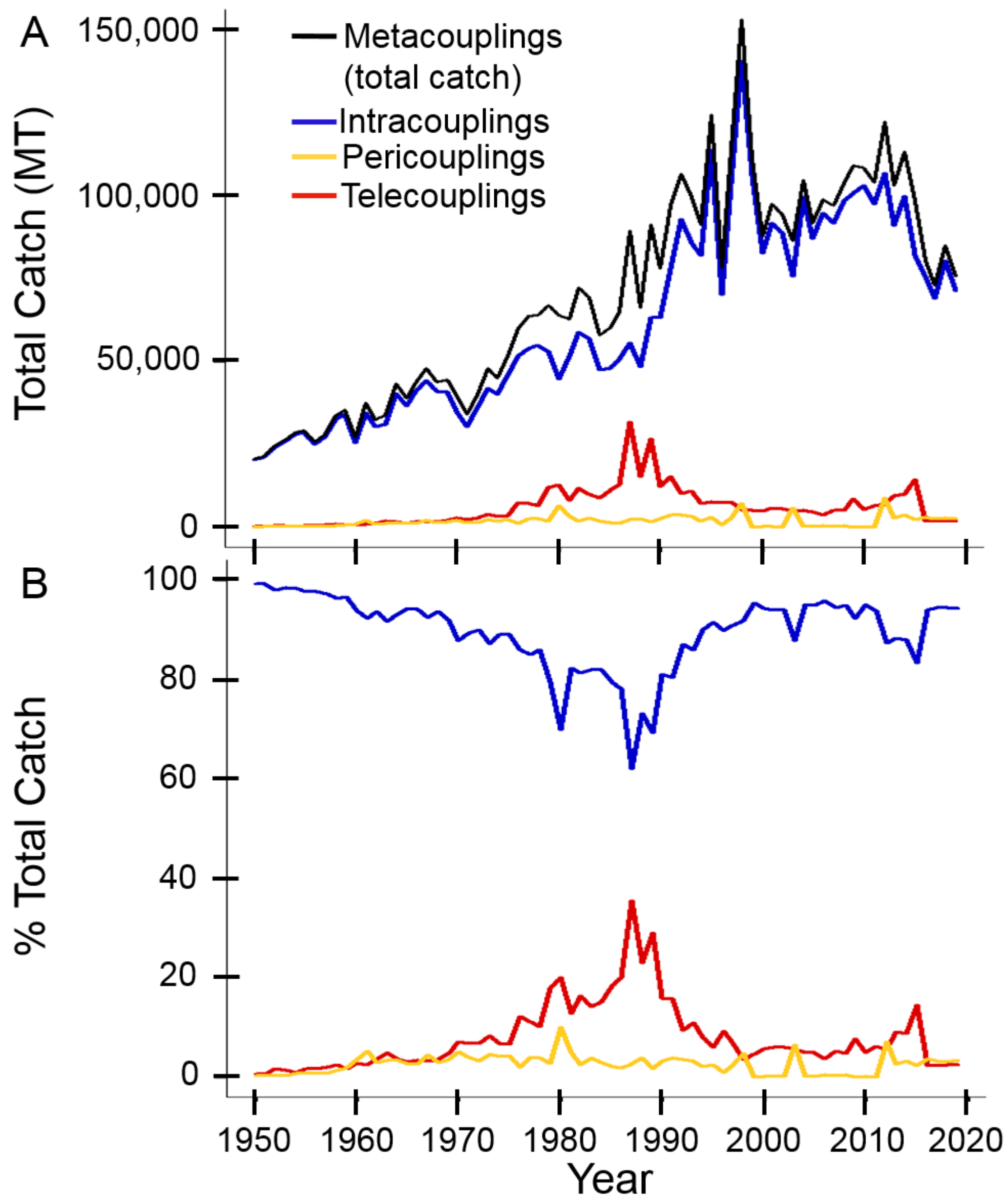

Figure 3. Temporal trends in dolphinfish metacouplings (total catch), intracouplings (catch within a nation's own exclusive economic zone [EEZ]), pericouplings (catch in adjacent EEZs), and telecouplings (catch in distant, non-adjacent EEZs). Panel A depicts catches in metric tons, whereas panel B depicts intracouplings, pericouplings, and telecouplings as a percentage of metacouplings.

The majority of EEZs (73.7%, N = 14) exhibited an increase in dolphinfish metacouplings in 1950–2019, although 15.8% of EEZs (N = 3) showed a decrease, and 10.5% (N = 2) had stable dolphinfish catches (Figure 4). Intracoupled artisanal fishing was the largest-tonnage fishing type in 52.6% of EEZs (N = 10; Table 1). Other fishing types predominated in

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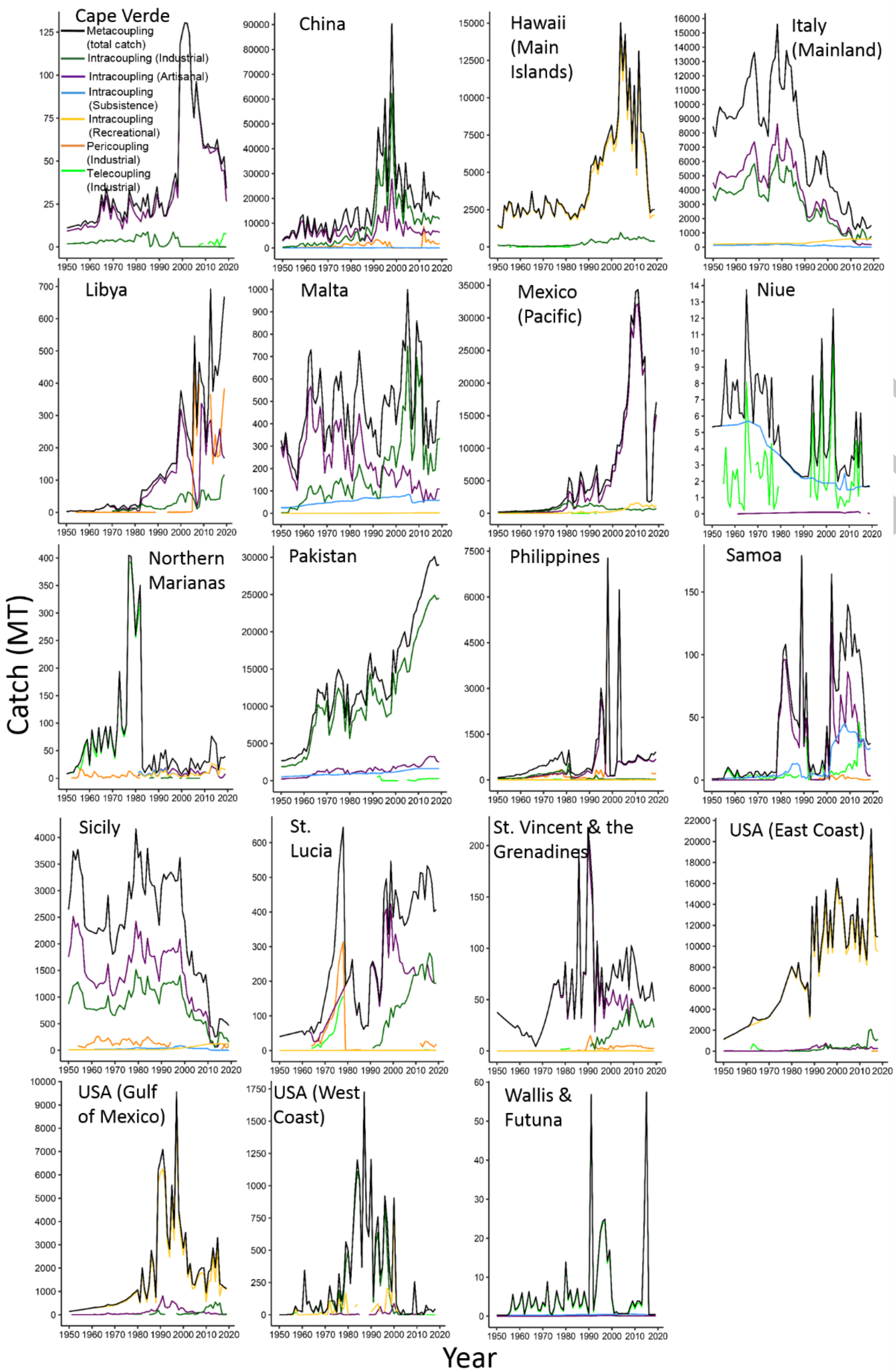

Figure 4. Dolphinfish catch (metric tons, MT) in 1950–2019 within 19 exclusive economic zones (EEZs). Catch types include metacouplings (total catch), intracouplings (catch within a nation's own EEZ), pericouplings (catch in adjacent EEZs), and telecouplings (catch in distant, non-adjacent EEZs) across artisanal, industrial, recreational, and subsistence sectors.

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fewer EEZs: intracoupled industrial (15.8% of EEZs, N = 3), recreational (15.8%, N = 3), telecoupled industrial (10.5%, N = 2), and subsistence (5.3%, N = 1). Overall, industrial fishing accounted for 49.0% of metacouplings (2.38 x 10^6 MT) across EEZs in 1950–2019, followed by artisanal (29.2%, 1.42 x 10^6 MT), recreational (19.8%, 9.64 x 10^5 MT), and subsistence (1.9%, 9.28 x 10^4 MT) fishing.

Dolphinfish flows: local, adjacent, and distant

Dolphinfish intracouplings were largest by tonnage in China (94.3% of metacouplings, 1.16 x 10^6 MT), Pakistan (99.6%, 9.49 x 10^5 MT), and the USA (East Coast, 99.6%, 5.26 x 10^5 MT; Table 1, Figure 4, 5). In contrast, the smallest intracouplings occurred in island EEZs: Wallis & Futuna (7.1% of metacouplings, 3.02 x 10^1 MT), Niue (65.0%, 2.50 x 10^2 MT), and Northern Marianas (23.2%, 1.10 x 10^3 MT).

Dolphinfish pericouplings were largest in China (5.7% of metacouplings, 7.00 x 10^4 MT), Mexico (4.3%, 1.98 x 10^4 MT), and the Philippines (37.1%, 1.84 x 10^4 MT), and second largest by percentage in Libya (28.0%, 2.88 x 10^3 MT; Figure 4, 5). By comparison, pericouplings were smallest in an island EEZ (Cape Verde, 0.002% of metacouplings, 7.15 x 10^{-2} MT), USA Gulf of Mexico (0.0001%, 1.58 x 10^{-1} MT), and USA West Coast (0.001%, 2.60 x 10^{-1} MT), and absent in four EEZs (Hawaii Main Islands, Malta, Pakistan, Wallis & Futuna).

Dolphinfish telecouplings were largest in Pakistan (0.4% of metacouplings, 4.09 x 10^3 MT), Northern Marianas (73.8%, 3.50 x 10^3 MT), and USA East Coast (0.39%, 2.05 x 10^3 MT), and largest by percentage in an island EEZ, Wallis & Futuna (92.9%, 3.95 x 10^2 MT; Figure 4, 5). In contrast, telecouplings were smallest in Sicily (<0.0001% of metacouplings, 5.62 x 10^{-3}

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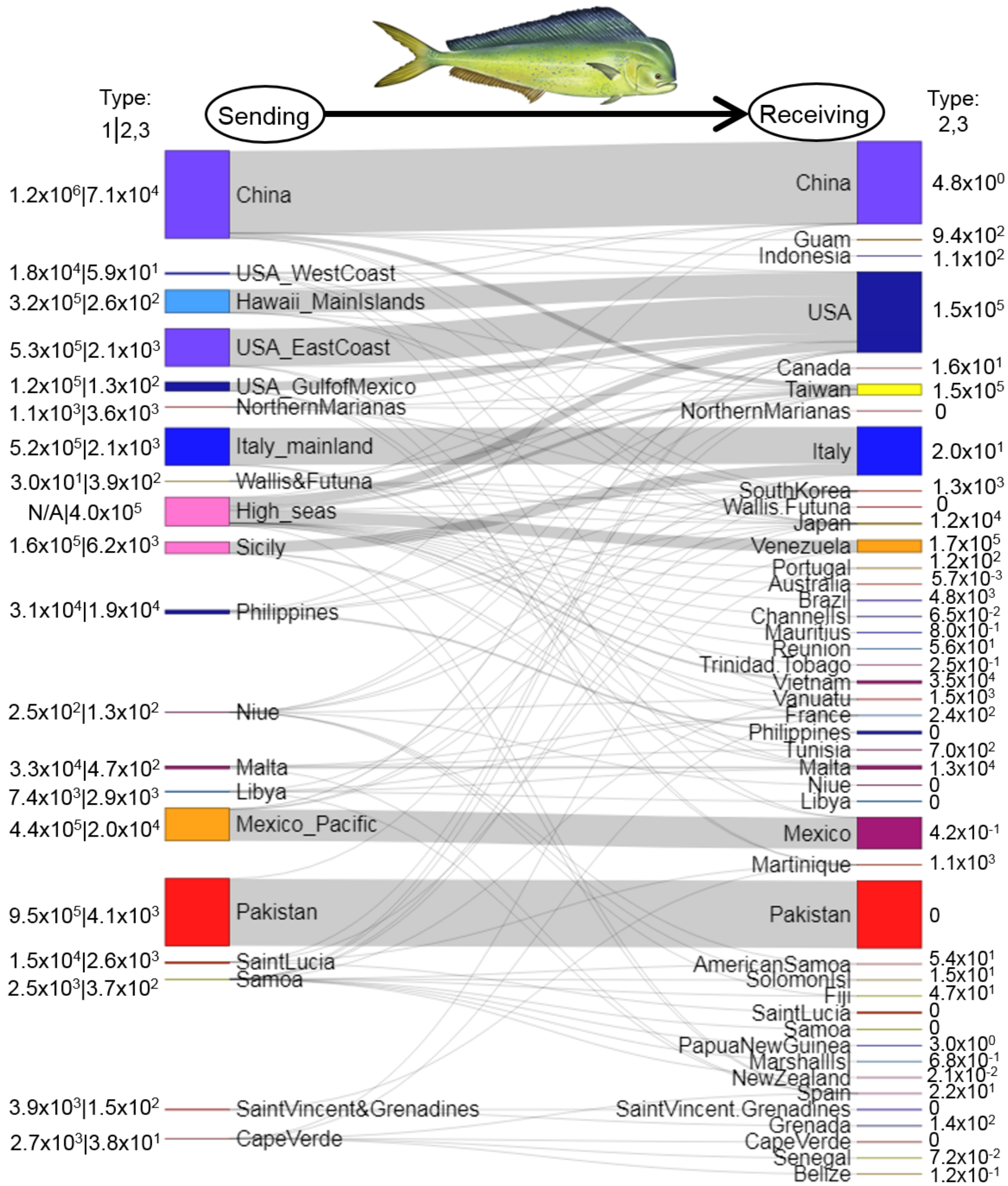

Figure 5. Sankey diagram depicting flows of dolphinfish (metric tons) from sending to receiving systems across the world in 1950–2019. Numbers to the left of the divider in the left margin are intracouplings (catch within a nation's own exclusive economic zone [EEZ]); numbers to the right of the divider represent pericouplings and telecouplings (catch by nations that are adjacent to or distant from the labeled EEZ). Numbers in the right margin are pericouplings and telecouplings by the labeled nation in other EEZs.

MT), Libya (0.006%, 6.51 x 10^{-1} MT), and St. Vincent & the Grenadines (0.3%, 1.03 x 10^{1} MT), and absent in two EEZs (Italy [mainland], Malta).

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Across EEZs in 1950–2019, the largest-tonnage fishing nations were China (1.16×10^6 MT) and the USA (1.01×10^6 MT; Figure 4, 5). The smallest-tonnage nations were Portugal (6.97×10^{-3} MT) and New Zealand (2.08×10^{-2} MT). By comparison, in the high seas, the largest-tonnage fishing nations were Venezuela (1.71×10^5 MT) and the USA (1.30×10^5 MT); the smallest-tonnage nations were Australia (5.72×10^{-3} MT) and Canada (9.99×10^{-3} MT).

Metacoupling interactions and projections

The most common fishing-sector interactions were bidirectional positive relationships between artisanal and intracoupled industrial fishing (42.1% of EEZs, N = 8), and between recreational and intracoupled industrial fishing (21.1%, N = 4; Table 1, Supplementary Tables S1–20, Figure 6). The most common unidirectional relationships—each occurring in 10.5% of EEZs (N = 2)—were negative effects of pericoupled industrial on artisanal fishing, negative effects of recreational on pericoupled industrial fishing, positive effects of artisanal on pericoupled industrial fishing, positive effects of artisanal on subsistence fishing, and positive effects of recreational on artisanal fishing.

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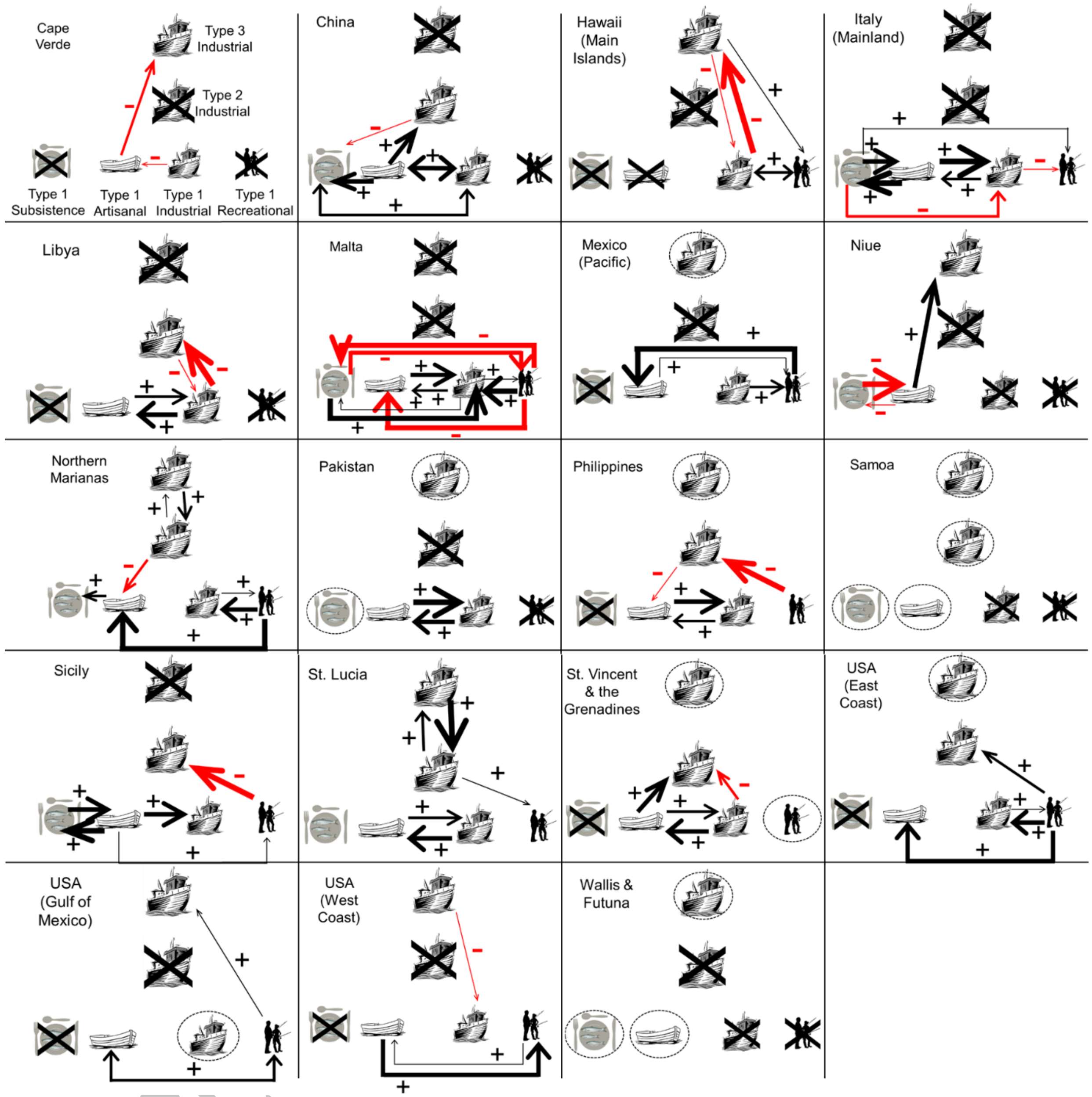

Figure 6. Metacoupling interactions among fishing types in 19 exclusive economic zones in 1950–2019. Arrow width is proportional to interaction strength. Arrow color corresponds with interaction direction: black (positive), red (negative). "X" symbols represent fishing types that were absent or did not meet criteria for inclusion in modeling, whereas dotted circles depict fishing types that were unaffected by, and did not affect, other fishing types.

The 19 EEZs encompassed 78 unique EEZ–fishing type combinations, of which 32.1% (N = 25) were projected to increase, 24.4% (N = 19) were predicted to decrease, and 43.6% (N = 34) were projected to remain stable in 2020–2035 (Table 1, Supplementary Figures S1–19). Fishing types with the largest percentage of EEZs having projected increases in 2020–2035 were

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artisanal (44.4%, N = 8) and intracoupled industrial (43.8%, N = 7). By comparison, predicted decreases were most common for subsistence (44.4%, N = 4) and pericoupled industrial (33.3%, N = 3) fishing (Table 1, Supplementary Figures S1–19). Stable catches were most commonly predicted for telecoupled industrial (71.4%, N = 10) and pericoupled industrial (44.4%, N = 4) fishing in 2020–2035.

Discussion

The long-term up-and-down pattern of dolphinfish metacouplings indicates changes in fish abundance or availability in 1950–2019. Indeed, the decline in dolphinfish metacouplings, intracouplings, and telecouplings in recent years is particularly noteworthy for a species with "common" in its name. Although this may be an appropriate adjective in some circumstances, recent declines in dolphinfish catches are consistent with a documented decrease in dolphinfish abundance and individual size in the western Atlantic Ocean (Damiano *et al.*, 2024; Rudershausen *et al.*, 2024). Decreases in global dolphinfish catches may reflect overexploitation by recreational and commercial fishing or changes in ocean environmental conditions (e.g., warming, upwelling) that affect fish productivity (Damiano *et al.*, 2024; Rudershausen *et al.*, 2024). They may also reflect management failures or lack of sufficient management attention (e.g., no stock assessments; Lynch *et al.*, 2018; Rudershausen *et al.*, 2024). Despite these declines, dolphinfish have been the subject of comparatively limited research and fisheries governance measures in the western Atlantic and other regions (Moltó *et al.*, 2020; Merten *et al.*, 2022b). Add to this information gap the paucity of knowledge on human–nature interactions in dolphinfish fisheries, and it becomes clear that more ecological and social–ecological research is important for informing management and conservation of this species.

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This study provided novel information that expands the knowledge base on dolphinfish fisheries, building on previous research (Carlson et al. 2020, 2021) but containing distinct objectives, a new species, new EEZs and associated fish-catch datasets, new models, and novel implications for fisheries management and governance. For instance, I found that dolphinfish catches are often intracoupled, occurring by nations within their own EEZs, unlike Atlantic herring *Clupea harengus*, for which pericouplings prevail (Carlson *et al.*, 2021). Despite their prevalence, dolphinfish intracouplings are not uniform, spanning diverse industrial, artisanal, subsistence, and recreational sectors. Likewise, dolphinfish telecouplings and pericouplings accounted for a not-insignificant 10.4% of catches 1950–2019, on average. In other words, a moderate but important portion of dolphinfish were caught by nations fishing beyond their own EEZs, as exemplified by the 4.05 x 10^5 MT of dolphinfish caught in the high seas where national ownership is nonexistent and telecouplings are inherent. The peak in dolphinfish telecouplings in 1987, followed by a decline in recent years, may reflect a shift in fishing effort toward other species, changes in fishing regulations and governance approaches, shortcomings of historical or current management approaches, increasing popularity of intracoupled recreational fisheries in nations like the United States, or alterations in ocean environmental conditions. For example, the decline in western-Atlantic dolphinfish abundance and size is believed to have resulted from high fishing pressure from industrial, recreational, and artisanal sectors and environmental changes (e.g., warming sea surface temperatures; Lynch *et al.*, 2018; Damiano *et al.*, 2024; Rudershausen *et al.*, 2024). The decline has not gone unnoticed, with hundreds of anglers from Florida, USA, expressing concern about decreased dolphinfish abundance as a result of what they believe are "domestic and international issues" (Merten *et al.*, 2022a)—in other words, intracouplings, pericouplings, and telecouplings have contributed to angler dissatisfaction.

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Several U.S. state fisheries management agencies have met with dolphinfish stakeholders and implemented stricter harvest regulations (Merten *et al.*, 2022a) to protect dolphinfish stocks. Clearly, there is a social layer in the landscape of dolphinfish management, highlighting the importance of novel research on human–nature interactions, particularly metacouplings, in dolphinfish fisheries.

This innovative research helps address the shortage of multiscalar social–ecological information on dolphinfish fisheries. For example, despite the widely recognized importance of dolphinfish as a sport fish, I found that intracoupled recreational fishing was the largest-tonnage fishing type in only 15.8% of EEZs (N = 3). In contrast, intracoupled artisanal fishing predominated in more than half of EEZs (N = 10). This novel finding reinforces the importance of viewing dolphinfish from a global perspective as a species that supports high-value commercial and artisanal fisheries (Damiano *et al.*, 2024) and enriches human livelihoods and cultures throughout its range (Carlson *et al.*, 2020), in addition to its recreational value. Although subsistence fishing for dolphinfish predominated in only one EEZ studied (Niue), subsistence fishing was documented in 47.4% of EEZs and is often numerically smaller than other fishing types despite rising to nutritionally and gastronomically important levels (Carlson *et al.*, 2020; Moltó *et al.*, 2020). Certainly, the recreational, economic, cultural, and nutritional importance of dolphinfish were well established before this study (Moltó *et al.*, 2020; Merten *et al.*, 2022a,b), but this research makes an original contribution: comparing the relative importance of these dolphinfish values in particular places and times across the world from the perspective of multiscalar social–ecological linkages. Indeed, the metacoupling framework is an innovative tool for understanding how dolphinfish and humans are connected over space and time.

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This study also facilitated the development of new, original knowledge regarding the types of nations where intracoupled, pericoupled, and telecoupled fishing predominated in 1950–2019. Dolphinfish intracouplings were largest by tonnage in large, populous nations (e.g., China, Pakistan, United States) and smallest by tonnage in island EEZs with small human populations and comparatively limited fishing capacity (e.g., Wallis & Futuna, Niue, and Northern Marianas). Interestingly, pericouplings predominated in geographically, demographically diverse nations (e.g., China, Mexico, Philippines), whereas pericouplings were smallest in lightly populated island nations (e.g., Cape Verde) and large, populous mainland countries such as the United States. Similarly, telecouplings predominated in countries large and small (e.g., Pakistan, Northern Marianas, United States), reached their largest percentage of metacouplings in an island EEZ (Wallis & Futuna), and were smallest in EEZs as diverse as Sicily, Libya, and St. Vincent & the Grenadines. Hence, compared to intracouplings, dolphinfish pericouplings and telecouplings are relatively unpredictable by land area or human population size, depending more on the proximity of, and pathways connecting, EEZs to particular fishing nations. This novel finding is consistent with previous research demonstrating the complexity of metacouplings within and among fisheries (Carlson *et al.*, 2020, 2021).

Another innovative contribution of this research—metacoupling interactions between different fishing types—has important ramifications for dolphinfish management and governance. The most common metacoupling interactions were bidirectional positive relationships between artisanal and intracoupled industrial fishing. In the eight EEZs that exhibited this interaction, intracoupled industrial fishing did not impair catches of intranational artisanal fishers, likely reflecting fisheries management and governance approaches that encourage synergy or prevent discord between these sectors. At the same time, policy and

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environmental conditions that promote artisanal catches may also support industrial catches in these EEZs. For unidirectional fishing-type interactions, the most common relationships included negative effects of pericoupled industrial on artisanal fishing, an interplay that has been observed in other fisheries (e.g., Atlantic bluefin tuna *Thunnus thynnus*; Carlson *et al.*, 2020) and often arises in cases where neighboring fishing nations have fishing policies that are not aligned with those of "donor" EEZs. Negative relationships between industrial pericouplings and artisanal intracouplings could induce consequences for artisanal fishers' livelihoods, well-being, and, in cases where they consume their catch, food supply or nutrition. It is important to use this novel information to create fisheries governance strategies that, through synthesis of social–ecological information across scales, are effectively "metacoupled." Incorporating metacouplings into management is important not only for the tradeoffs associated with negative fishing-type interactions. For instance, positive effects of artisanal on subsistence fishing, and recreational on artisanal fishing, observed herein are important for managers and policymakers to consider because they signal areas of synergy that can help streamline achievement of multiple management goals simultaneously, a metacoupling insight that represents an original contribution to the dolphinfish literature.

The metacoupling framework emphasizes that each EEZ is a unique entity. An EEZ's environmental and social conditions, fisheries management–agency structure and function, and extant policy and governance approaches affect the relative influence of local versus distant fisheries. For instance, management strategies in the USA (Gulf of Mexico) are scaled to local and distant fisheries, promoting a harmonious, bidirectional positive interaction between local artisanal and recreational fishing as well as recreational and distant-water industrial fishing (Figure 6). In contrast, the management environment in Malta is more locally focused and

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promotes negative interactions between local artisanal, recreational, and subsistence fishing and few interactions with fisheries in other countries (Figure 6). These and all EEZs, with their different environmental and social conditions, and distinct management and policy environments, can be better understood through continued qualitative and quantitative application of the metacoupling framework.

Much like fishing-type interactions, novel metacoupling predictions derived from ARIMA models are relevant for dolphinfish management and governance. For example, artisanal and intracoupled industrial catches were commonly projected to increase in 2020–2035, which is consistent with their mutual positive interaction in many EEZs and indicates that artisanal and small-scale industrial fishing may be viable areas for growth in dolphinfish fisheries. However, subsistence and pericoupled industrial catches were projected to decline in 2020–2035. This innovative prediction is unfavorable for fishers who rely on dolphinfish for food supply or nutrition, although subsistence fisheries are inherently small-scale and may be sustainable with concerted management and governance activities, along with continued positive relationships between artisanal and subsistence fishing. Moreover, if projected decreases in pericoupled industrial catches are manifested, these declines could amplify artisanal catches given that artisanal intracouplings were negatively associated with industrial pericouplings in some EEZs.

Despite possessing life history traits that are believed to make them resilient to exploitation (e.g., rapid maturation, short generation time, fast growth, large size), dolphinfish have declined in abundance and size in some areas (Damiano *et al.*, 2024; Rudershausen *et al.*, 2024) and exhibited decreases in metacouplings, intracouplings, and telecouplings herein. Indeed, resilience may require precautionary management approaches (Merten *et al.*, 2022a) and other strategies for sustainable management not commonly associated with such a prolific

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species. For example, the innovative concept of "metacoupling-informed management" refers to fisheries management that explicitly considers and incorporates multiscalar human–nature interactions, including metacoupling synergies and tradeoffs that may affect sustainability, into management processes and decisions (Carlson *et al.*, 2021). This strategy for sustainable management can be operationalized in numerous ways, including directly using the metacoupling framework when setting safe harvest levels; developing gear, season, and harvest regulations; evaluating synergies and tradeoffs between different fisheries; structuring value chains; designing data collection systems; and communicating science and management information to diverse audiences. The common theme connecting these diverse activities is that the metacoupling framework is a novel, central element of planning, implementation, and monitoring, and an instrument for balancing positive and negative interactions among different types of fisheries. Before it is feasible to apply metacoupling-informed management at a large scale, it is important to address innovative questions that were beyond the scope of this study. There is a need to fill ecological and social–ecological data gaps on dolphinfish. For instance, the human and natural components of dolphinfish fisheries are embedded in social and ecological networks that can be better described using formal network analyses and agent-based models (Schaffer-Smith *et al.*, 2018; Dou *et al.*, 2019). Fisheries researchers would also benefit from conducting additional time-series analyses and implementing other advanced modeling techniques (e.g., state space models) to examine the plethora of fisheries data—on dolphinfish and many other species—that are publicly and privately available. Filling data gaps regarding dolphinfish ecology and population declines would increase understanding of the drivers of dolphinfish fisheries (Damiano *et al.*, 2024) and their structure as coupled human and natural systems. Likewise, it is important to apply the metacoupling framework to inland and freshwater

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fisheries, which have received less attention in global sustainability dialogues and social–ecological research but benefit many millions of people globally (Cooke *et al.*, 2016). The metacoupling framework also has promise as a tool for novel social–ecological integration in a variety of other disciplines—including wildlife management, agriculture, land change science, and epidemiology—and for a number of other species, both aquatic and terrestrial. Applying the metacoupling framework in these new contexts will first involve qualitative investigation of CHANS components (i.e., systems, flows, agents, causes, and effects) followed by use of quantitative tools (e.g., time-series models, agent-based models, network analyses), as in the present study.

Conclusion

Metacouplings are abundant and diverse in dolphinfish fisheries across the world. Despite the well-recognized importance of dolphinfish for recreational, industrial, and artisanal fisheries, the species has key information gaps (e.g., ecology, stock assessment, governance; Moltó *et al.*, 2020; Merten *et al.*, 2022b) and a shortage of social–ecological research, hindering the development of robust management approaches that fully account for human–nature linkages across scales. I helped fill these knowledge gaps by applying the metacoupling framework to develop a modeling approach for understanding multiscalar human–nature interactions in dolphinfish fisheries. This novel research illustrated the utility of the metacoupling framework for systematically understanding reciprocal interactions between humans and fish. The innovative methods are broadly applicable to other aquatic and terrestrial systems at this important moment in the science and management of coupled human and natural systems.

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Author Contributions

AKC conceived and designed the study, collected the data, performed statistical analyses, and wrote the manuscript.

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Figure captions

Figure 1. Illustration of metacoupling: human–nature interactions within a coupled human and natural system (intracoupling) and between adjacent (pericoupling) and distant (telecoupling) systems.

Figure 2. Map of the world's exclusive economic zones (EEZs). The 19 EEZs included in this dolphinfish study are labeled. The map was created by Dr. Jean-Paul Rodrigue and is freely available at https://transportgeography.org/wp-content/uploads/Map_Exclusive-Economic-Zones.pdf.

Figure 3. Temporal trends in dolphinfish metacouplings (total catch), intracouplings (catch within a nation's own exclusive economic zone [EEZ]), pericouplings (catch in adjacent EEZs), and telecouplings (catch in distant, non-adjacent EEZs). Panel A depicts catches in metric tons, whereas panel B depicts intracouplings, pericouplings, and telecouplings as a percentage of metacouplings.

Figure 4. Dolphinfish catch (metric tons, MT) in 1950–2019 within 19 exclusive economic zones (EEZs). Catch types include metacouplings (total catch), intracouplings (catch within a nation's own EEZ), pericouplings (catch in adjacent EEZs), and telecouplings (catch in distant, non-adjacent EEZs) across artisanal, industrial, recreational, and subsistence sectors.

Figure 5. Sankey diagram depicting flows of dolphinfish (metric tons) from sending to receiving systems across the world in 1950–2019. Numbers to the left of the divider in the left margin are intracouplings (catch within a nation's own exclusive economic zone [EEZ]); numbers to the right of the divider represent pericouplings and telecouplings (catch by nations that are adjacent to or distant from the labeled EEZ). Numbers in the right margin are pericouplings and telecouplings by the labeled nation in other EEZs.

Figure 6. Metacoupling interactions among fishing types in 19 exclusive economic zones in 1950–2019. Arrow width is proportional to interaction strength. Arrow color corresponds with interaction direction: black (positive), red (negative). "X" symbols represent fishing types that were absent or did not meet criteria for inclusion in modeling, whereas dotted circles depict fishing types that were unaffected by, and did not affect, other fishing types.

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