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Combining interdisciplinary approaches to evaluate policies on bottom trawl fisheries in China over seven decades:

Quantify policy impacts on fisheries

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Running title: Quantify policy impacts on fisheries

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Abstract

Quantitatively evaluating policy effectiveness is vital to evidence-based decision making. Such analysis is, however, rare in natural resource management. We here initiate a novel framework that integrates econometric models, ecological approaches, and novel performance indices. Our focus lies in regulations of bottom trawl fisheries (BTF), a destructive form of exploitation that is executed globally, led by China. We examine effects of China's national policies on its BTF (1949 – 2018). Our results indicated that only 22% of the policies had the intended conservation-oriented effects in curtailing BTF, 29% had non-significant effects, and others mainly produced growth or a mix of effects. Overarching policy, international law & agreement, output control, and law enforcement were significant in curtailing China's BTF. In contrast, ban & protection policies and input controls – the dominant types of policies in China – failed to curtail BTF. Central government policies were disproportionately more powerful than those from specific ministries. China's BTF policies can be classified into three groups: (i) those with comprehensive effects; (ii) those mainly affecting fishing capacity & yield of distant-water fisheries; and (iii) those that slightly affected total landings. To rein in bottom trawling, China needs to consider a more conservation-oriented and adaptive policy framework, one that is directly endorsed by the central government and embraces rights-based output control and comprehensive law enforcement. Our study pioneers a new and easier path for quantitatively evaluating fishery policies, one that helps promote real change while limiting futile repetition of ineffectual policies.

Keywords: classification, decision making, dominance analysis, dynamic linear model, ordination, resource management

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Introduction

One of the greatest global challenges in natural resource management in the marine realm is constraining bottom trawl fisheries (BTF) through effective policy interventions (Gillett, 2008; Pauly, 2018; Pauly et al., 2003). As a dominant form of industrial fisheries, BTF have long raised concerns because of their worldwide ecological and socioeconomic impacts (Dureuil et al., 2018; Pauly et al., 2003). These impacts include (but are not limited to) (i) removing all marine life indiscriminately at levels that deplete populations, (ii) damaging benthic communities (e.g., coral & sponge reefs), and (iii) threatening sustainable livelihoods of coastal communities that depend on small-scale fisheries (Hiddink et al., 2006; Jones, 1992; Virdin et al., 2019). Yet success and failure of policies to address BTF impacts has generally been assessed only through qualitative reviews and local empirical studies (Costello & Ballantine, 2015; Gillett, 2008; Grech & Coles, 2011; Pipitone et al., 2000). Quantitative assessments of policy effectiveness could greatly help in regulating bottom trawling in meaningful ways.

In economic affairs, quantifying the effects of policies has played an essential role in decision making for decades (Wieland et al., 2012). Government decision makers, including fisheries managers, often seek evidence-based policy advice based on robust analyses (Parkhurst, 2017). Economists have long developed and applied macroeconomic models (e.g., Dynamic stochastic general equilibrium) to understand economic phenomena and effects of different policies (Li, 2011). Such modeling studies provide evidence that help drive policy making. Although the reliability of these models for forecasting economic trajectory has been questioned especially in the global financial crisis 2008 - 2009, statistical models are evolving and remain essential in evaluating effectiveness of policies in many domains (Linde, 2018).

In natural resource sectors, evaluations of the effectiveness of policies have mostly taken the form of qualitative reviews (Imperial & Yandle, 2005; Novaglio et al., 2018; Shiffman & Hammerschlag, 2016). Some studies have used meta-analyses and complicated econometric models (general equilibrium models) in environmental-policy analyses (Evans et al., 2011; Floros & Failler, 2004). Others have applied ecosystem models in fishery-policy analyses (e.g. Ecopath with Ecosim, Atlantis) (Christensen & Walters, 2004; Natugonza et al., 2019). However, such applications are relatively rare, perhaps because they are rather complex, data-demanding, and costly (Wieland et al., 2012). Additionally, these models (general equilibrium models & ecosystem models) are designed to examine future policy options rather than to evaluate past policies. Studies have proposed identifying effects of previous policies by detecting breakpoints (e.g. shocks) on timeseries trajectories of natural resource metrices (e.g. fish or food production) (Cottrell et al., 2019; Gephart et al., 2017). One problem is that such breakpoints might be also explained by other factors (e.g. financial issues), making it difficult to determine the role of any policy change. Failure to understand the effectiveness of these policies means that politicians tend to repeatedly enact the same flawed policies (Howlett & Joshi-Koop, 2011; Zhang & Vincent, 2020a). There is a great need for easily applicable, quantitative approaches to evaluate effects of management policies in natural resource sectors.

Evaluations of policy effectiveness in natural resource management (e.g. fisheries) might benefit from quantitative approaches developed in economics and ecology. National fisheries data are commonly reported in the forms of annual timeseries of various variables of interests including fishing capacity and yield. These fisheries timeseries are often equivalent to those in econometrics (e.g., GDP) and thus suitable for applying similar models. For instance, the dynamic linear models (DLMs) can be useful quantitative tools to examine statistical effects of fishery policies upon their targeted fishery input or output indices (Ianchovichina & Walmsley, 2012; Petris et al., 2009). The

DLMs can correlate the response variable (timeseries attributes) with endogenous factors (temporal autocorrelations and trends), exogenous regressors (e.g. policy interventions and other factors), and random errors. Such models are much more simplified and have been popularly applied in analyzing unstable timeseries data in econometrics and other timeseries-based studies (Ianchovichina & Walmsley, 2012; Sánchez-Balseca & Pérez-Foguet, 2020). Meanwhile, classification and ordination techniques may help to identify grouping patterns of various policies as well. They have been widely used in ecology and other domains to determine latent variables and find similarities among samples across multiple variables (Gauch, 1982; Jaworska & Chupetlovska-Anastasova, 2009). However, to the best of our knowledge, no one has integrated these two approaches to evaluate policy effectiveness in fisheries.

Even though few of the management plans and policy initiatives directed at regulating BTF seem to make any difference, they are re-used repeatedly. All over the world, most BTF are poorly managed with many trawlers implicated in illegal, unregulated, and unreported (IUU) fishing (Belhabib et al., 2019; Cho, 2012; Öztürk, 2015). Vessels are also often dependent on perverse subsidies and/or forced labour (Ratner et al., 2014; Sumaila et al., 2016). To address these problems, a range of policies (e.g. input and output controls) have been used worldwide (Gillett, 2008). For instance, many countries have banned BTF in all or part of their exclusive economic zones (EEZs) in recent decades (Chuenpagdee et al., 2003; Mazor et al., 2017; Pipitone et al., 2000; Stiles et al., 2010). Seasonal fishing closures and other policies (e.g. gear modification, catch quota) have also been decreed in a bid to reduce bycatch and protect fishery stocks from BTF worldwide (Gillett, 2008; Melli et al., 2020). With exception to a few regions (e.g. Australia), trawl pressure still mounts with dire consequences for the ocean and for many ocean-associated people (Amoroso et al., 2018; Pauly, 2018; Peristeraki et al., 2020).

China, currently the world largest in terms of fishing capacity or yield, has enacted many policies to manage its BTF over the past seven decades (Zhang & Vincent, 2020a). Overexploitation, largely because of the nationwide BTF, has caused dramatic declines of some major benthic stocks (e.g., the great yellow croaker) since mid-1970s (Su et al., 2020). To manage its BTF, the Chinese central government has launched 103 national policies over the past seven decades (1950 – 2018), including 29 unimplemented policies (Zhang & Vincent, 2020a). Learning from these existing policy attempts (success and failure) is valuable and urgent, given that China wants to be effective in sustaining its marine fisheries (Cao et al., 2017). A recent study has reconstructed BTF inputs (e.g., total number of vessel) and outputs (e.g., total landings) over the same period (Zhang & Vincent, 2020b), enabling us to closely examine the effects of China's national policies upon its BTF. Such an analysis is hugely relevant to other countries, given that ~1500 Chinese bottom trawlers are operating in foreign EEZs (especially in Asia and Africa), and there is some indication that China's foreign fleet will expand further (Zhang & Vincent, 2020a). Any effective move by China to constrain and curb its BT fisheries would have global benefits.

We here develop an innovative framework to examine policy effects in the case of China's BTF. To this end, we took the novel step of integrating simple econometric models with ecological techniques. Our major interests were to (i) build a framework for policy-effectiveness analysis in natural resource management, and (ii) test this framework in the study on China's BTF from 1950 to 2018. Our framework includes three steps: (1) identifying potential explanatory factors (including policies and other socioeconomic factors) for each fisheries variable, (2) examining statistical effects of these explanatory factors on fishery variables, and (3) generalizing and visualizing the patterns of policy effects and performance. We expected that our framework could help derive new insights from the seven-decade policies to guide current reforms in China's fisheries management towards sustainability.

Methods

Our methods contain two major sections (data collection and data analysis), with the latter consisting of three steps that detailed our framework for analyzing policy effects (Figs 1&2). We collected two sets of data for China's BTF: (i) fishery variables (Table 1), and (ii) fishery policies (Table 2). We then describe our framework step by step in analyzing the effects of the collected fishery policies (and other factors) on fishery variables. Based on the data analyses, we calculated eight novel indices to measure the performance of the policies (Table 3).

Data collection

We collected a total of 13 variables for China's BTF covering six categories (Table 1): (i) total fishing capacity; (ii) mean fishing capacity; (iii) total landings; (iv) catch per unit effort; (v) ratio statistics; and (vi) fishing expansion. The fishing expansion was measured by fishing-in-balance index, which is commonly used in fisheries analyses (Pauly et al., 2000). These timeseries data were all from the recent reconstruction of China's BTF from 1950 to 2018 (Zhang & Vincent, 2020b). Different analyses covered different fishing areas, according to data availability (e.g. China's claimed EEZ, China's four seas; see an illustration on Fig. S1.1).

We used policy data from our recent review of China's history (1949-2018) with BTF (Zhang & Vincent, 2020a), examining their effects (positive or negative) on the corresponding fishery variables (Table 1). That review drew from a total of 103 policy documents.

Data analysis

While evaluating the fishery policies in the following three steps, we used four stratified terms: policy (lowest stratum, narrowest category), policy factor (2nd lowest stratum), policy type (2nd highest stratum), and administrative level (highest stratum, broadest category). Policy refers to each of the collected policy documents (e.g. a specific seasonal closure, examined in Step One). Policy factor refers to a collection of policies with a common policy approach (e.g. seasonal closure policies for all years). They were created to examine statistical effects of fishery policies on fishery variables (in Step Two) and explore patterns of policy effects (in Step Three). We also grouped all collected policies into seven policy types and two policy levels (see definition in Table 2), as we were interested in generalizing their performance in managing BTF (in Step Three). The seven types were: (i) international law & agreement; (ii) overarching policy; (iii) ban & protection; (iv) input control; (v) output control; (vi) law enforcement; and (vii) fuel subsidy (Zhang & Vincent, 2020a). Policies were created at two administrative levels: central level and ministry level (Table 2). Central-level policies were generally very broad (largely overarching policies) and had stronger force of law (e.g. fisheries laws and development outlines), while ministry-level policies were relatively more specific with smaller scopes (e.g., input control regulations).

Step One: Identifying potential explanatory factors for each fishery variable

In Step One, we identified breakpoints (turning/inflection points where a relationship changes) in the collected fishery variables, and then qualitatively assessed which policies (lowest stratum) and other socioeconomic factors could be the potential explanatory factors responsible for these changes (Fig. 1).

We applied three approaches to identify breakpoints in variables (see detailed methods on Appendix S1). Our first approach was detecting breakpoints in segmented linear regressions based on the 'Bellman principle of optimality' (function 'breakpoints' in r package 'strucchange') (Zeileis, Leisch, Hornik, & Kleiber, 2001). Our second technique was detecting 'outliers' in fitting local polynomial regression models with a span of 0.6 to the selected variables (function 'loess' in r) (Balke & Fomby, 1994; Cottrell et al., 2019). These two approaches are not very applicable for highly variable timeseries (Cottrell et al., 2019). To address this, our third approach was to inspect data visually to identify additional abrupt fluctuations on the trajectories. We consider all break points detected from these three approaches in further analyses below.

We identified potential policies that might explain the detected breakpoints. To this end, we followed a decision tree (Fig. 2) to classified the collected policies (n = 103) into four groups: (i) unimplemented policies (n = 29) that were not implemented based on the previous study (Zhang & Vincent, 2020a), (ii) unexaminable policies whose impacts on the fishery variable could not be assessed, (iii) potentially influential policies which likely created the expected effect on a fishery variable, and (iv) influence-uncertain policies which likely had some uncertain effects (including unexpected) upon a fishery variable. During this process, we used a 'five-year rule' to determine the impact of a policy, given China's political characteristics (see more in Appendix S1).

The identified potentially influential policies and influence-uncertain policies were then converted into potential explanatory factors (2nd lowest stratum) in Step Two for quantitative analyses. For obvious reasons, the unimplemented and unexaminable policies were excluded. We also searched for information on other socioeconomic factors (e.g. financial crises) that might explain the breakpoints on fishery trajectories. These socioeconomic factors were also carried into Step Two as potential explanatory factors. By doing so, we reduced the chance of overestimating the effects of fisheries policies.

Step Two: Examining the statistical effects of these explanatory factors upon fishery variables

In Step Two, we used econometric models to examine statistical effects of the potential explanatory factors converted from the potentially influential policies, influence-uncertain policies, and other socioeconomic factors identified in Step One (Fig. 1). In the end, we also conducted dominance analyses to derive a dominance score matrix for further analyses in Step Three (Fig. 1).

We examined the main effects of these explanatory factors on each fishery variable with dynamic linear models (DLMs) (function 'lm' with a lag function for regressors in r) (R Core Team, 2017). To fit the models, we first converted the relevant policies and other factors into nominal variables (dummy variables) as the explanatory factors. We integrated policies with a common approach (e.g. summer moratorium policies issued in different years) into one policy factor (2nd lowest stratum) with different integers to simplify the analysis (see Appendix S1). The response variable was the annual change (i.e. difference between consecutive values) in the original fishery variable. If the annual difference was consistent, then the policy was deemed to have had no influence. However, if the annual difference suddenly increased or decreased, then this was inferred to result from the policy (and potentially other factors, too) (see Appendix S1).

We conducted the following model process for each fishery variable. First, we constructed a contrast model without any policy variables except (i) a linear trend in fishery variable (i.e., differences between year), (ii) other external factor (here, financial crises, if applicable), and (iii) partial autocorrelation (function 'acf' in r), which was included only if the coefficient was statistically significant. Second, we built a full model by adding all relevant policy regressors to the contrast model. We examined and recorded the statistical effects of each policy in this full model. For those policy predictors that had no significant effects in the full model (or that were omitted because of non-independence), we further checked their effects in simplified models. This was done by adding only one of the 'non-significant' regressors to the contrast model each time. By doing so, we reduced the risk of rejecting statistically meaningful policies masked by their covariates in the full model (Fig. 1). We examined the statistical effects of the coefficients in the above models by using Welch's t tests with Bonferroni corrections on p-values, allowing for heteroscedastic samples (functions 'vcovHC' and 'coeftest' in r packages 'sandwich' and 'lmtest') (Derrick et al., 2016; Hothorn et al., 2019; Lumley et al., 2015). These detected statistical effects were further used to generalize performance indices in Step Three (Fig. 1).

Based on the above models, we then conducted four sections of additional analyses (see details in Appendix S1). First, we discriminated policies into five groups based on their statistical effects: (i) conservation-oriented policies, (ii) growth-promoting policies, (iii) efficiency-promoting policies, (iv) efficiency-reducing policies, and (iv) diverse-effect policies. Second, we examined the extent that qualitative analyses in Step One might have been wrong about policy effects (e.g. overestimation), compared with results from Step Two. Third, we examined whether adding policies could significantly better explain variance within a fishery variable, by comparing the full model with the contrast model (F-tests). If the full model did not perform significantly better, we used a forward selection process to derive an optimal model with the lowest values of the corrected Akaike information criterion (AICc) for small samples (function 'stepAICc' based on the function 'stepAIC', r package 'MASS') (Hurvich & Tsai, 1989; Read et al., 2018; Ripley et al., 2013). The forward selection was executed in an iterative randomized fashion in terms of predictor involvement. We then examined whether the optimal model performed significantly better than the contrast model (using F-tests, function 'anova' in r). Finally, we measured the relative importance of each policy factor to its response variable based on the dominance analysis (function 'dominanceAnalysis' in r package 'dominanceanalysis') (Bustos & Soares, 2019). This analysis measures the average contribution to explain model variances across all subset models of the full model (Budescu, 1993). This dominance matrix was then used in Step Three (Fig. 1).

Step Three: Generalizing and visualizing the patterns of policy effects and performance

In Step Three, we applied classification and ordination analyses to generalize the patterns of policy effects on fishery variables based on the dominance matrix (Step Two; Fig. 1). Based on statistical results (Step Two), we created eight performance indices to generalize the performance of different policies at three strata: policy factors (2nd lowest stratum), policy types (2nd highest stratum), and policy levels (highest stratum).

To conduct classification and ordination analyses, we first applied the Bray-Curtis dissimilarity to derive a dissimilarity matrix based on the dominance matrix from Step Two (function 'vegdist' in r package 'vegan') (Oksanen et al., 2019). This dissimilarity index is widely used in ecology to quantify the difference in community composition (e.g., abundance of species) between pairwise sampling sites (Bray & Curtis, 1957). Here, correspondingly our dominance scores of policy factors served as the ecological 'abundance of species', and our fishery variables served as the ecological 'sampling sites'. Before deriving the dissimilarity matrix, we normalized the dominance scores by range (scaled to 0 – 1) to prevent the dominance of certain variables in the dissimilarity calculation (Quinn & Keough, 2002).

We built the dendrogram of the policy factors based on agglomerative hierarchical clustering (AHC) methods (function 'hclust' in r package 'fastcluster') (Müllner, 2013). The AHC methods are the dominant classification techniques that group objects of interest into larger clusters that together create a dendrogram (Murtagh & Contreras, 2012). Here, the dendrogram was constructed with the Bray-Curtis dissimilarity and the Ward's minimum-variance linkage algorithm (Murtagh & Contreras, 2012; Ward Jr & Hook, 1963). This enabled us to identify grouping patterns in policy influence.

We employed a non-metric multidimensional scaling (NMDS) to demonstrate the dissimilarity among policy factors in a 2D space (Oksanen et al., 2010), making no assumptions about the relationship between the two dimensions (Shepard, 1962). The goodness of fit (i.e., how well the distance in the ordination diagram represents the rank of dissimilarity between objects of interest) was measured by a stress function, which ranges from 0 – 1. As a rule of thumb, a stress < 0.2 represent a fair goodness of fit (Clarke, 1993). We generated a stable solution from random starts (function 'metaMDS' in r package 'vegan') (Oksanen et al., 2019). We then added the biplot of the fishery variables to the scaling diagram to examine the correspondence correlation between policy factors and fishery variables (function 'envfit' in r package 'vegan') (Oksanen et al., 2019).

We determined the grouping of policy factors by comparing the interpretability of choosing different numbers of groups from the AHC dendrogram. Our primary rule is that the identified groups should correspond well to the grouping patterns on the NMDS diagram. We employed the analysis of similarities (ANOSIM) to examine whether there was a significant difference among the identified groups (function 'anosim' in r package 'vegan') (Clarke, 1993; Oksanen et al., 2019). This test produces a statistic R which measures the difference between the mean of ranked dissimilarities between groups to the mean of ranked dissimilarities within groups, and the closer the value to 1, the greater the difference among groups.

To generalize the performance of policies, we created a total of eight indices (see formula in Table 3): two for the 13 policy factors (2nd lowest stratum), and six for the seven policy types (2nd highest stratum) and two policy levels (highest stratum; Tables 2&3). For each policy factor, we measured (i) the mean dominance score of each policy factor in affecting the fishery trajectory (i.e. mean dominance index); and (ii) the proportion of fishery variables that were significantly affected by the policy factor (i.e. influence breadth index). We explored the distributions of the policy factors in the 2D space of the two indices. For each policy type/level, we measured the contribution of that type/level to the total number of policies that were statistically examined in our models (i.e. policy contribution index), and compared it with the proportion of these statistically examined policies that had the intended and significant effects (i.e. influence contribution index). Within each type/level, we also measured the proportion of the total policies (excluding unexaminable ones) that were statistically examined (i.e. potential usefulness index), and compared it with the proportion of the total policies that had intended and significant effects (significant usefulness index). If a policy type/level had a higher influence contribution index than its policy contribution index, we considered that type/level had contributed disproportionally more effects. If significant usefulness index of a policy type/level was higher than its potential usefulness index, that type/level was more useful than would be expected.

Results

Identifying potential explanatory factors for each fishery variable

We identified a total of 107 breakpoints across the 13 fishery variables (Figs S2.1 & S2.2). We found 12 of these fishery variables contained breakpoints that could be potentially explained by the effects of a total of 49 (out of 74) policies (lowest stratum; Table S2.1 in Appendix S2) and two financial crises (i.e., 1997 Asian Financial Crisis, and 2008 Global Financial Crisis). Overall, there were 172 potential effects and 33 uncertain effects (Table S2.2). For example, China's economic reform 1978 had a potential positive effect on both the number of trawlers and their horsepower. In contrast, China's UNCLOS Ratification 1996 had a potential negative effect on the same two variables, and an uncertain effect on the horsepower per vessel of distant-water trawlers beyond C4S.

Some breakpoints couldn't be explained. We couldn't find any policies to explain the breakpoints of one fishery variable: the number of bottom trawlers in waters beyond C4S (Fig. S2.1b). Additionally, we identified a total of 25 policies that were unexaminable in terms of their effects in our study (Table S2.2). For instance, the Shrimp protection regulations in Bohai 1962 were issued to constrain domestic trawling in the Bohai Sea (one of C4S) and thus difficult to examine at the national level. As well, the juvenile-catch ratio 1980, which was enacted to constrain by-catch in China's domestic BTF, was unexaminable based on our fishery variables.

Based on these results, we carried 49 policies (with potential or uncertain effects), two financial crises and 12 fishery variables into our analyses in Step Two.

Examining the statistical effects of these explanatory factors upon fishery variables

We grouped the 49 policies (lowest stratum) into 13 policy factors (2nd lowest stratum), each group representing a commonality of policy approach (e.g. Fishery Overarching Policies) and we grouped the two financial crises into one financial-crisis factor (Table 4, also see Tables S2.2). Their statistical effects were then examined in regression models for the 12 relevant fishery variables.

Our quantitative analyses (Step Two) revealed important new insights in comparison to the qualitative analyses (Step One). Among the 49 statistically examined policies, 11 (~ 22%) were conservation-oriented policies, 10 were growth-promoting policies, one was efficiency-promoting policy, 13 were diverse-effect policies, and 14 policies (~ 29%) had no significant effects on any fishery variable (Table S2.2; Figs 3 & S2.3).

The 11 conservation-oriented policies were dominated by three no-trawl zone policies (in 1955, 1957, and 1980), three overarching policies (Protecting inshore fisheries 1981, Ocean Agenda 1996, EEZ Law 1998), and two fishery agreements. These eight policies were followed by one summer moratorium policy (in 1999), one output control policy (Negative Growth 2000), and one law enforcement policy (Protecting Fisheries 2011). For instance, we considered the no-trawl zone 1955 to be a conservation-oriented policy, because it had significant effects on reducing (i) the ratio of trawlers to all Chinese motorized fishing vessels, and (ii) the fishing-in-balance index within China's claimed EEZ (i.e. constraining trawling expansion; Figs 3 & S2.3).

We found 10 growth-promoting policies that included three fishing permit regulations (two in 2004 and one in 2013), two overarching policies (Developing distant-water fisheries 1985, Accelerating economic reform 1992), two summer moratorium policies (in 1998 & 2000), one fishery agreement (Sino-Japanese Fishery Agreement 1975), one law enforcement policy (Protecting Fisheries 2009), and one fuel subsidy policy (2010). For instance, the two provisions issued in 2004 that decentralized authority for permits to local government agencies were accompanied by increases in the horsepower of distant-water trawlers beyond C4S (Fig. 3).

The 13 diverse-effect policies were complicated in that they each did more than one thing: 12 had conservation-oriented effects, 11 had growth-promoting effects, four had efficiency-promoting effects, and two had efficiency-reducing effects (Table S2.3). For instance, the Opinion 2013 (for accelerating fishery "upgrading"[1]) had a conservation-oriented effect (i.e. reducing the number of

[1] An overarching policy issued by the central government (China's State Council in 2013) to promote sustainable and healthy development of marine fisheries by transferring the development mode from intensive growth to quality-oriented development. The major guideline is to constrain the development of domestic fisheries while advancing

trawlers), but it also had a growth-promoting effect (i.e. increasing the horsepower of distant-water trawlers beyond C4S; Fig. 3).

The 14 policies without significant effects on BTF variables included four policies for summer moratoria (in 2001, 2003, 2006, and 2009), three fishery overarching policies (one in 1983, two in 2006), two vessel buyback policies (in 2003 & 2015), two fuel subsidy policies (in 2006 & 2015), two law enforcement policies (in 2006 & 2007), and one output control policy (Zero Growth 1999; Tables S2.1 & S2.2).

In contrast to qualitative analyses (from Step One), we found that only 28% of the potential effects in these quantitative analyses were statistically significant (from Step Two). For instance, economic reform 1978 apparently increased the potential number of trawlers but had no effect on the horsepower of trawlers. In addition, a small portion (3%) of the potential effects (five out of 171) were mistakenly identified during qualitative analyses (i.e., false positive or false negative). Similarly, we found that only one third (33%) of the uncertain effects were statistically significant. For example, we judged that UNCLOS Ratification 1996 to have an uncertain effect; it may have increased the mean horsepower of distant-water trawlers beyond C4S, but not significantly. In contrast, we found that vessel buyback 2002, another uncertain effect, coincided with (but may not have caused) significant increases in mean horsepower of Chinese trawlers.

Our policy factors (2nd lowest stratum) were statistically meaningful in explaining the trajectories of 11 out of the 12 fishery variables (Fig. 4). Ten out of the 12 examined fishery variables could be significantly better explained by the full models (which included policy factors) than by the contrast models (F-tests, all $P < 0.05$ with six P values < 0.001; Fig. 4). For instance, the annual change in the number of bottom trawlers was significantly better explained with the full model (including six policies; adjusted R-squared = 0.790) than with the contrast model (without policies; adjusted R-squared = 0.268; Fig. 4a). Among the other two fishery variables, the mean horsepower of distant-water BTs could be significantly better explained by an optimal model (included two policy factors) than by the contrast model ($P < 0.01$, Fig. 4g). However, the catch ratio between BTF and all marine fisheries in China's claimed EEZ could not be better explained by the full or the optimal model, in contrast to the contrast model (Fig. 4k). It suggests this variable was not effectively regulated by any policies we have examined in this study.

Given the above results, only 11 fishery variables, along with the 13 policy factors, were retained for dominance analyses and further cluster and ordination analyses. All 13 policy factors had some significant effects on at least one of the 11 fishery variables (Table S2.3). The dominance scores differed significantly among the policy factors (Kruskal-Wallis rank sum test, $p < 0.001$), with the Fishery Overarching Policies significantly more dominant than other factors (Fig. S2.4).

Generalizing and visualizing the patterns of policy effects and performance

We found that the impacts of the 13 policy factors upon the 11 fishery variables can be well interpreted by creating three groups (Fig. 5a, ANOSIM R statistic = 0.75, $P < 0.001$). These groups were well separated in the ordination diagram (Fig. 5b), with a fair goodness of fit (stress = 0.12). Group 1 contained six policy factors (e.g. Fishery Overarching Policies; Fig 5a) that had comprehensive impacts on a variety of fishery variables, including fishing capacity, fishing efficiency, ratio statistics, and fishing expansion of China's BTF (Fig. 5b). Group 2 contained four policy factors (e.g. Fuel Subsidy; Fig. 5a), which generally affected fishing capacity & yield of China's distant-water BTF (Fig. 5b). Group 3 was composed of three policy factors (e.g. Output

distant-water fisheries and aquaculture development, with a focus on constraining the construction of bottom trawlers and other destructive fishing vessels.

Control; Fig. 5a), which generally affected the total yield of China's BTF, but the influence was relatively weaker (Fig. 5b). The results suggested that China's policies lacked impact on BTF output variables.

Among the 13 policy factors (2nd lowest stratum), Fishery Overarching Policies (i.e. Fishery OPs; Fig. 6a) had the highest mean dominance index (MDI = 12.2%) and second highest influence-breadth index (IBI = 50.0%; Fig. 6a), suggesting this policy factor had higher impacts upon relatively more fishery variables than most of other policy factors. In contrast, Output Control had the least values on both indices (MDI = 0.4%, IBI = 8.3%), suggesting it had both narrower and lower impacts than other policy factors (Fig. 6a). Double Control had the highest influence-breadth index (IBI = 58.3%), but a medium level of mean dominance index (MDI = 4.3%; Fig. 6a), meaning its impacts spread across more fishery variables than other policy factors, but were generally not very high on any one variable.

Among the seven policy types (2nd highest stratum), three of them (overarching policy, input control, and international law & agreement) contributed disproportionately more significant effects (influence contribution index > policy contribution index; Fig. 6b). For instance, although the overarching policies only contained 19.4% of all policies (or 22.5% of statistically examined policies; Fig. 6d), they contributed 30.9% of the significant effects, the most of all seven types; Fig. 6b). In terms of usefulness, most policies of four policy types (output control, international law & agreement, overarching policy, and law enforcement) were important (all significant usefulness indices > 66%: Fig. 6c). In addition, output control was more useful than expected (significant usefulness index > potential usefulness index; Fig. 6c); however, only two policies belonged to this type (Fig. 6d) and both had statistically significant effects (Table S2.2). Only less than one third of the remaining three types (input control, ban & protection, fuel subsidy) were useful (all significant usefulness indices < 30%; Fig. 6c).

At the administrative level (highest stratum), we found central level policies contributed proportionately more significant effects than ministry-level policies (Fig. 6b). The central level actually contributed fewer absolute significant effects than the ministry level (44.1% and 55.9%, respectively; Fig. 6b), but this was largely because the latter rolled out more policies than the former (Fig. 6d). All statistically examined policies from the central level were useful (significant usefulness index = 100%), while a slightly lower proportion (97%) of the examined policies from the ministry level were useful (significant usefulness index = 97%; Fig. 6c).

Discussion

We open a new path for evaluating policy effectiveness in natural resource management, here revealing that China's efforts to control its BTF for sustainability have been largely ineffectual. Despite China's repeated declarations that it wishes to constrain BTF (Zhang & Vincent, 2020a), fewer than one-quarter of its many fisheries management policies have achieved meaningful progress toward conservation. In this, our findings concur with previous studies showing that policy implementation has long been poor in China's fisheries management, including for BTF (Cao et al., 2017; Su et al., 2020; Zhang & Vincent, 2020a). Of note, though, high level strategic plans from central government apparently had more resonance than bans and protective measures issued from specific ministries. From a technical perspective, our study produces the innovative discovery that marrying simple econometric models (e.g. DLMs) with ecological techniques (classification & ordination) based on dominance analyses offers promise when it comes to examining the effects of policies on timeseries statistics. Our novel framework is conceptually simpler and less data-demanding than previous quantitative approaches (Christensen & Walters, 2004; Floros & Failler, 2004; Natugonza et al., 2019). We highlight that simple econometric models can quantify potential policy effects detected by breakpoint analyses (Cottrell et al., 2019; Gephart et al., 2017). Our performance indices can help identify success and failure of different types of policies, thus guiding resource managers into promising policy avenues (Howlett & Joshi-Koop, 2011).

New insights for understanding China's policies on BTF and their implications

Our study should encourage China (and, by extension, many other countries) to reconsider its trawl management policies, given that one-third of policies we examined here had no significant effects on its BTF variables. For instance, we agree with previous studies that the summer moratoria (started in 1981) are not very successful in China (Shen & Heino, 2014; Su et al., 2020), by finding that they have not influenced catch or CPUE of BTF since 2001. Such lack of effect might be explained by three factors: (i) overcapacity in China's claimed EEZ after fishery agreements with Japan and South Korea came into effect (in 2000 and 2001, respectively) (Zhang & Vincent, 2020a); (ii) intensified trawling pressure after each moratorium ends (Yu & Yu, 2008), and (iii) the long term destructive effect of trawling upon benthic fishery stocks and communities (Oberle et al., 2016). In any case, the poor results indicate a need for a new policy framework that actively reduces fishing pressure, rather than merely redistributing it temporally. Furthermore, such framework needs to be designed directly by the central government, given that its policies are more influential than those from the specific ministries.

We provide a warning that designing fisheries policy is a complex undertaking, one that can backfire. A total of 27% of previous policies we examined had diverse (often controversial) effects instead of simply meeting their intentions of promoting growth or fostering conservation. A prominent example is the vessel buyback programs (started in 2002), which were intended to reduce fishing capacity of China's marine fisheries (Cao et al., 2017; Zhang & Vincent, 2020a). Our study indicates that although this policy may well have driven a reduction in the total number and horsepower of trawlers, it likely led to increases in mean horsepower of trawlers and encouraged the spatial expansion of China's BTF.

Our study highlights that China's future policy making and actions should consider more conservation-oriented approaches including more effective output controls and law enforcement activities. We demonstrated that only one fifth of the examined policies had pure conservation-oriented effects (Table S2.2), and previous policies only exerted some weak output-control effects on China's BTF (Fig. 5b). FAO identifies output control (based on robust stock assessment) and consistent law enforcement as indicators for better BTF management (Funge-Smith, 2014). A rights-based output control (e.g. individual catch quota) has the capacity to stem fishing pressure when used with vessel-buyback programs (Holland et al., 2017). Unfortunately, China's national policy system has been largely dominated by ban & protection measures and input controls, most of which we find not useful. To date, the truly conservation-oriented policies only included a few output controls and law enforcement policies, which we found to be among China's most useful types of domestic policies. Notably, China's rare output controls (N = 3) were all total-allowable-catch policies that were not set based on robust stock assessments, and its law enforcement was largely limited to specific periods (i.e. summer moratoria) (Zhang & Vincent, 2020a). To meet its own objectives, China's fisheries reforms must advance more conservation-oriented policies, and particularly rights-based output control (e.g. individual catch quota) and comprehensive law enforcement (Cao et al., 2017; Su et al., 2020)

In general, our analysis should prompt China to take a more adaptive approach in meeting its declared intention to curtail BTF, with a focus on policies that can truly reduce fishing pressure. To this end, China needs to consider how best to (i) expand its high-level policies explicitly directed at winding down BTF (both inputs and outputs); (ii) implement all such policies more effectively (through comprehensive law enforcement actions); (iii) seek fishers' participation and draw on scientific evidence in its policy making; and (iv) evaluate and modify policies as needed based on robust fisheries monitoring and assessment (Su et al., 2020).

Novelty and caveats of our approaches in policy-effect analysis

Our pioneering experiment in integrating econometric models with ecological approaches has produced a new framework for quantitatively analyzing policy effects in natural resource management. Unlike previous quantitative methods such as general equilibrium models and ecosystem models (Christensen & Walters, 2004; Floros & Failler, 2004; Natugonza et al., 2019), our framework requires fewer data and modeling skills, is conceptually simpler, and is capable of evaluating large numbers of past policies. These characteristics are advantageous in fisheries management and other natural resource sectors, where data-poor scenarios are common and science-based decision making is badly needed (Jones et al., 2017). For instance, scientists can use our approach to further quantify potential effects of policy on food or fish production, once these have been detected by breakpoint analyses (Cottrell et al., 2019; Gephart et al., 2017). Importantly, we creatively apply dominance analyses to calculate similarity/dissimilarity for policy factors, enabling further classification & ordination analyses based on results from econometric models. Such a novel application has proven useful in discerning patterns in how different policies work, helping to identify response variables that have been less affected. Broad geographic application of our approach could help generate a global understanding of the effects of different fishery or environmental policies, thus promoting better decision-making worldwide (Howlett & Joshi-Koop, 2011).

We provide novel indices to help decision makers evaluate performance of different policies. Understanding the contribution and usefulness of different policies is meaningful to decision makers. By using our indices, one can identify policy types that contribute disproportionately more significant effects or those that are more useful. As well, in a situation where multiple types of policies might generate similar effects, our approach helps to choose the one with the highest significant usefulness index. Such insights are vital to future policy making, reducing the chance of policy makers continuously re-enacting failed policies, as has so often been the case across different domains (Gailmard & Patty, 2007; Howlett & Joshi-Koop, 2011). Scientists can also use our indices to quantify policy performance, thus creating response variables of use in examining influence of underlying socioeconomic factors (e.g. fishers' compliance) on policy effectiveness (Boonstra et al., 2017; Thomas et al., 2016).

We highlight two caveats to be addressed in future application of our approaches. First, it would be useful to quantify the policy data into numeric regressors rather than nominal regressors, thus increasing the degree of freedom in the statistical model. Potentially, policies with the same general approach (e.g., summer moratoria revised multiple times over time) should also be separated according to their degree of 'strictness'. However, this would require robust expert evaluation at a level that is currently challenging for most of our policies. Second, although we derived useful models for many fishery variables, the explained variance was not high for some variables (e.g. catch from distant-water BTF; Fig. 3). Understanding which factors might have driven unexplained residuals in the model would be meaningful to policy makers, especially as these may include other socioeconomic and environmental factors.

Management implications for global BTF

Our study suggests that a 'command-and-control' management approach - one that focuses on input control and total output control – has not served China any better in pursuit of fisheries sustainability than it has served other nations (Cardinale et al., 2017; Colwell et al., 2019; Kompas & Gooday, 2007; Warlick et al., 2018). For instance, Australia has sequentially executed seasonal closures (since 1971), input control on boat replacement (1980s), and vessel buyback programs (mide-1980s – 1990s) to reduce fishing effort and sustain Australian northern prawn fishery (established in late 1960s). However, the effects of these measures were short lived and failed to meet declared targets (Kompas & Gooday, 2007), similar to the case of China. One explanation is that controls on some inputs incentivize fishers to increase investment in other inputs, those without controls (e.g. technological creep, gear shift: Colwell et al., 2019; Kompas & Gooday, 2007). Another explanation is that the 'command-and-control' regime provides no sense of ownership of fisheries resources (i.e. tragedy of commons) (Kompas & Gooday, 2007). Furthermore, worldwide, vessel buyback programs have often been offset by reinvestment in fisheries (Newby et al., 2004; Teh et al., 2017), such that the major outcome of many such programs is merely a renewal of the fleet (Squires et al., 2010; Quijano et al., 2018), as shown in China (Zhang & Vincent, 2020a). Qualitative reviews have generalized some common lessons from these failures and highlighted the importance of four key elements: (i) fishers participation (e.g. co-management), strong leadership, and transparency in policy making; (ii) robust monitoring on fishing activities (e.g. vessel monitoring system) and catch (e.g. remote electronic monitoring, onboard observers); (iii) science-based targets (e.g. total allowable catch); and (iv) right-based policy instruments (e.g. individual catch quota) that incentivize reductions in fishing capacity & effort and increases in fishing efficiency or profitability (Chu, 2009; Condie et al., 2014; Gutiérrez et al., 2011; Hoefnagel & de Vos, 2017).

We provide a new framework to quantitatively analyze the effectiveness of previous policies worldwide in managing BTF. Our approach can improve the understanding of many potentially influential and influence-uncertain policies. Although some lessons in managing BTF worldwide have been generalized from qualitative reviews, it would be valuable to further quantify effectiveness of the many previous policies and understand the patterns of policy influence in greater detail (Warlick et al., 2018). For instance, with our framework, researchers and managers could quantify the effects of policies in regulating different BTF around the Australian coast, and then generalize new lessons to inform BTF management reforms (Novaglio et al., 2018). As well, the European Union could use our approach to reanalyze its historical policies in managing Mediterranean BTF and thus improve reforms directed at sustainability (De Nicolò, 2018). When using our framework, colleague elsewhere will want to identify their own fishery metrices for management targets to be evaluated. For instance, in relatively well studied BTF of developed countries, such as the northern prawn fisheries in Australia, the maximum economic yield or population status could serve as useful fishery variables when evaluating policy (Kompas & Gooday, 2007). For many developing countries, such as Thailand, where fisheries data are limited and diverse species are caught in BTF (Brittany et al., 2017), researchers may choose more available timeseries of fishery metrices (e.g. total landings) as we do in our study.

To achieve a sustainable future, the world's fishing nations need to conduct evidence-based fisheries reforms that effectively reduce fishing capacity, fishing effort, catch, and spatial expansion of BTF (Pauly, 2018; Tickler et al., 2018; Worm et al., 2009). The key is adaptive management, which depends heavily on repetitive monitoring and evaluation of all initiatives and ventures, along the lines of what we have undertaken here, while also engaging industry and government stakeholders (Sampedro et al., 2017). While some major fishing nations (e.g. Japan, Russia) have gradually shrunk their fishing efforts, other countries (e.g. China, South Korea, Spain) have been expanding theirs for decades along with globalization of seafood trade (Tickler et al., 2018). However, such an expansion cannot be sustained given the widespread declines of many fisheries stocks, including those from BTF (Edgar et al., 2018; Thurstan et al., 2010). Our approach can help facilitate science-based policy making worldwide to better curtail BTF and thus inform future reforms that make real advances in fisheries sustainability worldwide.

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Data availability Statement

All data (including original data and R code for data analyses) are deposited in Github (https://github.com/XiongZhang825/Policy-effect-analysis).

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Table 1. Thirteen fishery variables selected for analyzing policy impacts on China's bottom trawl fisheries.

Category	Fisheries statistics	Duration
Total fishery capacity	Number of bottom trawlers (BTs)	1950-2018
	Number of BTs in waters beyond China's four seas (C4S) †	1985-2018
	Horsepower of BTs	1950-2018
	Horsepower of BTs in waters beyond C4S	1985-2018
Mean fishing capacity	Horsepower per BT	1950-2018
	Horsepower per BT in waters beyond C4S	1985-2018
Total landings	Catch by BTs	1950-2014
	Catch by BTs from waters beyond C4S	1950-2014
Catch per unit effort	Catch per horsepower per year by BTs	1950-2014
Ratio statistics	Vessel ratio between BTs and all motorized catchers ‡	1950-2018
	Horsepower ratio between BTs and all motorized catchers	1950-2018
	Catch ratio between BTs and all motorized catchers in China's claimed EEZ §	1950-2014
Fishing expansion	Fishing-in-balance index of China's BTF in its claimed EEZ	1950-2014

† China's four seas (see SI): Bohai Sea, Yellow Sea, East China Sea, South China Sea (Fig. S1.1)

‡ All motorized catchers: all motorized fishing vessels registered in China's national administration system

§ China's claimed EEZ: marine territory claimed by the People's Republic of China in 1996, including disputed waters (Fig. S1.1)

Table 2. Categorization of the seven policy types (2nd highest stratum) and two administrative levels (highest stratum, broadest category).

Term	Description
International law and agreement	International law that was ratified by China, and agreement on fisheries affairs between nations
Overarching policy	Development strategy, development opinion or outline, comprehensive regulations and laws, Five-Year Plans (notably, these policies may not specifically about fisheries, in contrast to the Fishery Overarching Policies defined in Table 4)
Ban & protection	Restrictions on the use of bottom trawl in terms of time and/or space, including non-trawl zone, summer moratorium, eternal ban on using bottom trawlers, protection area for important stocks
Input control	Regulations on fishing gears, vessels, and fishing permits; controls on the number of vessels and horsepower
Output control	Regulations targeted on the catch, including juvenile catch regulations, catch quota, resource fee, and minimum catchable size.
Law enforcement	Instructions and Special Actions to enhance law enforcement
Fuel subsidy	Regulations on fuel subsidy
Central administrative level	Policies directly issued or approved by the central government (i.e., State Council) or its legislature (i.e., The National People's Congress, and its Standing Committee) in China
Ministry administrative level	Policies issued by the ministries (e.g., Ministry of Agriculture) of the State Council of China.

Table 3. Policy performance indices for policy factors (2nd lowest stratum), policy type (2nd highest stratum), and policy level (highest stratum).

Stratum	**Performance index**	**Formula**	**Explanation**
Policy factor	Mean dominance index (MDI_f)	$100\% * \sum_{i=1}^{k} DS_{i,f}/k$	$DS_{i,f}$ is the dominance score of policy factor *f* in the models for fishery variable *i* (*i* = 1, 2, 3, …, *k*); *k* is the total number of fishery variables included in the dominance analysis; NV_f is the number of fishery variables that were significantly affected by policy factor *f*.
	Influence breadth index (IBI_f)	$100\% * NV_f/k$	
Policy type/level	Policy contribution index (PCI_c)	$100\% * NE_c/\sum_{c=1}^{j} NE_c$	NE_c is the total number of policies (within type/level *c*) that were included in regression models (hereafter, statistically examined policies); NSE_c is the total number of significant and expected effects contributed by policy type/level *c*; *j* is the total number of policy types/levels; NP_c is the total number of statistically examined policies and unimplemented policies within policy type/level *c*; NS_c is the total number of policies (within type/level c) that derived significant and expected effects.
	Influence contribution index (ICI_c)	$100\% * NSE_c/\sum_{c=1}^{j} NSE_c$	
	Potential usefulness index (PUI_c)	$100\% * NE_c/NP_c$	
	Significant usefulness index (SUI_c)	$100\% * NS_c/NP_c$	

Table 4. Summary of the 13 policy factors (2nd lowest stratum) derived from a total of 49 policies (lowest stratum).

Term	Description	No. of policies
Summer Moratoria	China's seasonal fishing closure in China's four coastal seas during summer season, started in 1981, and revised multiple times in the history	8
Fishery Overarching Policies	Overarching policies that were specifically for guiding fisheries development and management	7
Law Enforcement	Policies for conducting law enforcement programs largely for combatting illegal fishing and gears during summer moratoria	6
Vessel Buyback	Polices for scrapping old fishing vessels and providing allowance and training programs to fishers who want to change jobs	4
Fishery Agreements	Fishery agreements between China and the neighboring three nations: South Korea (2001), Japan (1975, 2000), and Vietnam (2004). Two versions for China and Japan, one was agreed in 1975 and its replacement was agreed in 2000.	4
No-trawl Zones	Policies for establishing inshore protected waters that prevent bottom trawling	3
Double Control	Input control policies that restrict total number of fishing vessels and their total horsepower, initiated in 1997	3
Fuel Subsidy	Policies related to fuel subsidy management, started in 2006, although the subsidy has been reduced since 2015	3
Permit Regulations	Regulations related to fishing permit application and management	3
Economic Reform	Policies related to China's market opening-up and economic reform, initiated in 1978	2
EEZ Laws	Laws that were established regarding China's exclusive economic zone, claimed in 1996	2
Agenda 21	China's strategical plans to meet the commitment to the world Agenda 21, started in 1994	2
Output Control	Policies that control the growth of fisheries yield, started in 1999 with a Zero Growth policy, followed by a Negative Growth policy in 2000	2

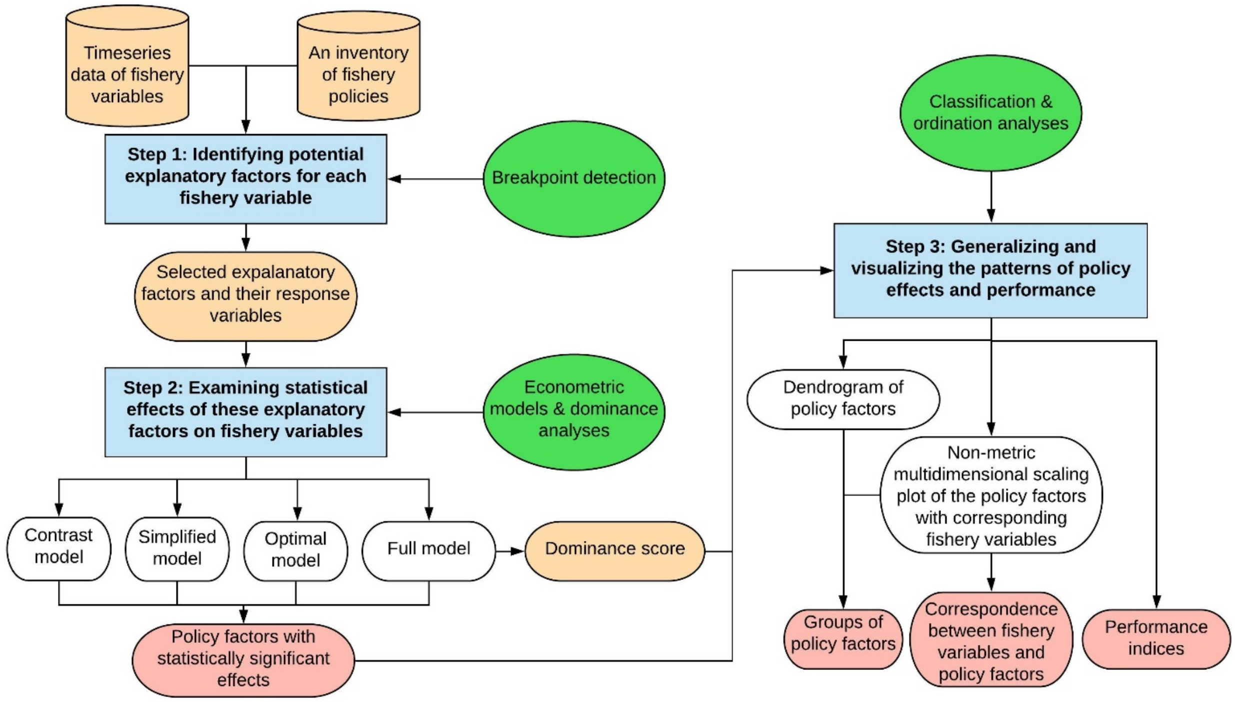

Figure 1. Framework for policy-impact analyses including three steps: 1) identifying potentially relevant factors for each fishery variable, 2) examining statistical effects of policies upon fishery variables, and 3) generalization and visualizing the influence of policy factors.

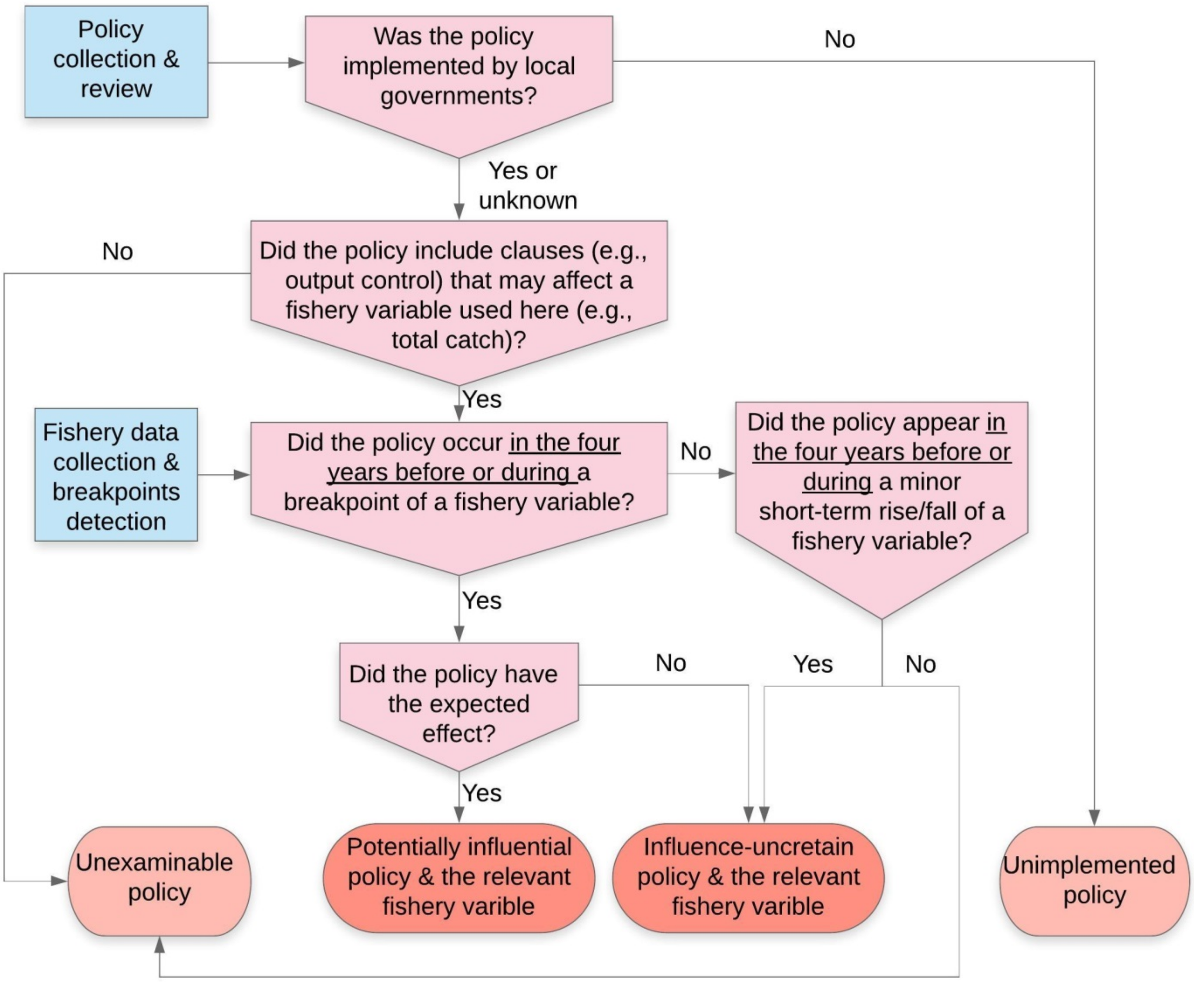

Figure 2. Decision tree for splitting policies into four categories: unexaminable policy, potentially influential policy, influence-uncertain policy, and unimplemented policy.

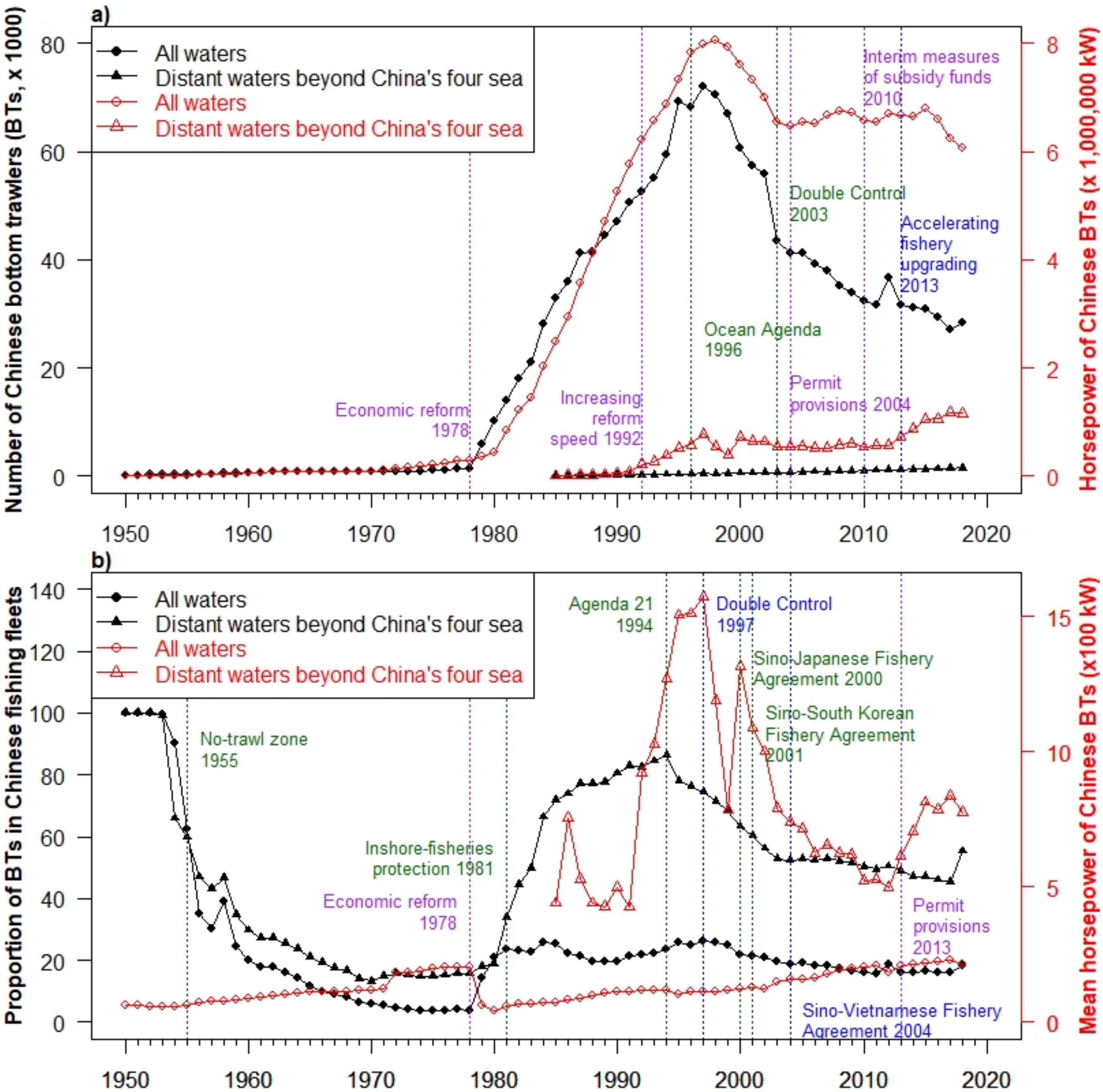

Figure 3. Timeseries of eight (out of 13) fishery variables for China's bottom trawlers (BTs) from 1950 to 2018 (see Table 1 for full list of fishery variables and Supplementary Fig. S2.3 for similar plots of the rest five variables). A total of 15 major policies with statistical effects are shown in dark green (policies with conservation-oriented effects), in purple (policies with growth-promoting effects), and blue (policies with diverse effects, both conservation-oriented and growth-promoting). See detailed explanation of each policy by a policy review (Zhang & Vincent, 2020).

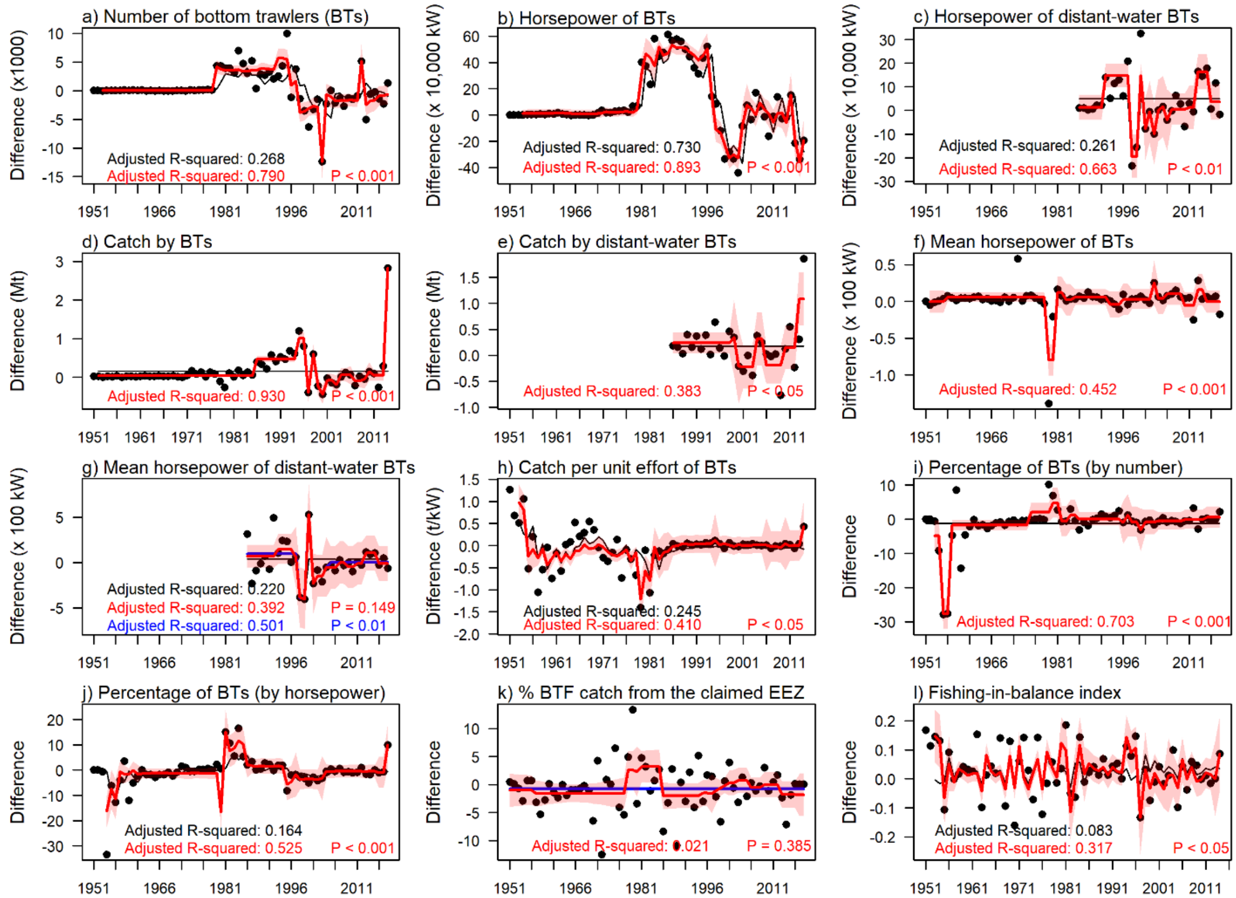

Figure 4. Comparisons between the prediction with the full model (red line, shade for 95% CI) or the optimal model (blue line in g & k) with that from the contrast model (black line) for each of the 12 fishery variables of China's bottom trawl fisheries (black dots). P values are given for the comparisons. The full model is built by adding all relevant policy factors to the contrast model. The optimal model is selected by a forward stepwise process (starting from the contrast model and ending at the full model), and it is conducted (in g & k) only if the full model does not differ significantly from the contrast model in explanation power. The annual difference of each fishery variable (y-axis) was used in the dynamic linear models. The adjusted R-squared values for different models are shown in colors that match the lines. Note there are no adjusted R-squared values for the contrast models in d, e, f, i, and k since the contrast models did not include any predictors; the contrast model and optimal model in k are the same.

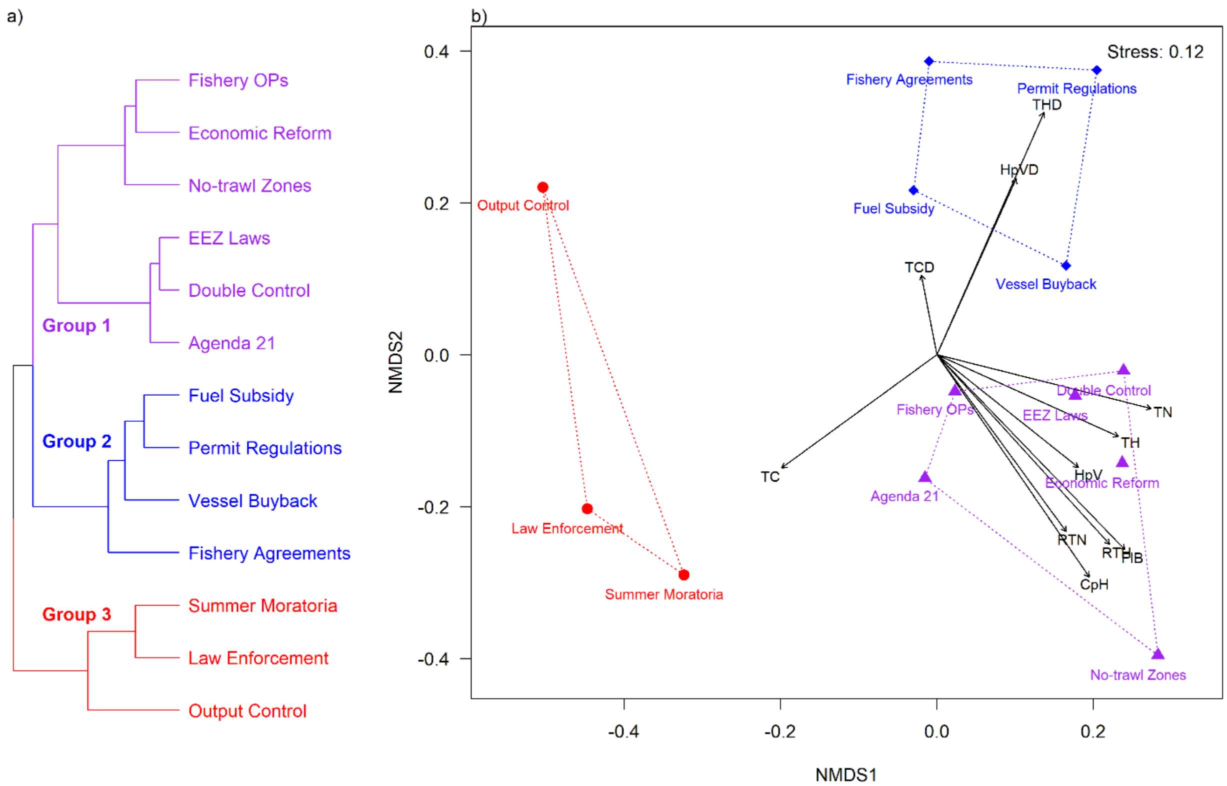

Figure 5. Agglomerative hierarchical cluster and ordination of 13 policy factors relevant to China's bottom trawl fisheries: a) the dendrogram of the policy factors based on the calculated Bray-Curtis dissimilarity and the Ward's minimum-variance linkage algorithm, and b) the non-parametric multidimensional scaling plot overlaid with the biplot of the corresponding fishery variables. Fishery OPs refers to fishery overarching policies specifically for fishery development and management in China. The 11 fishery variables are in black: TN, total number of bottom trawlers; TH, total horsepower of bottom trawlers; THD, total horsepower of distant-water bottom trawlers beyond China's four seas; HpV, horsepower per vessel of bottom trawlers; HpVD, horsepower per vessel of distant water bottom trawlers; RTN, Ratio of total number of bottom trawlers in all motorized marine catchers; RTH, ratio of total horsepower of bottom trawlers in all motorized marine catchers; TC, total catch by bottom trawlers; TCD, total catch by distant-water bottom trawlers; CpH, catch per unit horsepower per year by bottom trawlers; FIB, fishing-in-balance index of bottom trawl fisheries in China's claimed EEZ.

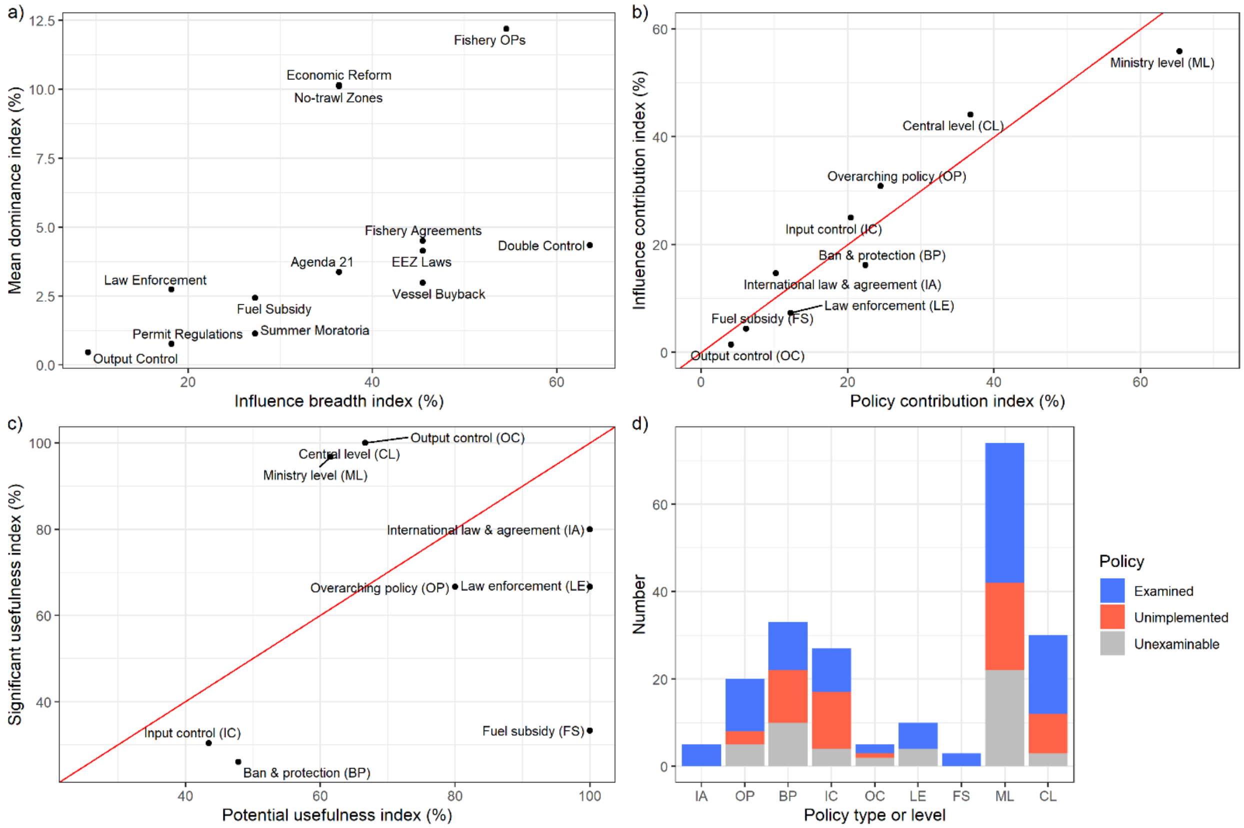

Figure 6. Distributions of a) fishery policy variables in the 2-D space of mean dominance index vs. influence breadth index; b) fishery policy types and levels in the 2-D space of influence contribution index vs. policy contribution index; c) fishery policy types and levels in the 2-D space of significant usefulness index and influence contribution index; and d) the total number of examined, unimplemented, and unexaminable policies across the seven policies types and two policy levels. Abbreviations for Fig d can be found in Fig b & c.

Supplementary Information

Appendix S1 Supplementary Information for Methods

Detailed approaches for detecting break points in Step One

We used three approaches to detect break points.

Our first approach was exploring break points in segmented linear regressions based on the 'Bellman principle of optimality' (function 'breakpoints' in r package 'strucchange') (Zeileis et al., 2001). This optimization algorithm detected the minimum number of breakpoints (or segments) based on the lowest Bayesian information criterion (BIC) score. We chose three as the minimum number of data points for each linear regression segment and allowed variable regression slopes for different segments.

Given that a trend could be non-linear, we used a second technique of detecting 'outliers' in fitting local polynomial regression models with a span of 0.6 to the selected variables (function 'loess' in r) (Balke & Fomby, 1994; Cottrell et al., 2019). We detected the 'outliers' based on deviations in autocorrelation, which is a commonly used method in spatial statistics and has been adapted to examine shocks in timeseries (Anselin, 1995; Gephart et al., 2017). This was done by regressing model residuals against lag-1 residuals and determined outliers in the regression where the Cook's distances of data points were higher than specific thresholds (Gephart et al., 2017). We plotted the total number of outliers identified to a range of distance thresholds (0.05 – 1, interval = 0.05; function 'cooks.distance' in r package 'car'), and identified the specific threshold where the curve became flat (Gephart et al., 2017). We ultimately used different thresholds (mean ± SD, 0.22 ± 0.02) for different variables.

We were aware that the above approaches might not be applicable for identifying break points or outliers in highly variable factors where the time series had many fluctuations (Cottrell et al., 2019). To fill this gap, our third approach was to inspect data visually to identify additional abrupt fluctuations on the time series plots.

Rationale for the five-year rule in Step One

In our analysis in Step One, we focused on detecting effects in the four years after each given policy came into effect. We made this decision for two reasons. First, China's top-down government regime (i.e. command and control) demands quick policy implementation. Second, Chinese leaders have five-year terms, leading them often to manage economic sectors (including fisheries) with five-year plans. Note that a policy could be potentially influential for one fishery variable but influence-uncertain or unexaminable to another. We identified all potentially influential and influence-uncertain policies for each fishery variable and their effects (i.e., potentially positive, potentially negative, and uncertain).

Conversion of policy data and fishery timeseries in Step Two

To prepare the predictor and response datasets for dynamic linear models, we conducted considerable data conversion.

We first converted the relevant policies and other external factors into categorical variables. Many policies or public factors only had two states (e.g. financial crises), either 0 (absent or expired) and 1 (present). However, a policy that was repeatedly introduced (e.g., summer moratorium policies in different years) was considered to have multiple states, starting from 0 (absent or expired) to a higher integer (1, 2, 3, ...) for each repetition across the years. We used these integers only for the ease of coding the differences and they were treated as categorical factors rather than true values of numerical levels in the regression. For those policies that were correlated and came into effect in the same year, we could not discriminate them with a categorical variable and only used one integer to represent them. For instance, Outline 2006 (for aquatic life conservation) and the MOA's Opinions on Implementing the Outline 2006 were two policy documents issued in the same year (Zhang & Vincent, 2020). We integrated them (with other fishery overarching policies) into one policy factor (i.e. Fishery Overarching Policies) and assigned a single integer (level = 4) to represent both policies (Table S2.1), since their relative effects on the annual response variables (e.g. total landings by BTF) could not be discriminated. Therefore, the detected results of the effects of this policy factor (Fishery Overarching Policies) at level 4 should be viewed as the combined effect of both policies.

We determined the effect time lag for each pair of policy factor and fishery variable. This was done by comparing (i) the year when the policy came into effect with (ii) the breakpoint year of the fishery variable. We recognized that multiple policies contained in a policy factor may have different time lags on the same fishery variable. For instance, a policy factor P = (0,0,1,1,1,2,2,2,3,3,3) was used to represent the emergences of three consecutive policies (P1, P2, and P3) with the same approach (e.g. fishing permit regulations); and we detected this policy factor to have potential influence on a fishery variable F (e.g. number of vessels). Suppose both P1 and P2 had a time lag = 1, while P3 had a time lag = 2. If we simply assign time lag = 1 for the policy factor P while building our regression model, it will not correctly estimate the effect of P3 on F. To solve this problem, we manually shifted the first value of P3 (=3) in the vector of P one year backward so that we can then use time lag = 1 for all three policies. This resulted a new vector P' = (0,0,1,1,1,2,2,2,2,3,3). We then use this new vector with a time lag = 1 to build regression models.

Our regression was built to examine the impact of policy and other external factors on change in the focal fishery variable across consecutive years (i.e., in terms of annual change). Therefore, we converted the original fishery variables to a new timeseries of such difference values (e.g., $\Delta Y = y_2 - y_1, y_3 - y_2, y_4 - y_3, ..., y_n - y_{n-1}$, where Y is a fishery variable, y_n refers to its value in year n). In this way, the converted fishery variable started from the second year as there was no difference value for the first year.

Additional analyses based on model results in Step Two

We discriminated policies into five groups based on their statistical effects in the dynamic linear models: (i) conservation-oriented policies, (ii) growth-promoting policies, (iii) efficiency-promoting policies, (iv) efficiency-reducing policies, and (iv) diverse-effect policies. The conservation-oriented policies (vs. growth-promoting policies) were policies that were associated with significant negative (vs. positive) effects on at least one of the growth indicators of China's BTF: (i) fishing capacity, (ii) yield, (iii) capacity (or yield) ratio of BTF in China's marine capture fisheries, (iv) mean horsepower, and (v) fishing-in-balance (FIB) index. The efficiency-promoting policies (vs. efficiency-reducing policies) were associated with significant positive (vs. negative) effects on CPUE (catch per unit horsepower per year) of China's BTF. The diverse-effect policies were other policies which had more complicated effects that could fall into more than one of the above four groups.

We compared results between statistical analyses (based on dynamic linear models) and qualitative analyses (from Step One). To this end, we calculated three scores: (i) overestimation score, the percentage of potential positive/negative effects (identified in Step One) that was not statistically significant (in Step Two); (ii) underestimation score, the percentage of uncertain effects that was statistically significant; and (iii) misidentification score, the percentage of potential positive (or negative) effects that was statistically negative (or positive). The last one is possible given that the breakpoint-based effect examination in Step One could only detect potential 'acute' effects in a short period, while neglecting long-term changes, which could be better examined with regression models.

We examined whether adding policies could significantly improve the model quality (F-tests, r function 'anova'). We first compared the full model (including all relevant policy factors) with the contrast model (without any policy factors). If the full model did not perform significantly better than the contrast model, we used a forward selection process on the contrast model to identify a combination of predictors that derived an optimal model with the lowest values of the corrected Akaike information criterion (AICc) for small samples (r function 'stepAICc' based on the function 'stepAIC', r package 'MASS') (Hurvich & Tsai, 1989; Read et al., 2018; Ripley et al., 2013). The AICc is a goodness measure of model fit penalized for the number of selected parameters and has been widely used in model selection for small sample sizes (Burnham & Anderson, 2004; Hurvich & Tsai, 1989). The forward selection was executed from the contrast model to the full model, in an iterative randomized fashion in terms of predictor involvement. We then examined whether the optimal model performed significantly better than the contrast model (F-tests).

We measured the relative importance of each policy predictor to its response variable based on the dominance analysis (function 'dominanceAnalysis' in r package 'dominanceanalysis') (Budescu, 1993; Bustos & Soares, 2019). This analysis measures the average contribution to explain model variances across all subset models of the full model for predicting the fishery variable of interest. Based on this analysis, we built a dominance matrix consisted of the dominance scores of policy factors (rows) to their relevant fishery variables (columns). We only did this for the fishery variable if its full model (or optimal model included policy factors) explained significantly more variance than its contrast model (without policies). Because there were irrelevant policies not included in the full model for each fishery variable, these policy factors would have no scores in the derived dominance matrix. We filled these absences with zeros. This dominance matrix was then used in Step Three.

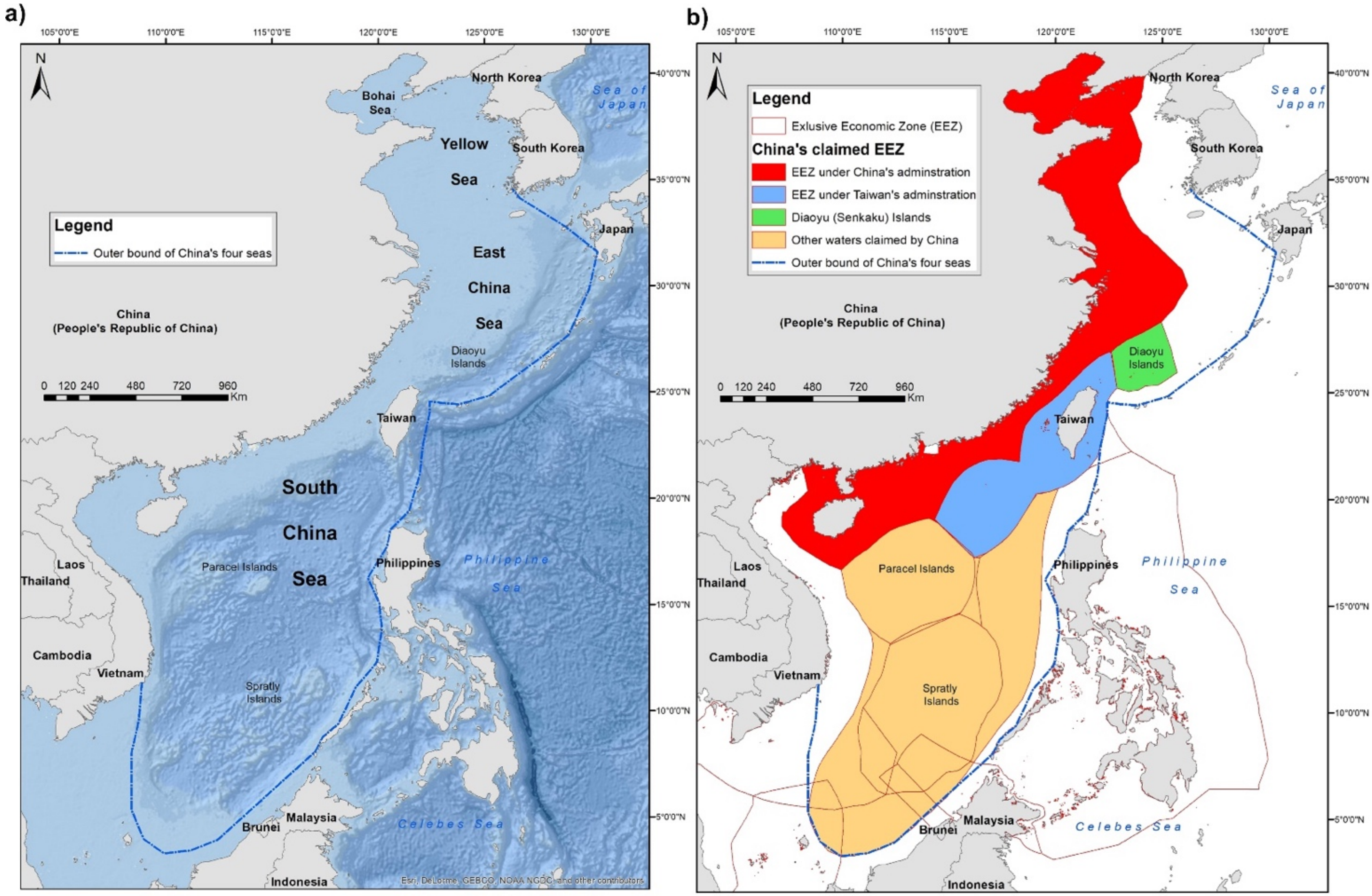

Figure S1.1. The four coastal seas and Exclusive economic zone (EEZ) claimed by China (the People's Republic of China).

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Appendix S2 Supplementary Information for Results

Table S2.1. A matrix of the 49 examined policies relevant to 13 fishery variables in China's bottom-trawl fisheries. The policy types included seven categories: international law & agreement (IA), (domestic) overarching policy (OP), ban & protection (B&P), input control (IC), output control (OC), law enforcement (LE), and fuel subsidy (FS). The fishery variables contain 12 variables: TN, total number of bottom trawlers; TH, total horsepower of bottom trawlers; THD, total horsepower of bottom trawlers operating in distant waters beyond C4S; HpV, horsepower per vessel of bottom trawlers; HpVD, horsepower per vessel of distant-water bottom trawlers beyond C4S; TC, total catch by bottom trawlers, TCD, total catch by distant-water bottom trawlers beyond C4S; RN, ratio of bottom trawlers in all motorized catchers by number; RH, ratio of bottom trawlers in all motorized catchers by horsepower; RC, ratio of catch by bottom trawlers in all catches from China's claimed EEZs; CpH, catch per unit horsepower per year, FIB, fishing-in-balance index of bottom trawl fisheries in China's claimed EEZs. The lag value shown in the bracket after each fishery variable indicates the time lag of the effect.

Effective Date (yyyy-mm-dd)	Policy Level	Policy Type	Policy	Policy factor (categorical)	Fishery variable
1955-5-8	State	B&P	No-trawl zone 1955	No-trawl Zones (L=1)	HpV (Lag=1), CpH, RN, RH, FIB
1957-07-26	State	B&P	No-trawl zone extension 1957	No-trawl Zones (L=2)	CpH, RN, RH, RC, FIB
1975-12-22	State	IA	Sino-Japanese Fishery Agreement 1975	Fishery Agreements (L=1)	RN
1978-12-13	State	OP	Economic reform 1978	Economic Reform (L=1)	TN (Lag=1), TH (Lag=3), HpV (Lag=1), CpH (Lag=1), RN (Lag=2), RH (Lag=3), RC (Lag=1), FIB (Lag=2)
1980-01-01	State	B&P	No-trawl zone extension 1980	No-trawl Zones (L=3)	HpV (Lag=1), RC, FIB
1981-05-04	State	OP	Inshore-fisheries protection 1981	Fishery OPs (L=1)	HpV, TH, CpH (Lag=1), RN (Lag=1), RH (Lag=1), FIB (Lag=1)
1983-09-01	State	OP	Marine fishery policy 1983	Fishery OPs (L=2)	HpV, TH, CpH (Lag=1), RN (Lag=1), RH (Lag=1), FIB (Lag=1)
1985-03-11	State	OP	Accelerating fisheries development 1985	Fishery OPs (L=3)	HpV, TH, TC (Lag=1), CpH (Lag=1), RN (Lag=1), RH (Lag=1), RC (Lag=1), FIB (Lag=1)
1992-01-18	State	OP	Increasing reform speed 1992	Economic Reform (L=2)	TN (Lag=1), THD, HpV (Lag=1), HpVD, FIB (Lag=2)
1994-03-25	State	OP	China 21st Century Agenda 1994	Agenda 21 (L=1)	TH (Lag=1), TC (Lag=1), RH (Lag=1)
1995-02-07	State	B&P	Summer moratorium 1995	Summer Moratoria (L=1)	TC, CpH, RH, RC
1996-04-01	Ministry	OP	China 21st Century Ocean Agenda 1996	Agenda 21 (L=2)	TN, TH (Lag=1), TC (Lag=1), HpV, RH (Lag=1)
1996-05-15	State	OP	UNCLOS Ratification 1996	EEZ Laws (L=1)	TC (Lag=1), CpH, TN, TH, HpVD (Lag=1), RN, FIB (Lag=1)
1997-04-28	State	IC	Double Control 1997	Double Control (L=1)	TN (Lag=1), TH (Lag=1), HpVD (Lag=1), RN, RH (Lag=1), RC (Lag=1), FIB (Lag=1)
4/2/1998	Ministry	B&P	Summer moratorium 1998	Summer Moratoria (L=2)	TC, RC

Effective Date (yyyy-mm-dd)	Policy Level	Policy Type	Policy	Policy factor (categorical)	Fishery variable
1998-06-26	State	OP	EEZ Law 1998	EEZ Laws (L=2)	TC (Lag=1), HpVD (Lag=1), RN, FIB (Lag=1)
1999-01-01	Ministry	OC	Zero Growth 1999	OutCon (L=1)	TC, TCD
1999-01-01	Ministry	B&P	Summer moratorium 1999	Summer Moratoria (L=3)	TC, RC
2000-01-01	Ministry	OC	Negative Growth 2000	OutCon (L=2)	TC, TCD
2000-01-01	Ministry	B&P	Summer moratorium 2000	Summer Moratoria (L=4)	TC, RC
2000-06-01	Ministry	IA	Sino-Japanese Fishery Agreement 2000	Fishery Agreements (L=2)	HpVD (Lag=1), TC, TCD, THD (Lag=1), RN
2000-01-01	Ministry	B&P	Summer moratorium 2001	Summer Moratoria (L=5)	TC, RC
2001-06-03	Ministry	IA	Sino-South Korean Fishery Agreement 2001	Fishery Agreements (L=3)	TCD, THD (Lag=1), HpVD (Lag=1), RN
2002-06-23	Ministry	IC	Vessel-scrapping interim provisions 2002	Vessel Buyback (L=1)	TN (Lag=1), THD (Lag=1), HpV (Lag=1), RH (Lag=1), FIB (Lag=1)
2002-07-30	Ministry	IC	Fisher-transfer interim measures 2002	Vessel Buyback (L=1)	TN (Lag=1), THD (Lag=1), HpV (Lag=1), RH (Lag=1), FIB (Lag=1)
2003-01-01	Ministry	B&P	Summer moratorium 2003	Summer Moratoria (L=6)	TC, RC
2003-09-18	Ministry	IC	Fisher-transfer provisions 2003	Vessel Buyback (L=2)	TN (Lag=1), THD (Lag=1), TH (Lag=1), HpV (Lag=1), HpVD (Lag=1), RH (Lag=1), FIB (Lag=1)
2003-11-12	Ministry	IC	Double Control 2003	Double Control (L=2)	TN (Lag=1), TH (Lag=1), HpVD (Lag=1), RH (Lag=1), RC (Lag=1), FIB (Lag=1)
2004-06-30	State	IA	Sino-Vietnamese Fishery Agreement 2004	Fishery Agreements (L=4)	TC, TCD, THD (Lag=1), HpVD (Lag=1), RN
2004-07-01	Ministry	IC	Permit provisions 2004	Permit Regulations (L=1)	TH (Lag=1), THD, FIB
2004-07-20	Ministry	IC	Permit-approval decentralization 2004	Permit Regulations (L=1)	TH (Lag=1), THD, FIB
2006-02-14	State	OP	Outline 2006	Fishery OPs (L=4)	TC (Lag=1), TCD, CpH (Lag=1), RC, FIB (Lag=1)
2006-04-17	Ministry	LE	*Protecting Fisheries 2006*	Law Enforcement (L=1)	CpH
2006-05-01	Ministry	B&P	Summer moratorium 2006	Summer Moratoria (L=7)	TC, RC
2006-05-15	Ministry	OP	MOA's Opinions on Implementing the Outline 2006	Fishery OPs (L=4)	TC (Lag=1), TCD, CpH (Lag=1), RC, FIB (Lag=1)
2006-05-30	State	FS	Fuel subsidy opinions 2006	Fuel Subsidy (L=1)	TH, THD (Lag=1), HpV
2007-03-27	Ministry	LE	*Protecting Fisheries 2007*	Law Enforcement (L=2)	TC
2009-03-23	Ministry	LE	*Protecting Fisheries 2009*	Law Enforcement (L=3)	TC

Effective Date (yyyy-mm-dd)	Policy Level	Policy Type	Policy	Policy factor (categorical)	Fishery variable
2009-05-01	Ministry	B&P	Summer moratorium 2009	Summer Moratoria (L=8)	TC, RC
2010-01-01	Ministry	FS	Interim measures of fuel-subsidy funds 2010	Fuel Subsidy (L=2)	TN (Lag=2), TH, THD (Lag=1), TC, TCD, HpV, RN
2010-02-05	Ministry	LE	*Protecting Fisheries 2010*	Law Enforcement (L=4)	TC, CpH
2011-04-02	Ministry	LE	*Protecting Fisheries 2011*	Law Enforcement (L=5)	TC, CpH
2013-01-01	Ministry	IC	Permit provisions 2013	Permit Regulations (L=2)	THD, HpV, HpVD, FIB
2013-03-08	State	OP	Opinions 2013	Fishery OPs (L=5)	TN, TH, THD, HpV, HpVD, TC (Lag=1), TCD, CpH, RC, FIB (Lag=1)
2013-07-05	Ministry	OP	Detailed rules for implementing Opinions 2013	Fishery OPs (L=5)	TN, TH, THD, HpV, HpVD, TC (Lag=1), TCD, CpH, RC, FIB (Lag=1)
2014-01-28	Ministry	LE	Implementing minimum-mesh-size standards & forbidden gears 2014	Law Enforcement (L=6)	CpH, TC,
2015-09-06	Ministry	FS	Subsidy reduction 2015	Fuel Subsidy (L=3)	TH, THD (Lag=1), HpV, HpVD (Lag=1)
2015-11-09	Ministry	IC	Vessel scraping and standardization 2015	Vessel Buyback (L=3)	TN (Lag=1), THD (Lag=1), TH (Lag=1), RH (Lag=1)
2017-01-12	Ministry	IC	Double Control 2017	Double Control (L=3)	HpV (Lag=1), RH (Lag=1)

Table S2.2. Policy-effect matrix indicating potential effect (P) and statistically significant effect (S) on 12 fishery variables: TN, total number of bottom trawlers; TH, total horsepower of bottom trawlers; THD, total horsepower of bottom trawlers operating in ‘distant waters’; HpV, horsepower per vessel of bottom trawlers; HpVD, horsepower per vessel of distant-water bottom trawlers beyond C4S; TC, total catch by bottom trawlers, TCD, total catch by distant-water bottom trawlers; RN, ratio of bottom trawlers in all motorized catchers by number; RH, ratio of bottom trawlers in all motorized catchers by horsepower; RC, ratio of catch by bottom trawlers in all catches from China’s claimed EEZs; CpH, catch per unit horsepower, FIB, fishing-in-balance index of bottom trawl fisheries in China’s claimed EEZs. The three types of potential effects (P): +, potentially positive; -, potentially negative; 0, influence-uncertain. Three types of statistical effects (S): +, significant positive; -, significant negative; N, not significant. The policy groups: (i) conservation-oriented policy (COP), (ii) growth-promoting policy (GPP), (iii) efficiency-promoting policy (EPP), (iv) efficiency-reducing policy (ERP), and (iv) diverse-effect policy (ECP).

Policy factor (categorical)	TN		TH		THD		TC		TCD		HpV		HpVD		CpH		RN		RH		RC		FIB		Group
	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	
No-trawl Zones (L=1)											+	N			-	N	-	-	+	N			-	-	COP
No-trawl Zones (L=2)															-	N	-	N	+	N	-	N	-	-	COP
Fishery Agreements (L=1)																	0	+							GPP
Economic Reform (L=1)	+	+	+	N							-	N			-	-	+	+	+	N	+	N	+	N	DEP (GPP, ERP)
No-trawl Zones (L=3)											+	N									-	-	0	N	COP
Fishery OPs (L=1)			+	N							+	N			-	N	-	-	-	N			-	N	COP
Fishery OPs (L=2)			+	N							+	N			-	N	0	N	+	N			+	N	NS
Fishery OPs (L=3)			+	N			+	+			+	N			+	N	-	N	-	N	-	N	+	N	GPP
Economic Reform (L=2)	+	+			+	+					+	N	+	N									+	N	GPP
Agenda 21 (L=1)			-	N			+	+											-	-					DEP (COP, GPP)
Summer Moratoria (L=1)							+	-							+	+			-	N	-	N			DEP (COP, EPP)
Agenda 21 (L=2)	-	-	-	-			-	-			+	N							-	N					COP
EEZ Laws (L=1)	-	-	-	N			-	+					0	N	-	-	-	N					-	-	DEP (GPP, ERP, COP)
Double Control (L=1)	-	-	-	-									-	N			-	+	-	-	-	N	0	-	DEP (COP, GPP)
Summer Moratoria (L=2)							+	N													-	+			GPP
EEZ Laws (L=2)							-	N					0	N			-	-					-	-	COP
Output Control (L=1)							-	N	+	N															NS
Summer Moratoria (L=3)							+	N													-	-			COP
Output Control (L=2)							-	N	-	-															COP
Summer Moratoria (L=4)							+	N													0	+			GPP
Fishery Agreements (L=2)			-	N	-	-	-	-	-	-			-	-			-	N							COP
Summer Moratoria (L=5)							+	N													0	N			NS

Policy factor (categorical)	TN		TH		THD		TC		TCD		HpV		HpVD		CpH		RN		RH		RC		FIB		Group
	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	P	S	
Fishery Agreements (L=3)			-	N	-	-	-	N	-	-			-	-			-	N							COP
Vessel Buyback (L=1)	-	-			-	-					0	+							-	N			0	-	DEP (COP, GPP)
Vessel Buyback (L=1)	-	-			-	-					0	+							-	N			0	-	DEP (COP, GPP)
Summer Moratoria (L=6)							+	N													-	N			NS
Vessel Buyback (L=2)	0	N	0	N	0	N					0	N	+	N					0	N			0	N	NS
Double Control (L=2)	-	-	+	N									+	+					0	N	+	N	0	N	DEP (COP, GPP)
Fishery Agreements (L=4)					+	-	-	N	-	N			-	-			0	+							DEP (COP, GPP)
Permit Regulations (L=1)			+	N	+	+																	+	N	GPP
Fishery OPs (L=4)							-	N	+	N					0	N					0	N	-	N	NS
Law Enforcement (L=1)															0	N									NS
Summer Moratoria (L=7)							+	N													0	N			NS
Fishery OPs (L=4)							-	N	+	N					0	N					0	N	-	N	NS
Fuel Subsidy (L=1)			+	N	+	N					+	N													NS
Law Enforcement (L=2)							+	N																	NS
Law Enforcement (L=3)							+	+																	GPP
Summer Moratoria (L=8)							+	N													0	N			NS
Fuel Subsidy (L=2)	+	+	+	N	+	+	+	+	+	N	+	N					+	N							GPP
Law Enforcement (L=4)							-	-							0	+									DEP (COP, EPP)
Law Enforcement (L=5)							-	-							0	N									COP
Permit Regulations (L=2)					+	+					-	N	+	+									+	N	GPP
Fishery OPs (L=5)	-	-	-	N	+	+	+	N	+	N	-	N	+	N	+	+					-	N	+	N	DEP (COP, GPP, EPP)
Fishery OPs (L=5)	-	-	-	N	+	+	+	N	+	N	-	N	+	N	+	+					-	N	+	N	DEP (COP, GPP, EPP)
Law Enforcement (L=6)							+	N							+	+									EPP
Fuel Subsidy (L=3)			-	N	-	N					0	N	-	N											NS
Vessel Buyback (L=3)	-	N	-	N	-	N													0	N					NS
Double Control (L=3)											-	-							0	+					DEP (COP, GPP)

Table S2.3. Unexaminable policies (UE, n = 25) and unimplemented policies (UI, n = 29) among the national policies affecting bottom trawl fisheries in China.

Effective Date	**Policy Level**	**Policy Type**	**Policy**	**Category**
1962-07-01	State	Ban & protection	Shrimp protection regulations in Bohai 1962	UE
1963-10-01	State	Ban & protection	No-trawl zone extension 1963	UE
1975-01-01	Ministry	Ban & protection	Fish & shrimp protection regulations in Bohai 1975	UE
1979-02-10	State	Ban & protection	Stock protection regulations 1979	UI
1979-12-24	Ministry	Ban & protection	Trawl ban in Bohai 1979	UI
1980-01-01	Ministry	Ban & protection	Summer moratorium 1980	UI
1980-01-01	Ministry	Output control	Juvenile-catch ratio 1980	UI
1981-01-01	Ministry	Ban & protection	Stock protection provisions in Bohai 1981	UI
1981-04-01	Ministry	Ban & protection	Summer moratorium 1981	UI
1981-04-22	State	Ban & protection	Fishery-conservation areas 1981	UI
1983-10-31	Ministry	Input control	Vessel-management interim measures 1983	UI
1986-07-01	State	Overarching policy	Fisheries Law 1986	UI
1987-05-01	Ministry	Ban & protection	Trawl ban in Bohai 1987	UI
1987-05-01	Ministry	Ban & protection	Summer moratorium 1987	UI
1987-05-01	Ministry	Input control	Single Control 1987	UI
1987-10-04	Ministry	Overarching policy	Fisheries Law implementation rules 1987	UI
1989-01-01	State	Input control	Resource fee 1989	UI
1989-05-01	Ministry	Input control	Permit-management measures 1989	UI
1989-05-01	State	Ban & protection	Fishery-conservation areas 1989	UI
1990-07-01	State	Input control	Minimum-mesh-size standards 1990	UI
1990-11-08	Ministry	Ban & protection	Protecting spawning shrimps 1990	UI
1991-04-13	Ministry	Ban & protection	Stock protection provisions in Bohai 1991	UI
1992-01-01	Ministry	Ban & protection	Summer moratorium 1992	UI
1996-01-22	Ministry	Input control	Vessel registration measures1996	UI
1997-12-25	Ministry	Input control	Permit management measures 1997	UI
1997-12-25	Ministry	Input control	Vessel registration measures 1997	UI
2000-12-01	State	Overarching policy	Fisheries Law 2000	UI
2001-10-20	State	Overarching policy	Distant-water fisheries plan (2001 - 2010)	UE
2002-12-01	Ministry	Input control	Permit provisions 2002	UI
2003-08-01	State	Input control	Vessel-inspection regulations 2003	UI
2004-05-01	Ministry	Ban & protection	Conservation regulations in Bohai 2004	UE
2004-07-01	Ministry	Input control	Minimum-mesh-size standards 2004	UI
2005-07-04	Ministry	Ban & protection	Prohibiting gear switch in moratoria 2005	UE
2005-07-20	Ministry	Ban & protection	Enhancing moratorium management 2005	UE
2005-08-03	State	Input control	Minimum-mesh-size standards 2005	UI
2006-11-07	Ministry	Overarching policy	The 11th Five-Year Plan for Fisheries	UE
2011-03-01	Ministry	Ban & protection	Conservation-area measures 2011	UE
2011-03-11	Ministry	Input control	Double Control 2011	UI

Effective Date	**Policy Level**	**Policy Type**	**Policy**	**Category**
2011-10-17	Ministry	Overarching policy	The 12th Five-Year Plan for Fisheries	UE
2014-01-01	Ministry	Ban & protection	Forbidden gears 2014	UE
2014-06-01	Ministry	Input control	Minimum mesh size standards 2014	UE
2015-01-01	Ministry	Input control	Resource fee exemption 2015	UE
2015-02-12	Ministry	Input control	Detailed rules for resource-fee exemption 2015	UE
2016-04-25	Ministry	Law enforcement	Combating illegal fishing gears 2016	UE
2016-05-04	Ministry	Ban & protection	Advancing fisheries transformation 2016	UE
2016-08-02	Ministry	Law enforcement	Provisions on hearing illegal-fishing cases 2016	UE
2017-01-12	Ministry	Output control	Total allowable catch 2017	UE
2017-01-19	Ministry	Ban & protection	Optimized summer moratorium 2017	UE
2017-02-20	Ministry	Overarching policy	The 13th Five-Year Plan for Fisheries	UE
2017-04-17	Ministry	Law enforcement	Combating illegal fishing gears 2017	UE
2017-10-10	Ministry	Overarching policy	The 13th Five-Year Plan for Distant-Water Fisheries	UE
2018-02-12	Ministry	Output control	Catchable size & juvenile ratio 2018	UE
2018-11-02	Ministry	Law enforcement	Combating illegal fishing gears 2018	UE
2018-12-14	Ministry	Input control	Permit provisions 2018	UE

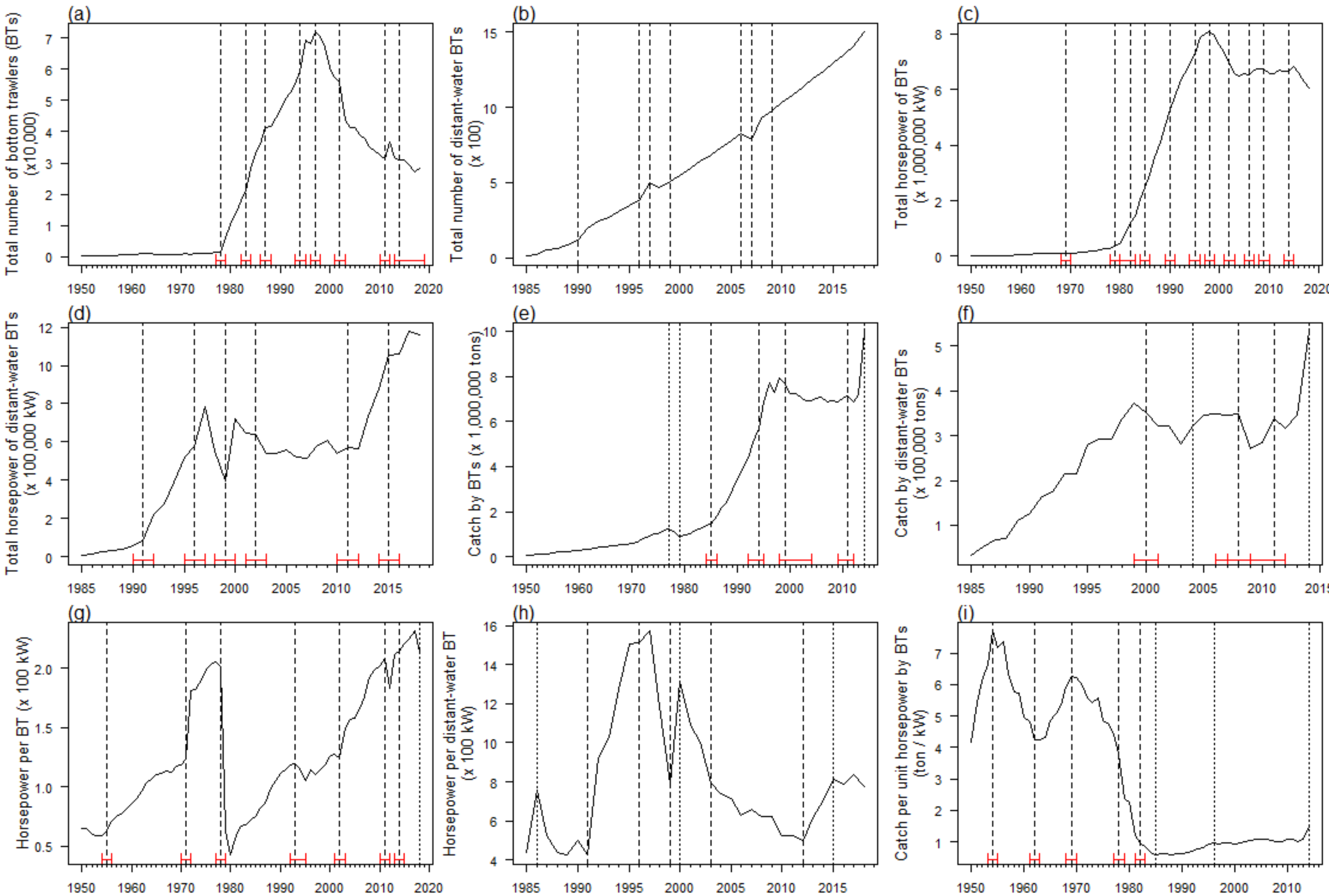

Figure S2.1. Breakpoints (vertical dotted lines) identified for nine fishery variables: a) total number of bottom trawlers (BTs); b) total number of distant-water BTs beyond C4S; c) total horsepower of BTs; d) total horsepower of distant-water BTs beyond C4S; e) catch by BTs; f) catch by distant-water BTs beyond C4S; g) horsepower per BT; h) horsepower per distant-water BT beyond C4S; and i) catch per unit horsepower per year by BTs.

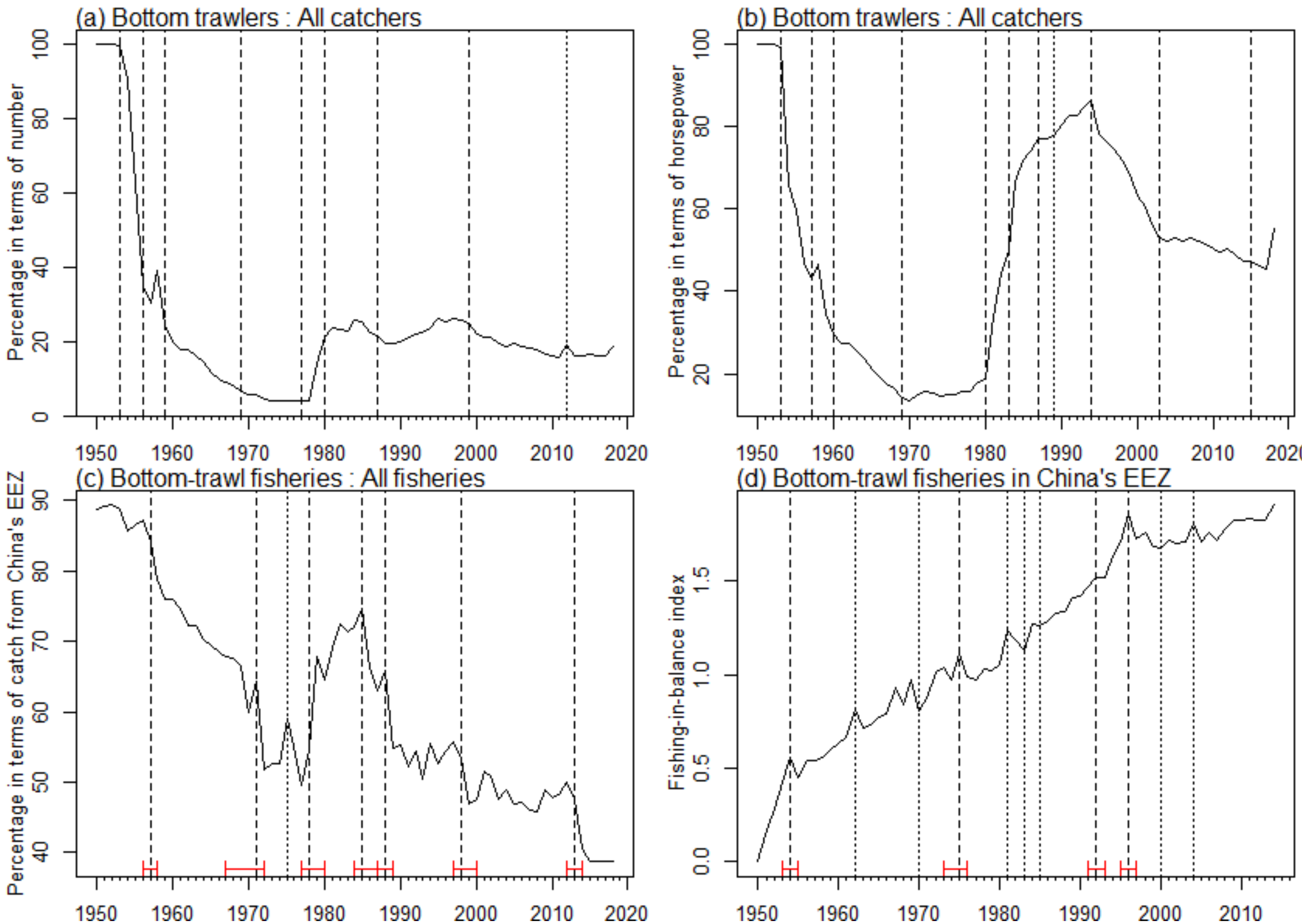

Figure S2.2. Breakpoints (vertical dotted lines) identified for four fishery variables: a) Percentage of bottom trawlers in all marine catchers (by number); b) Percentage of bottom trawlers in all marine catchers (by horsepower); c) Percentage of catch from China's claimed EEZ contributed by bottom-trawl fisheries; and d) fishing-in-balance (FIB) index of bottom-trawl fisheries in China's claimed EEZ.

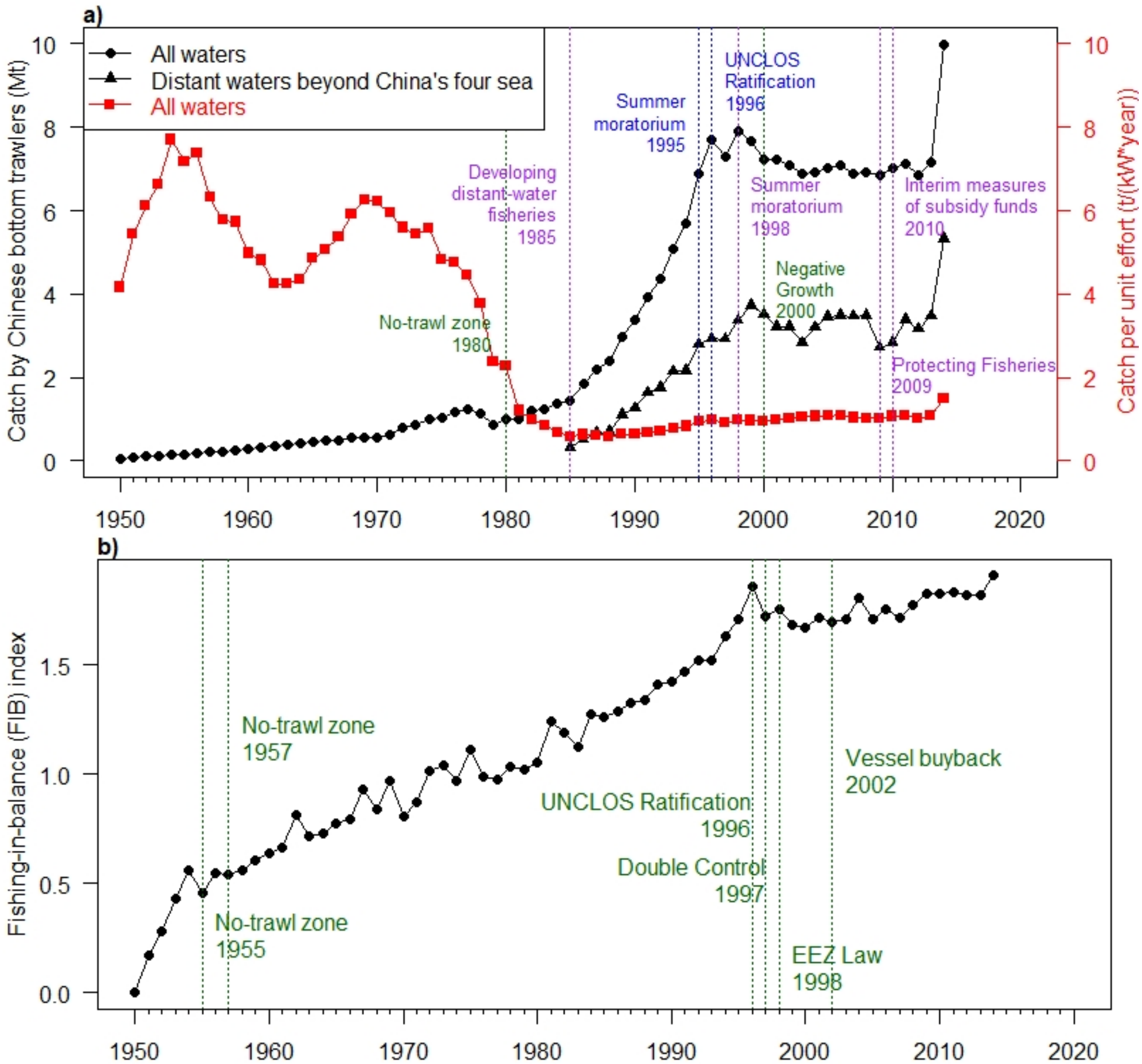

Figure S2.3. Timeseries of four fishery indices for China's bottom trawlers (BTs) from 1950 to 2018: a) catch and catch per unit effort; and b) fishing-in-balance index. Twelve major policies with statistical effects were shown in purple (policies with growth-promoting effects), dark green (policies with conservation-oriented effects), and blue (policies with both growth-promoting and conservation effects).

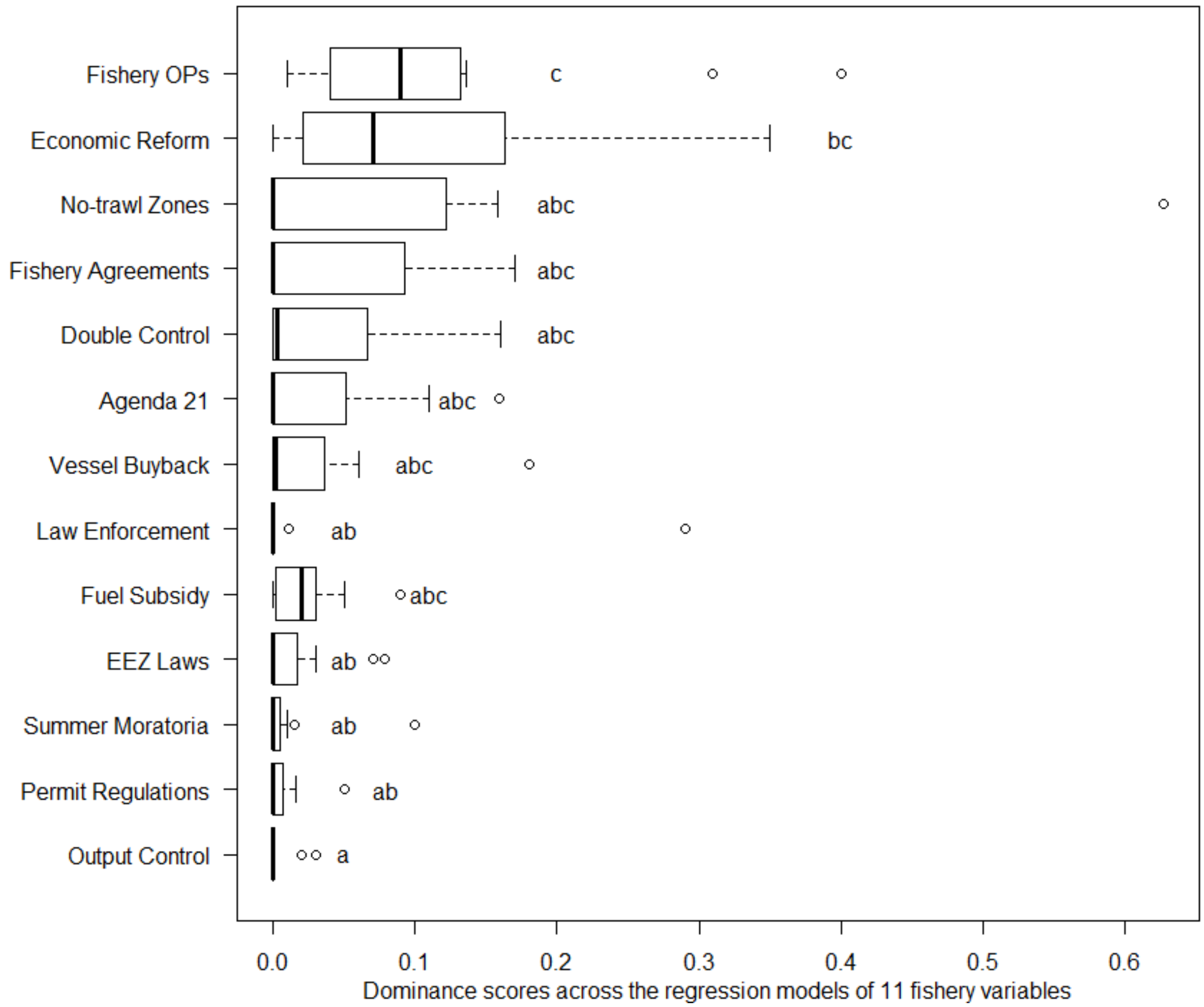

Figure S2.4. Dominance scores of the 13 explanatory policy factors across the linear regression models for 11 fishery variables. The levels of dominance (a, b, and c) are shown based on Pairwise Wilcox tests at a significance level of 0.05. The 13 explanatory policy factors were described in Table 4 of the main text.