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Research article

Comparing voluntary and government-mandated management measures for meeting sustainable fishing targets

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ABSTRACT

Management of natural resources and environmental systems has often involved top-down approaches in which government agencies set and enforce regulations on extractive activities. More recently, market-driven approaches were introduced to incentivise producers to voluntarily engage in practices that align with management objectives and support regulations. For the first time, we compare government and voluntary approaches within fisheries management systems and quantify their relative influences on the sustainability status of fish populations. Voluntary measures include eco-certification against the Marine Stewardship Council's (MSC) Fisheries Standard and Fishery Improvement Projects (FIP). Government-mandated measures are implemented for individual populations, or else at national and international levels. Using a hierarchical time series analysis, we treated each of these measures as independent interventions potentially affecting trends in fishing pressure and biomass of nearly 300 populations. Supporting earlier findings, we confirmed a strong effect of government rebuilding plans in sharply reducing fishing pressure and allowing population biomass to recover. Other government-mandated measures further contributed to reducing fishing pressure. While simultaneously accounting for government measures, we found that biomass increases were associated with stronger incentives generated by voluntary measures. This influence was attributed to the opening of conditions of certification or suspension of certification for MSC fisheries, while no clear influence was attributed to FIPs. MSC certification was rarely observed in the absence of strong government-mandated measures, however, suggesting that sustainability-related incentives associated with voluntary measures can promote more desirable environmental outcomes for target stocks if used in parallel with more conventional approaches to management of natural resources.

1. Introduction

Around the world, diverse approaches are taken to ensure a desirable balance between the extraction of natural resources for human use and avoidance of over-depleting these resources. In fisheries, this balance typically involves the capture of fish to meet seafood consumption demand while simultaneously avoiding overfishing of target fish populations and mitigating harmful impacts on broader marine ecosystems (Beddington et al., 2007). Common approaches to achieving this balance involve a variety of fisheries management measures, normally implemented by government agencies, which may be applied at a national or regional level, or for individual fish populations (Cochrane and Garcia, 2009; Langhammer et al., 2024). When fisheries management regulations are based on sound science and properly enforced, fish

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populations are usually fished within sustainable limits, or if they do become depleted, usually rebuild if fishing pressure is relaxed (Hilborn et al., 2020; Worm et al., 2009). Conventional fisheries management systems aimed at controlling fishing pressure have developed gradually over the past half-century and have generally been backed by national government agencies or international agreements (Melnychuk et al., 2021).

Though top-down governance systems can involve industry participation and co-management to varying degrees (e.g., Evans et al., 2011), market-based incentives were introduced as a complementary approach to increase industry buy-in, incentivise compliance with existing regulations, and even improve upon them through self-regulation or through advocacy targeting governing institutions to adopt new or stronger measures (Komives and Jackson, 2014; UNFSS, 2012). Market-based approaches may consist of a variety of measures and are adopted voluntarily by the fishing industry. One such measure is 'eco-certification' of products derived from natural resources, requiring that the harvesters involved adhere to a set of standards which align with more sustainable resource extraction practices (Roheim Wessels et al., 2001). Companies usually pay to be eco-certified, and in turn they may gain access to new markets or their certified products may fetch higher prices (Roheim et al., 2018). Especially in marine systems that are characterised by high implementation uncertainty (e.g., Link et al., 2012; Privitera-Johnson and Punt, 2020), outcomes of government regulations are intrinsically more uncertain and voluntary measures may be an important complement to enhance implementation of management policies.

In fisheries, the Marine Stewardship Council (MSC) is the largest and most widely-recognised organisation providing science-based standards against which fishing fleets, supply chains, and their seafood products may be certified by external third-party assessors as sustainably caught (Foley and McCay, 2014). The MSC Fisheries Standard comprises numerous performance indicators within three principles related to the sustainability of target populations, wider environmental impacts, and effective management systems (MSC, 2018). The certification process is intended to incentivise producers to improve their practices through better compliance with regulations of conventional management systems. The number of fish populations (or 'stocks') caught by fisheries that are MSC-certified has increased rapidly over the past two decades (Fig. 1), particularly in Europe and the west coast of the United States including Alaska (Fig. A.1 of Appendix A).

Another voluntary measure is a 'Fishery Improvement Project' (FIP), in which a fishery undertakes an action plan to make specified improvements, often with an objective of becoming MSC certified (Cannon et al., 2018). The number of fish stocks caught by fisheries under an active FIP has increased in the last decade (Fig. 1), particularly for tuna stocks managed under high-seas Regional Fisheries Management Organisations (RFMO) and in coastal West Africa (Fig. A.1). Compared to conventional fisheries management measures implemented by governments (Fig. 1), eco-certification and improvement projects in fisheries are relatively recent (Crona et al., 2019; Shelton, 2009).

In this study, we characterise several voluntary and government-mandated fisheries management measures implemented in 301 individual fish stocks, and then evaluate the influence of these measures on changes in stock sustainability status. To represent stock status, we use estimates of population biomass and fishing pressure relative to management targets, as estimated in stock assessments and assembled in a publicly-available database. We build on the analysis of Melnychuk et al. (2021), which considered only government-mandated measures, to additionally evaluate the potential influence of voluntary measures (MSC certification and FIPs) undertaken by fisheries linked to these stocks. We further build on a comparison of relative biomass between stocks caught by MSC-certified fisheries and non-MSC stocks (Melnychuk et al., 2022) using a formal time series framework for analyses. Various management measures have been applied to fish and invertebrate stocks around the world (Fig. 2b–f). These voluntary and government-mandated measures are treated as interventions that may alter the temporal trends in stock biomass and fishing pressure after implementation. First we ask whether the implementation of voluntary measures has affected the implementation rate of government-mandated measures. We then ask how the implementation of voluntary measures and government-mandated measures have each, and together, affected trends in stock status.

We recognise that focusing on biomass and fishing pressure of target

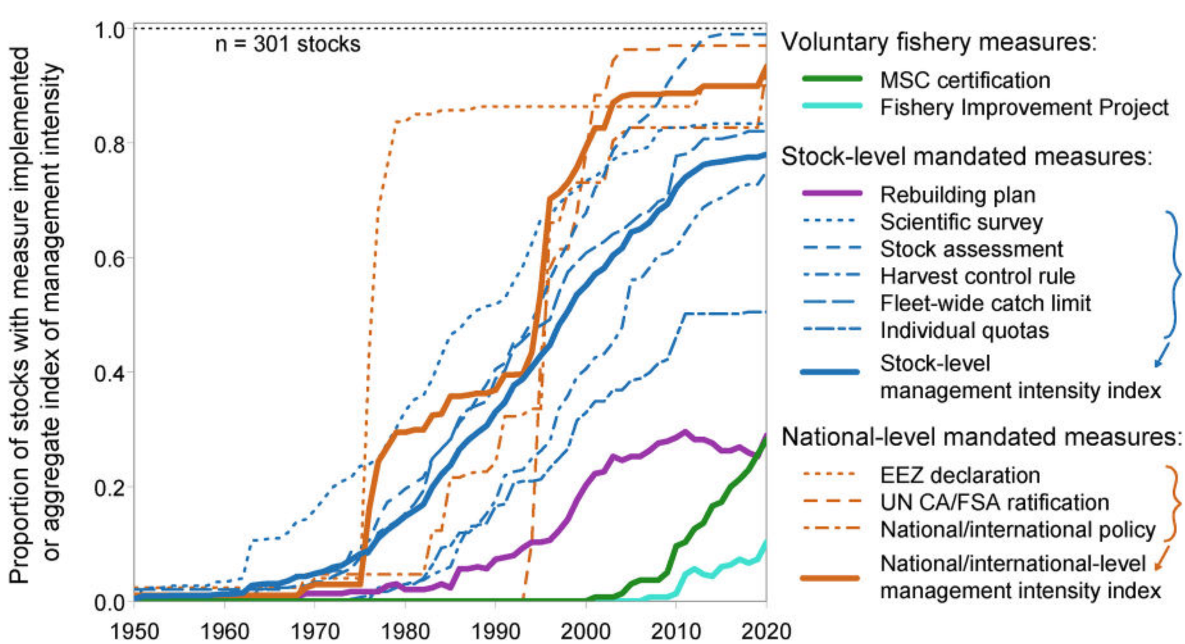

Fig. 1. Implementation history of voluntary fishery measures and government-mandated management measures for assessed stocks, showing steady increases globally over seven decades. Thick solid lines represent the proportion of stocks caught by fisheries that have been under MSC assessment (green) or under a stage-3 FIP (teal), those under a rebuilding plan (purple), and aggregate indices of management intensity at the stock level (blue) or national/international level (orange). Thin dotted/dashed lines show individual measures that comprise these aggregate indices. Implementation histories of these same measures in 17 individual regions are shown in Fig. A.1.

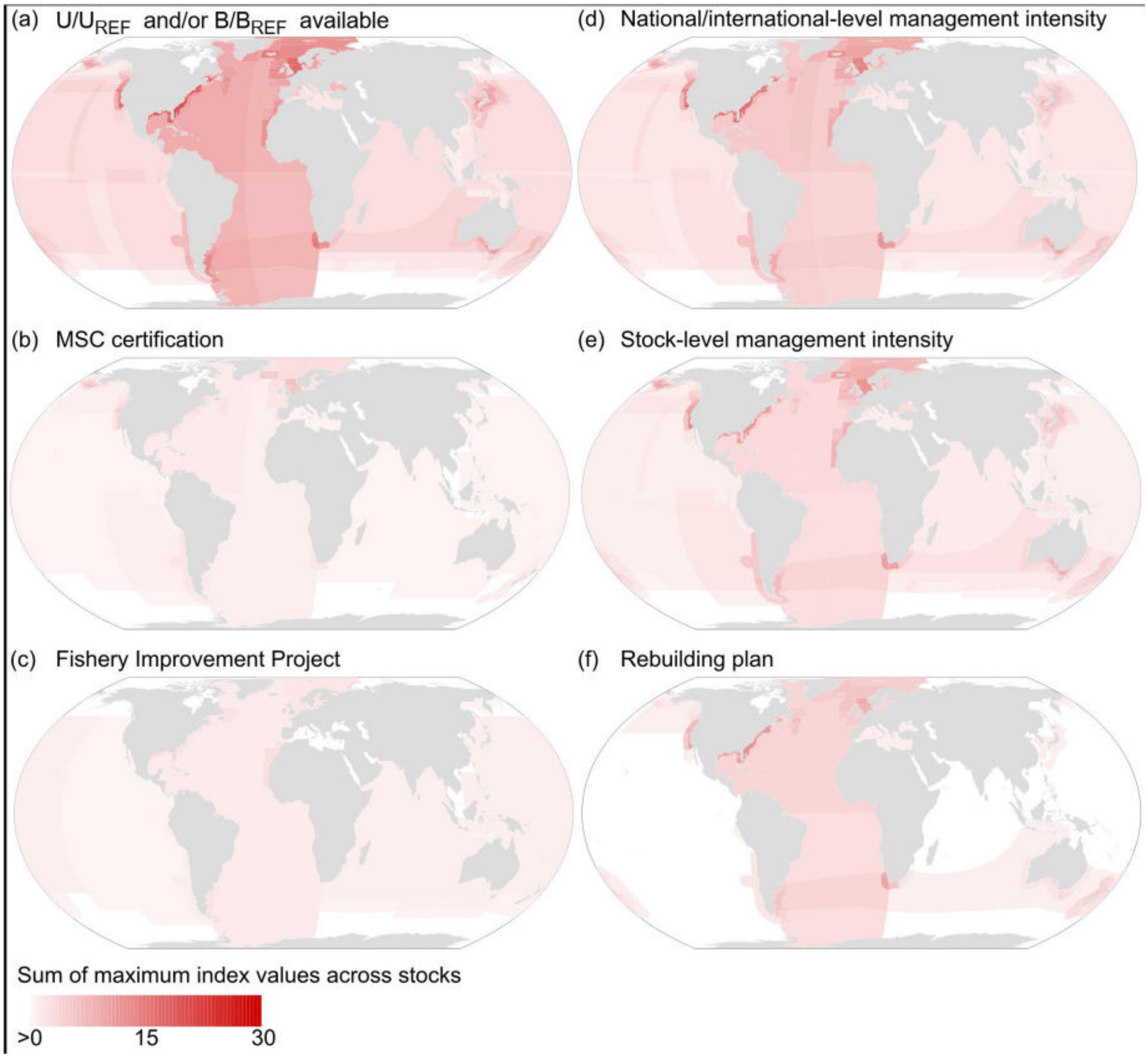

Fig. 2. Geographic coverage of stocks included in the analysis with voluntary or government-mandated measures in place for ≥1 years from 1950 to 2020. Distribution areas as defined in stock assessments are overlaid in each panel for stocks with: (a) available estimates of relative fishing pressure (U/U_{REF}) and/or relative biomass (B/B_{REF}); (b) ≥1 linked fisheries under MSC assessment; (c) ≥1 linked fisheries under a stage-3 FIP; (d) ≥1 national/international-level mandated measure in place; (e) ≥1 stock-level mandated measure in place; or (f) an active rebuilding plan. Darker shading in a given pixel reflects the combination of more stocks with the measure in place and a higher index value for those stocks (index values for a and f are either 0 or 1, but those for b–e may be intermediate between 0 and 1). Stock assessment areas are primarily drawn from the RAM Legacy Stock Boundary Database (https://github.com/cfree14/ram_boundaries).

stocks overlooks broader ecosystem consequences, including bycatch and habitat impacts, as well as the socioeconomic well-being of fishing communities and other social outcomes (e.g., Bene et al., 2015; Basurto et al., 2025; Evans et al., 2011). This focus also limits the availability of data from countries with developing economies, as formal stock assessments are usually conducted by well-funded fisheries management agencies which tend to be in countries with developed economies (Melnychuk et al., 2017).

2. Methods

2.1. Data sources

We evaluate how voluntary and government-mandated management measures potentially influence changes in the stock status of fish populations. We combine data from six sources to meet these objectives: (i) the RAM Legacy Stock Assessment Database (RAMLDB), which contains outputs of stock assessments and time series of estimated biomass and fishing pressure; (ii) MSC datasets containing information about when fisheries first entered into assessment for certification and potentially had conditions or suspensions of certification activated; (iii) the MSC pre-assessment database containing information about fisheries that arranged for a pre-assessment to be conducted before formally entering MSC assessment; (iv) a database of Fishery Improvement Projects (FIP-DB); (v) a management attributes dataset containing a range of government-mandated management measures for individual populations; and (vi) the online databases FishBase and SeaLifeBase which contain taxonomic, life-history, and ecological data for fish and invertebrate species, respectively.

(i) RAMLDB is a compilation of stock assessment outputs for assessed marine fish and invertebrate stocks (used interchangeably here with ‘populations’) around the world (Ricard et al., 2012). In RAMLDB version 4.66 (RAMLDB, 2024), 625 stocks contain time series of estimated biomass or fishing pressure relative to management targets that were extracted from stock assessments; 432 of these stocks contain both types. These management targets are often based on biological reference points

(REF) related to maximum sustainable yield (MSY), both for biomass (B_{REF}) and for fishing pressure (U_{REF}). For stocks that did not have values for one or both of these reference points presented in stock assessments, they were estimated *post-hoc* by fitting surplus production models to assessment outputs (Melnychuk et al., 2020). Using this method, one or the other *post-hoc* reference points were estimated for an additional 124 stocks, and both reference points were estimated for an additional 106 stocks, resulting in estimates of B_{REF} and/or U_{REF} for 731 stocks in total. The ratio of estimated biomass to the management target (B/B_{REF}) is termed 'relative biomass' and the ratio of estimated fishing pressure to the management target (U/U_{REF}) is termed 'relative fishing pressure', which together represent stock status. Time series of B/B_{REF} and U/U_{REF} are analysed separately, and are occasionally drawn from different stock assessments in cases where the most recent assessment did not report both of these variables.

(ii) By December 2023, 1748 fishery units of certification (UoC) across 438 fisheries had at some point been certified to the MSC's Fisheries Standard (MSC, 2018). MSC assessments of fisheries are conducted by third-party 'Conformity Assessment Bodies', and there may be multiple UoCs assessed within a fishery, typically representing different species or gear types. There is rarely a 1:1 relationship between fisheries or UoCs and fish populations; certified fisheries may catch only a small proportion of a stock's total catch, multiple fisheries (and hence even more UoCs) may link to the same stock, and in some cases multiple stocks may link to a single UoC. In addition to the years of initial entry into MSC assessment and initial certification, other certification-related events that may occur include suspensions of certification (which are often temporary) if MSC standards are no longer met, conditions placed on certification (which carry requirements for change before an agreed deadline), and withdrawals from certification (which has occurred in 19% of UoCs; Melnychuk et al., 2024). Only conditions and suspensions related to Principle 1 (Sustainable fish stocks) or Principle 3 (Effective fisheries management) of the Fisheries Standard were considered, as these are most relevant to managing target species (Table A.1). MSC datasets contain information about when conditions were opened or closed, when suspensions started or ended, when fisheries withdrew from certification, and catch weights by UoC.

(iii) The MSC pre-assessment database (Rasal et al., 2024) is a recent compilation of information from reports that summarise pre-assessment evaluations of a fishery. Fisheries may elect to be evaluated in a pre-assessment to better understand the likelihood of becoming MSC certified should they decide to enter assessment. There were 3063 pre-assessment units across 545 fisheries contained in the database by December 2023, and like UoCs, several pre-assessment units may link to the same stock. Pre-assessment reports summarise the evaluation, including an indication of whether each pre-assessment unit would be likely to pass or fail each of the three principles in a MSC assessment. These indications at pre-assessment reflect the extent of improvements that would be required of the fishery before becoming MSC certified; if pre-assessment results indicate a likely failure, that suggests greater improvements are required.

(iv) FIP-DB (UW and SFP, 2024) is a compilation of progress and results of FIPs that have been undertaken by fisheries around the world. Many of these FIPs are tracked by FishChoice and contained in their dataset (fisheryprogress.org), but FIP-DB also contains other FIPs tracked by the Sustainable Fisheries Partnership. Multiple species or stocks may be under a given FIP and multiple FIPs may link to the same stock, each covering a portion of the stock's catch; as of November 2023 there were at least 664 unique FIP-stock combinations across 323 active, inactive, or completed FIPs contained in FIP-DB. Of these, 622 FIP-stock combinations have reached 'FIP stage 3' meaning FIP activities in the FIP's workplan are implemented and reported. Earlier stages 1 (FIP development) and 2 (FIP launch) are concerned with planning and public announcement, whereas hypothesised influences on stock sustainability status align more closely with stage 3 and beyond (Table A.1). For each FIP, different stage-3 indicators recorded in any given year reflect different types of activities undertaken; the number of recorded stage-3 indicators per stage-3 FIP ranged from 1 to 30 (median 6). Indicators may be activated individually during the duration of a FIP and are thus cumulative. The final objective for some FIPs is MSC certification. Information used from FIP-DB included when a FIP reached stage 3, when stage-3 indicators were recorded, when it either achieved MSC certification or became inactive, and catch weights by FIP and species.

(v) A database of fisheries management attributes was assembled by regional experts from around the world, specific to a subset of stocks contained in RAMLDB and targeted in capture fisheries. This database was previously used and reported by Melnychuk et al. (2021), and has since been updated with stock data current through year 2020. With the addition of some stocks, the splitting of some stocks into separate assessment units, and merging of other assessment units into a common stock, it now contains information for 301 stocks. Management measures at the stock level include the year in which scientific surveys, full stock assessments, fleet-wide catch limits, harvest control rules, and individual quota systems were first implemented, in addition to the years during which a rebuilding plan was in place (Table A.1). Management measures at national or international levels include the year in which a country declared its Exclusive Economic Zone (EEZ; UNCLOS, 1982), the year in which a country first ratified either the FAO Fish Stocks Agreement (UN, 1995) or the UN Compliance Agreement (FAO, 1995), and the year in which a country or high seas RFMO first established a major piece of fisheries legislation such as national Fisheries Acts, the EU Common Fisheries Policy, the US Magnusson-Stevens Act, or RFMO convention agreements (Table A.2). See Melnychuk et al. (2021) for further details about these management attributes. These stock-level and national/international-level management measures would typically be considered as government-mandated measures (Table A.1), although there are certainly cases where the implementation of management measures has involved or even been spearheaded by the fishing industry.

(vi) Information from FishBase (Froese and Pauly, 2023) and SeaLifeBase (Palomares and Pauly, 2023) used in this study as predictor variables included age at 50% maturity (A_{M50}), maximum length (L_{MAX}), and habitat classifications, aiming to control for ecological variability among stocks. Taxonomic and habitat classifications were pooled into three general groups: demersal fishes (including benthopelagic and reef-associated fish), pelagic fishes (including bathypelagic fish), and invertebrates. For each of these variables, information was preferentially drawn from published stock assessments if available for the specific stock in question, and if not available, global species-level information was used from FishBase or SeaLifeBase, accessed through the R package 'rfishbase' (Boettiger et al., 2012).

These six data sources were merged to link response variables (relative biomass and relative fishing pressure) with predictor variables (voluntary and government-mandated management measures and life-history information). Complete cases were required for data analyses (i.e., no missing values for stock status variables or for predictor variables), so sample sizes were constrained by data availability. Of the 301 stocks with available government-mandated management measures, 294 had available biomass data and 289 had available fishing pressure data (Table A.3). All of these had available life-history data and habitat classifications. Associated with these 301 stocks were: 505 unique UoCs in fisheries that had entered into MSC assessment by the end of 2020, targeting 99 stocks (Table A.4); 471 units of pre-assessment targeting 131 stocks contained in reports published by the end of 2020 (21 units had >1 pre-assessments conducted); and 122 unique FIP-species combinations linked to 55 stocks and to 84 unique FIPs that reached stage 3 by the end of 2020 (Table A.5). Stocks without any such linkages to MSC or FIP fisheries did not constrain sample sizes, however, because portions of stock time series that are not associated with management attributes, MSC certification, or FIPs contribute to the baseline trend in biomass and fishing pressure across all stocks. Stocks included in analyses were assigned to regions based on their geographic distributions and management authorities (Table A.2). All data sources involved widespread geographic coverage (Fig. 2), although sample sizes were skewed towards regions in which formal stock assessments are commonly conducted, which tend to be in countries with developed economies. Included stocks also represented diverse taxonomic groups and were fished by diverse fishing gears and fleet structures.

2.2. Construction of management indices

Time series indices with values ranging from 0 to 1 were constructed for each stock, to represent the hypothesised influence of each of five management measures on changes in stock status. Two voluntary fishery measures (MSC assessment and certification; FIPs) represent incentives for fisheries to engage in more sustainable fishing practices. Three government-mandated measures (stock-level management intensity; national/international-level management intensity; rebuilding plans) represent the strength of management systems to meet stock status objectives, primarily through regulating fishing pressure. For all indices, values near 0 reflect limited measures in place potentially affecting a stock, while values near 1 reflect more intensive management measures and a greater proportion of the stock's catch covered by voluntary measures. Rules used to construct these indices are described below, with examples shown in Fig. 3.

MSC certification index: Events related to MSC pre-assessments, formal assessments, and certification were used to construct a 'MSC certification index' which comprises a pre-entry component and a post-entry component. For the 202 stocks not targeted by any UoC, the value for the index is 0 in all years 1950–2020. For the other 99 'MSC stocks',

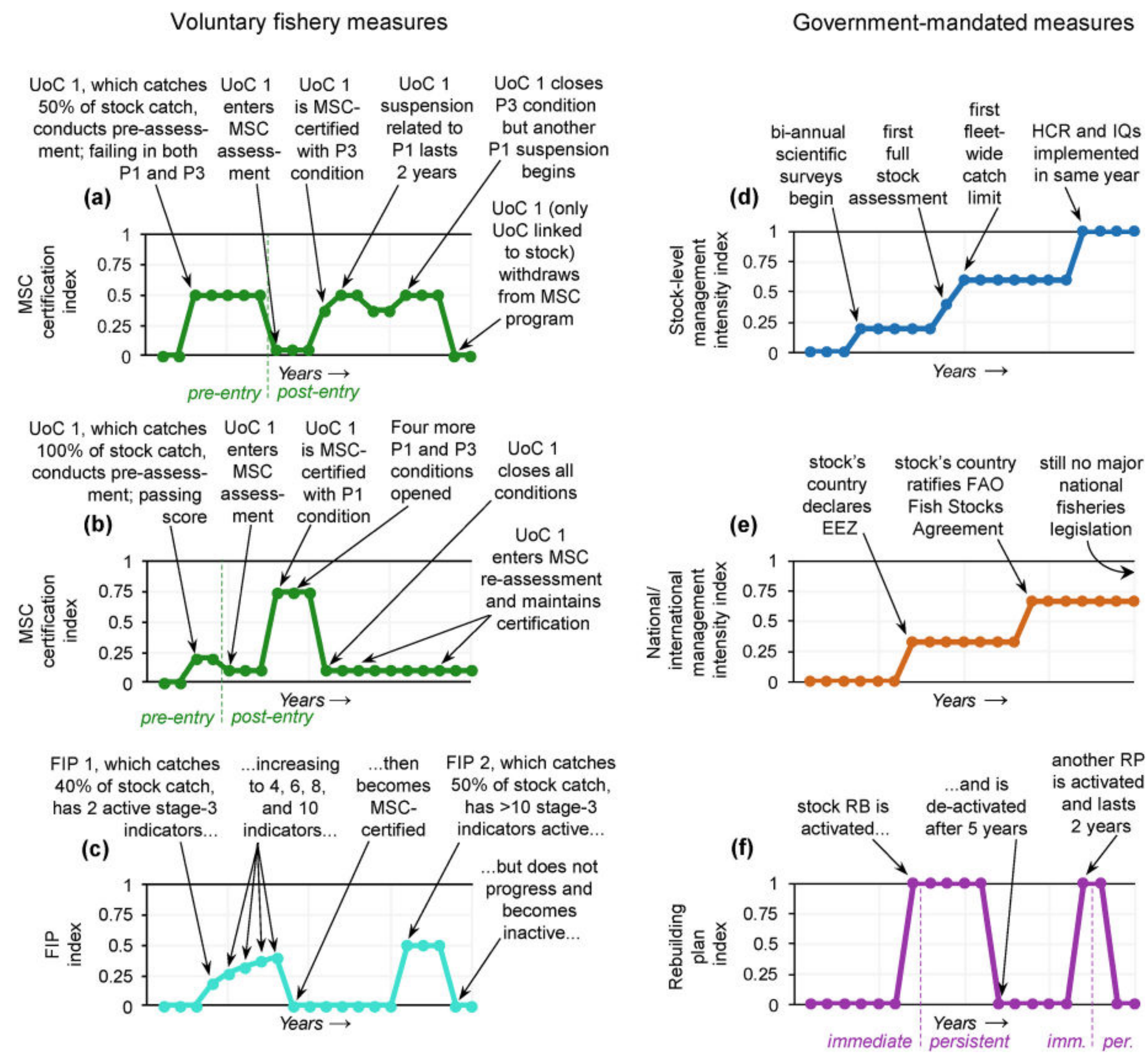

Fig. 3. Schematic of voluntary and mandated management indices used as time-varying predictor variables in analyses. Representative examples with explanations are shown for: (a, b) MSC certification index, separated into pre-entry and post-entry components; (c) Fishery Improvement Project index; (d) stock-level management intensity index; (e) national/international-level management intensity index; and (f) rebuilding plan index, separated into immediate and persistent components. See Table A.1 for further descriptions of management measures and abbreviations.

the index relies on information from all UoCs and all units of pre-assessment targeting the stock, accounting for the unit's fraction of the total stock catch. First, index values were calculated for each UoC individually, with a base value of 0.1 applied beginning with the year of entry into initial MSC assessment, and ending (with value falling back to 0) if the UoC withdrew from the MSC program (Fig. 3a). The year of first certification follows anywhere from 0.3 to 7.1 years after entry into first assessment (median 1.6 years across 405 UoCs). The base value of 0.1 is maintained after certification unless a condition related to Principles 1 or 3 is opened (in which case the index value increases to 0.75; Fig. 3a and b) or unless a suspension related to Principles 1 or 3 starts (index value increases to 1; Fig. 3a). The index value decreases again to the base value in the year that all conditions are closed or the suspension ends (Fig. 3b). This portion of the MSC certification index, beginning with the UoC's year of first assessment, is referred to as the 'post-entry' component.

A 'pre-entry' component of the MSC certification index represents years before first MSC assessment. The separation of pre-entry and post-entry components allows for distinguishing potential influences associated with the lead-up to MSC assessment from those occurring after first assessment which are primarily related to conditions and suspensions. For each unit of pre-assessment that later entered into MSC assessment, a value > 0 is assigned from the year of a published pre-assessment report until the year prior to entry into initial MSC assessment of the corresponding UoC(s), with the assumed value depending on the pre-assessment scoring evaluation. Indications of 'likely pass' in the pre-assessment result in an index value of 0.2, indications of 'likely fail' in either Principle 1 or Principle 3 result in an index value of 0.8, and indications of 'likely fail' in both principles result in an index value of 1 (Fig. 3a and b). These values are meant to reflect differences in the presumed effort that a fishery put into making improvements between the time of its pre-assessment evaluation and entry into MSC assessment. In other words, the change from a likely failure during pre-assessment to a level of confidence implied by entering MSC assessment provides evidence that fisheries made improvements against the Fisheries Standard during this period. If a unit of pre-assessment did not later enter into MSC assessment, its value remained at 0 irrespective of its pre-assessment scoring evaluation. If no pre-assessment units corresponded to a UoC entering MSC assessment, an index value of 0.1 was assumed for the two years prior to assessment entry, reflecting presumed baseline improvements by the fishery in the lead-up to MSC assessment even if a pre-assessment had not been carried out. The duration of this lead-up period was based on the overall median value of 1.9 years between the month of a published pre-assessment report and the month of MSC assessment entry for the corresponding UoC(s), grouping by stock (i.e., first a median across UoCs targeting a stock, then a median across stocks).

For the post-entry component, the vector of index values for each individual UoC was multiplied by the UoC's fraction of the total stock catch, with the resulting vectors summed across all linked UoCs. In any year, the overall stock index therefore represents a weighted average value across UoCs, weighted by the fraction of total stock catch. UoC fractions of stock catch were not year-specific, but were instead calculated for one or a few recent representative years based on available UoC catch data, so are considered approximate. For the pre-entry component, catch data were not available for units of pre-assessment, so catches of the corresponding UoC(s) eventually entering MSC assessment were assumed. Occasionally recorded UoC catch exceeded the total stock catch, usually resulting from a mismatch in calendar years, and in these cases UoC catch fractions were capped at 100% before aggregating individual indices into the overall MSC certification index for the stock.

FIP index: While Fishery Improvement Projects can be aimed at achieving MSC certification ('comprehensive' FIPs), they can also be used independently, so the FIP index is treated as a separate predictor variable from the MSC certification index. For the 246 stocks not targeted by any FIP, the value of the index is 0 in all years 1950–2020. For the other 55 'FIP stocks', the index value in a given year depends on the number of stage-3 indicators active for individual linked FIPs and is weighted by the fraction of the stock's catch covered by the FIP. First, an index was constructed for each individual FIP using a capped, saturating function of the form $\min(1, \ln(x+1)/\ln(10+1))$, where x is the number of stage-3 indicators. This saturating form implies, for example, a steeper increase in the index value as the number of indicators increases from 1 to 2, compared to an increase from 8 to 9. The index reaches a maximum value of 1 once 10 indicators are active (it is capped at 1 for >10 active indicators). Indicators may close individually if objectives are achieved, or simultaneously if the FIP reaches MSC certification or otherwise becomes inactive (Fig. 3c). For each FIP targeting a stock, the resulting index vector was multiplied by the FIP's fraction of the total stock catch in a recent year(s), occasionally capping fractions at 100% if necessary. The resulting products were then summed across FIPs to produce a single FIP index for the stock.

Stage 3 indicators reflect a wide range of activities undertaken, including engaging with management agencies, improving data collection schemes, co-financing or collaborating on stock assessments, coordinating multistakeholder working groups to address specific fisheries issues, and creating codes of good practices to mitigate bycatch and reduce discard mortality of vulnerable species. Most FIPs had at least some indicators involving improvements related to MSC Principles 1 and 3, but two of the FIPs in our dataset had indicators relating solely to bycatch issues pertaining to Principle 2. Because our analysis focuses on management of target stocks, these two FIPs (each targeting the same two stocks) were excluded.

Stock-level management intensity index: Values of this index increment with the successive implementation of five stock-level management measures (Table A.1; Melnychuk et al., 2021). In the year that a measure is implemented, the index value increments by 0.2, so does not depend on the order in which measures were implemented (Fig. 3d). Once implemented, it is assumed these measures persist, so the index does not revert downward (it is rare that one of these management measures would be abandoned after it is first implemented). By 2020, all 301 stocks had at least one stock-level measure implemented.

National/international-level management intensity index: Similarly, values of this index increment with the successive implementation of three national or international-level management measures (Table A.1; Melnychuk et al., 2021). In the year that a measure is implemented, the index value increments by 1/3 (Fig. 3e). Once implemented, it is assumed these measures persist, so the index does not revert downward. By 2020, all 301 stocks had at least one national/international-level measure implemented.

Rebuilding plan index: Values of the rebuilding plan index are 1 during active rebuilding periods, beginning with the calendar year the rebuilding plan is activated (Fig. 3f; Melnychuk et al., 2021). In the calendar year following the end of the rebuilding period, the index value decreases to 0. Rebuilding plans may be re-activated in later years. Details of rebuilding plans vary among regions and management agencies, but typically they involve substantial decreases in fishery catch limits (Table A.1). By 2020, 147 of the 301 stocks had had a rebuilding plan in place for at least one year in the 1950–2020 period (ranging from 1 to 35 years, median 13 years, across the 147 stocks).

For each stock, the five management indices described above were constructed and were aligned with stock status data for analyses. An example is provided for North Sea cod (*Gadus morhua*), where management measures (both voluntary and government-mandated measures) are shown in relation to time series of relative biomass and relative fishing pressure (Fig. 4). Similar plots are shown for each of the 296 stocks in our dataset with available time series data (Fig. A.2). Two further-aggregated indices were constructed to evaluate relationships between voluntary and government-mandated measures. The MSC certification index and FIP index were combined into a single voluntary index for each stock, taking the maximum value in any given year. Similarly, the stock-level management index and national/

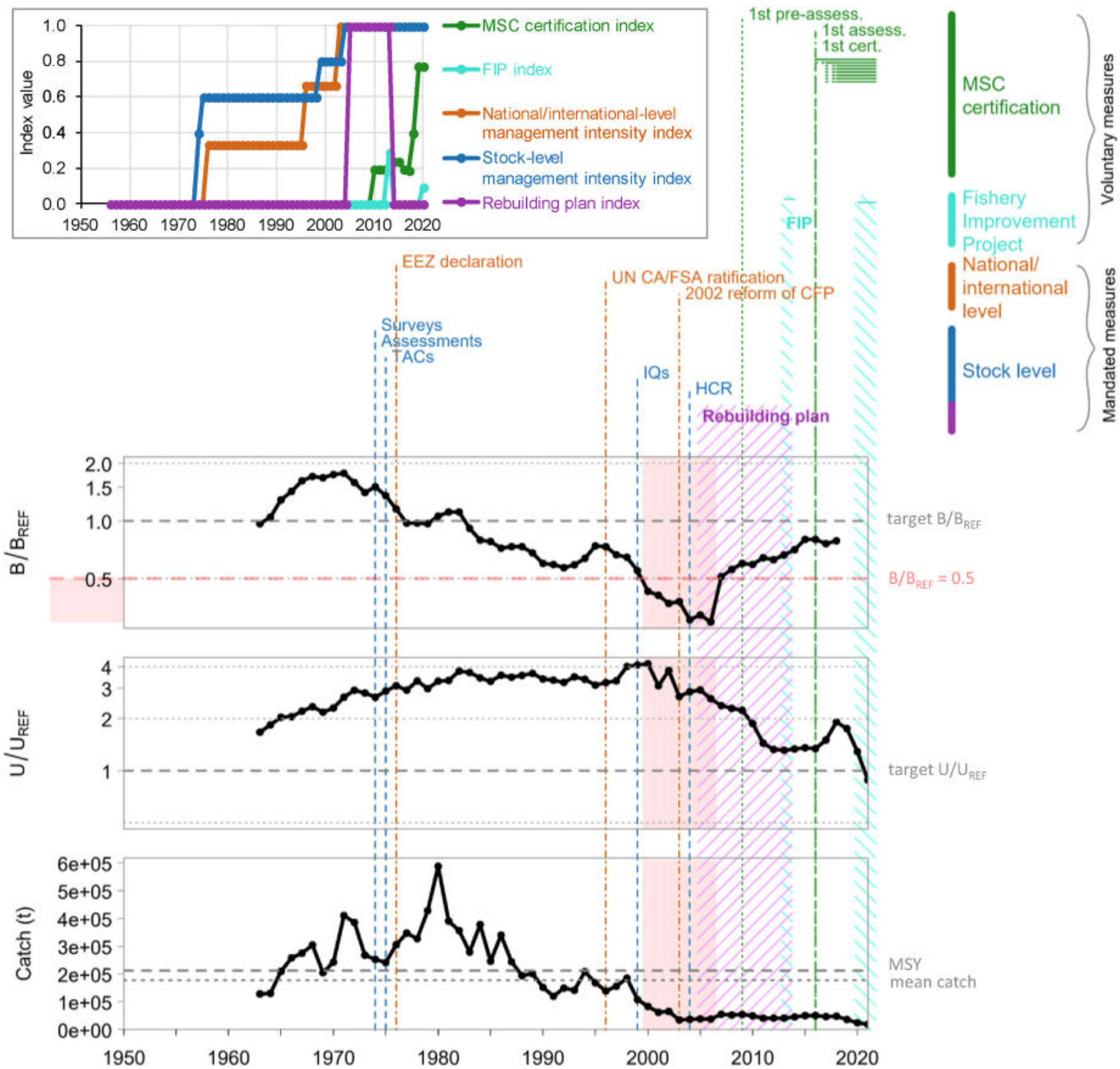

Fig. 4. Stock status history relative to the timing of voluntary fishery measures and government-mandated management interventions. Data for North Sea cod (*Gadus morhua*; ICES statistical areas 27.3 aW, 27.4, 27.7d) are shown as an example. Similar figures are provided for 296 stocks in Fig. A.2. Lower panels show time series of relative biomass (B/B_{REF}), relative fishing pressure (U/U_{REF}) and catch. Years during which $B/B_{REF} < 0.5$ are shaded light red. Years when linked fishery units of assessment were under MSC assessment or certified are shown with horizontal green dotted or solid lines, respectively. Years under a rebuilding plan or under a FIP are shown with purple or teal diagonal hatching. Years when other management measures were first implemented are indicated by vertical dashed lines. Inset panel at top shows the resulting five indices of voluntary and mandated management measures.

international-level management index were combined into a single government index for each stock based on the number of eight possible measures that had been implemented in any given year.

2.3. Influences of management measures on changes in stock status

Autoregressive integrated moving average (ARIMA) models were fit to time series of annual changes in relative fishing pressure (U/U_{REF}) and relative biomass (B/B_{REF}). These models attribute interannual changes in these response variables to a series of predictor variables. Some predictor variables were time series—the two voluntary and three government-mandated management indices (Fig. 3). Other predictor variables were static, representing taxonomic, life-history, and other fishery-related characteristics. The predictor variables that vary over time are treated as interventions, and used to evaluate how their temporal changes (e.g. MSC certification events; or implementation of a FIP or a management measure) potentially influence changes in stock status. For any one population, years before an intervention contribute information to the baseline trend, and years after the intervention contribute to the impacted trend. For populations that never had some measure implemented, or that were never targeted by MSC-certified UoCs or to fisheries under a FIP, their information similarly contributes to an overall baseline trend. Models are hierarchical, combining all stocks into the same analysis to quantify overall influences, while incorporating a stock-level random effect to allow for variability among individual stocks.

ARIMA models used in this analysis built on those described in Melnychuk et al. (2021). Data for response variables B/B_{REF} and U/U_{REF} were updated to incorporate more recent stock assessments (RAMLDB version 4.66), and data for management histories were updated and added for five more stocks. The most notable change, however, was the incorporation of the two voluntary fishery measures as predictor variables. Additionally, start-of-year biomass was included as a predictor variable to allow for the possibility of state-dependent change in stock status variables. Otherwise, the base model used here was consistent with the base model from Melnychuk et al. (2021). The potential influence of rebuilding plans was separated into an 'immediate' component, affecting the first year following activation of the rebuilding plan, and a 'persistent' component, affecting all remaining years of the rebuilding plan. The population's 'maximum sustainable landed value' (MSLV) was calculated as the product of MSY and average ex-vessel price and was used as a predictor variable. Stocks were weighted equally in the main analysis, and weighted in proportion to MSLV in a sensitivity analysis. In one part of the analysis, an interaction between voluntary and government-mandated management indices was also considered to allow for the possibility of redundancy or synergistic effects of the two aggregate indices.

We note that the analysis does not account for self-selection bias, which is particularly likely to be present for MSC certification, as certification is not a random event with respect to the response variables (i.e., certification is less likely if biomass has been declining for several years). Further details of the base model are described in Appendix B—Supplementary methods. Verification of model assumptions and model fit diagnostics are described in Appendix C—ARIMA model structures and diagnostics.

Variations of the base model were used to visually isolate the influence of specific measures on changes in stock status. These were fit to the same dataset and used to project estimates of relative fishing pressure and relative biomass forward over a 20-year period to evaluate alternative management scenarios. Starting conditions for projections were set to $U/U_{\mathrm{REF}} = 1.5$ and $B/B_{\mathrm{REF}} = 0.6$, representing levels under which management interventions would likely be considered. Similar to the approach used by Melnychuk et al. (2021), for the first 9 years of model projections, all management variables were 'turned off', i.e., had index values set to 0. In the 10th year, management interventions were 'turned on' for the following years. Three hypothetical scenarios of overall management intensity were considered: low (consisting of 1 of 5 stock-level management measures, and 1 of 3 national/international-level management measures), medium (3 of 5, and 2 of 3), and high (5 of 5, and 3 of 3). The low-intensity scenario was modelled either with or without a 5-year FIP implemented at the same time. The medium-intensity scenario was modelled either with or without MSC certification (including a 5-year pre-entry period with required improvements before entry into MSC assessment, followed by a 5-year period with an active condition of certification). The high-intensity scenario was modelled either with or without a rebuilding plan. These combinations were selected to represent possible pairings (for example, FIPs are implemented in fisheries across a wide range of regions including those that may have limited management capacity, whereas rebuilding plans are typically implemented when management systems already have several measures in place). The projection model omitted start-of-year biomass as a predictor variable to better isolate the influence of implementing management measures. Estimated uncertainty around projected trends included components of: variance across random samples used to generate predictions; variance of the stock-level random effect; variances and covariances of fixed effects; and incremental annual variances over the 20-year period (Melnychuk et al., 2021).

3. Results

3.1. Development of voluntary and government management measures

Management measures at the stock level and at national or international levels, most commonly implemented by national or regional government agencies, have increased steadily over the past 70 years (Fig. 1) for these well-studied stocks. At the individual stock level, scientific surveys, catch limits, and full stock assessments tended to be implemented earlier in the management history compared to harvest control rules and individual quotas, which have been more recent and implemented for fewer stocks. Rebuilding plans have been implemented at some point for nearly half the stocks in our dataset, with 20–30% of stocks under a rebuilding plan in any given year over the past 20 years (Fig. 1). In contrast, voluntary measures have been introduced more recently (Fig. 1 and Fig. A.3). Engagement of marine capture fisheries with the MSC program and certification to the MSC Fisheries Standard have become increasingly common since the program's establishment in 1999, with 95 stocks in our dataset targeted by one or more fisheries that were certified or in assessment in 2020 (Fig. 1; 32% of stocks, not including four stocks targeted by fisheries that were previously certified but withdrew from the program before 2020). Along with this increase, the number of conditions of certification has also increased at a similar rate throughout the period, while the number of suspensions increased after 2010. Of 88 stocks targeted by UoCs certified by 2020, 74 had a linked UoC having had an open condition for at least one year, and 13 had a linked UoC that was under suspension for at least one year (Table A.6). Implementation of FIPs has been even more recent, with a total of 55 stocks targeted by one or more FIPs that were active at stage 3 for one or more years by the end of 2020 (Table A.5). In any given year, up to 31 stocks (10% of stocks) had a linked FIP (Fig. 1).

Geographic representation of stocks with available management measures was widespread, but differed somewhat between voluntary and government-mandated measures. Patterns in the implementation histories of government measures were generally similar among regions (Fig. A.1). Some regions had measures implemented earlier than in other regions, but all regions showed gradual increases in the stock-level and national/international-level management intensity indices. Use of rebuilding plans was more variable among regions (Fig. A.1). Together this resulted in similar levels of geographic coverage for the two management intensity indices (Fig. 2d and e), but less homogeneous coverage and lower coverage overall for rebuilding plans (Fig. 2f). Voluntary measures were also heterogeneous in their geographic coverage. MSC certification of UoCs targeting these stocks was most common among stocks in Atlantic Europe and the west coast of the US including Alaska, followed by stocks on the Atlantic coasts of Canada and the US, and high seas tuna and billfish stocks (Fig. 2b). MSC certification was less common for UoCs targeting stocks from other regions in our dataset (Fig. A.1). For stocks in our dataset, FIPs have been most commonly implemented for high seas tuna stocks, followed by stocks in West Africa and South America (as a proportion of stocks in the region; Fig. 2c and Fig. A.1).

Before evaluating possible influences of voluntary and government-mandated measures on stock status, we consider the potential influence that voluntary measures may have on government measures, to evaluate whether these can be treated as independent factors. Since 2000, when voluntary measures were first adopted, the rate of increase in the implementation of government-mandated measures over periods of 1, 3 or 5 years does not seem to have been strongly affected by the magnitude of the voluntary index at the start of the period (Fig. 5). In other words, steeper increases in the government index were not consistently associated with higher values of the voluntary index (as we might have expected if use of these voluntary measures had a strong influence on the adoption of government-mandated measures). Although the magnitude of the voluntary index is limited not only by the activity of linked fisheries engaged with MSC or in a FIP but also by their catch as a fraction of the total stock catch, there were still high values of the voluntary index observed, usually occurring when government index values were also relatively high (at values of 0.75 or 0.875; Fig. 5). At these high levels of the government index which allowed for high contrast in the voluntary index, no consistent change in the government index across the range of the start-of-period voluntary index was observed. We proceed with treating voluntary and government-mandated measures as separate factors in their potential influence on stock status.

3.2. Influences of management measures on changes in stock status

The model (Eq. (B.2) in Appendix B) in which voluntary measures

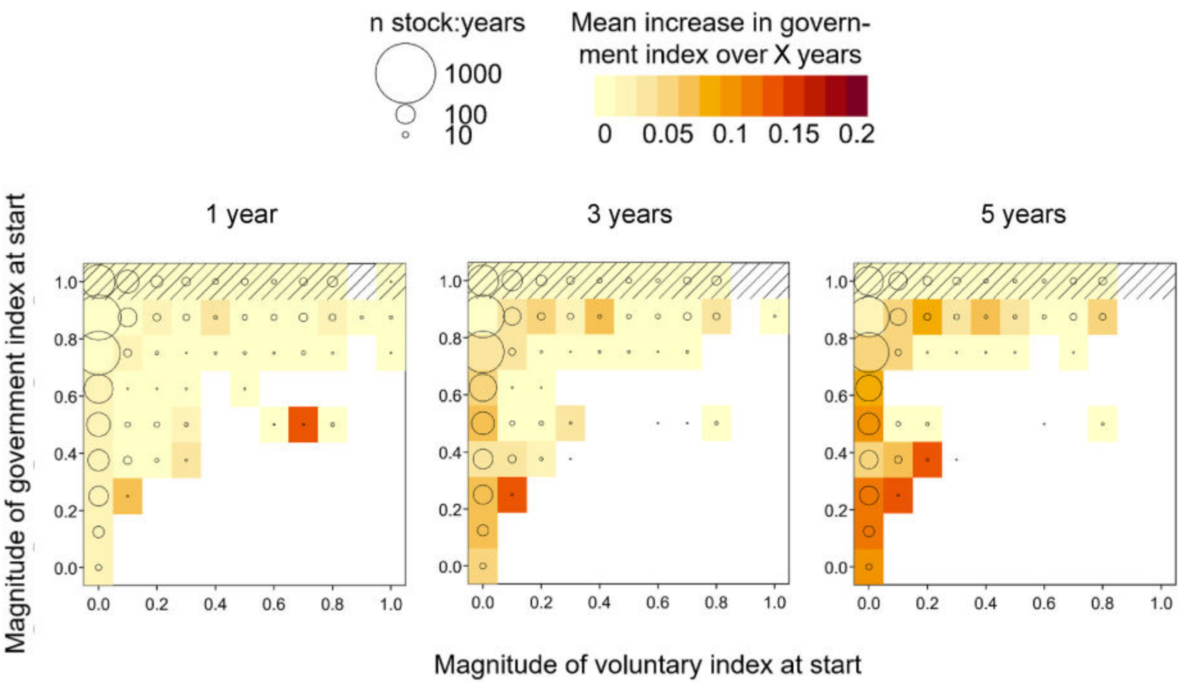

Fig. 5. Change in government-mandated management index in relation to values of government and voluntary index values at start of period. Government index comprises both stock-level and national/international-level management indices. Voluntary index comprises both MSC certification index and FIP index. Three panels show a 1, 3, or 5 year follow-up period, and colour shades show the mean increase over the period. Hatching at the government index value of 1 indicates that no further increase in the index is possible. Circle area within grid cells is proportional to sample size at each combination of starting values, and an absence of a grid cell reflects an absence of any stock:year data for that combination of values. Only data since 2000 are considered, when voluntary measures first became adopted.

were pooled into a single index and the stock-level management and national/international-level management indices were pooled into a single government-mandated measure index was preferred in terms of AICc scores to the model (Eq. (B.1)) with separate components (ΔAICc $= 11$ for U/U_{REF} and 14 for B/B_{REF}). As found previously (Melnychuk et al., 2021), a strong effect of rebuilding plans on change in U/U_{REF} was identified, with U/U_{REF} decreasing sharply in the first year of a rebuilding plan. This single-year change flipped the average trajectory from an increasing trend during a baseline period to a decreasing trend during a rebuilding period (Fig. 6; Table A.7). This influence persisted to a lesser extent during remaining years of a rebuilding plan, during which B/B_{REF} shifted from decreasing trends during a baseline period to increasing trends during a rebuilding period. Rebuilding plans were most commonly in place when government-mandated management intensity was already high, but did not show any association with index values of voluntary measures (Fig. A.4).

Decreases in U/U_{REF} were also associated with greater levels of the government-mandated measure index (Fig. 6; Table A.7). Accounting for these management influences simultaneously, an additional positive influence of voluntary measures was observed for change in B/B_{REF} (Fig. 6). Separating this voluntary index into components, the positive influence on change in B/B_{REF} is associated with the MSC post-entry component which involves conditions and suspensions of certification (Fig. A.5). No statistically significant results were observed for the FIP component on changes in either B/B_{REF} or U/U_{REF} (Fig. A.5).

Strong influences of start-of-year biomass on changes in stock status were observed. Higher starting levels of relative biomass were associated with greater increases in U/U_{REF} and decreases in B/B_{REF} over the following year (Fig. 6; Table A.7). In other words, when biomass was low, fishing pressure tended to decrease and biomass tended to increase. When biomass was high, opposite trends were observed. These influences, consistent with a negative feedback process that tends to bring biomass towards intermediate levels, are estimated simultaneously with the additional influences of management measures that also affect changes in U/U_{REF} and in B/B_{REF}.

Considering joint influences of the voluntary and government-mandated management measures (including an interaction between them) and start-of-year biomass, we observed different patterns for relative fishing pressure and relative biomass (Fig. 7). Start-of-year biomass levels considered here (0.6, 1, 1.4) bracketed target levels, and were selected ($B/B_{REF} \geq 0.6$) such that rebuilding plans would probably not yet be implemented (and were thus not activated for predictions). Moderate and high levels of government-mandated measures were sufficient to maintain a slight decline in relative fishing pressure across the full observed range of voluntary measures (i.e., ignoring hatched regions of Fig. 7 panels) and across start-of-year biomass levels. Only at low levels of both management indices and start-of-year B/B_{REF} ≥ 1 were increases in fishing pressure predicted (Fig. 7). Conversely, predicted changes in relative biomass were more variable and sensitive to start-of-year biomass. Increases in relative biomass were predicted at higher levels of the management indices, in particular for government-mandated measures, and especially when start-of-year B/B_{REF} was <1. Across combinations of management indices observed in the dataset (i.e., portions without hatching), declines in relative biomass were only predicted at low or moderate levels of one or both of the management indices and when start-of-year B/B_{REF} was ≥ 1 (Fig. 7). No strong interactions between the two management indices were observed for either relative fishing pressure or relative biomass.

3.3. *Predicted changes in stock status under alternative management scenarios*

Stock status projections for an average, intensively-fished stock showed that, in the absence of any management measures, fishing pressure increased further above management targets and biomass decreased further below management targets in the first 9 years (Fig. 8). By this 9th year or possibly sooner, U/U_{REF} would generally be deemed to be at ‘overfishing’ levels and B/B_{REF} would be deemed ‘overfished’. Considering only the activation of management intensity indices (i.e., the grey lines and confidence bands), when these hypothetical

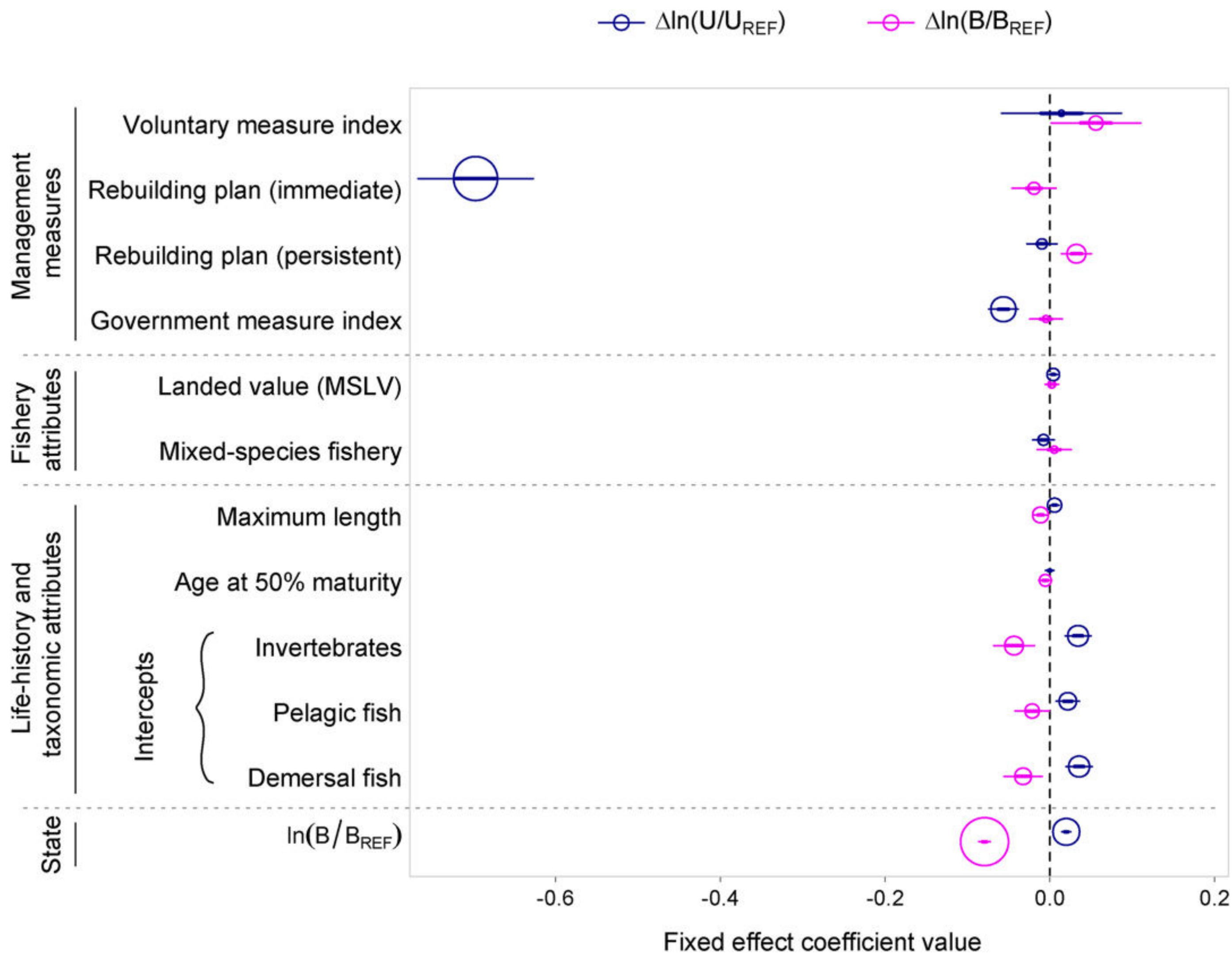

Fig. 6. Effects of voluntary fishery measures, government-mandated management measures, fishery, and life-history attributes on annual changes in relative fishing pressure and relative biomass. Positive (or negative) coefficients reflect increasing (or decreasing) contributions to trends in fishing pressure (U/U_{REF}) and biomass (B/B_{REF}) during the mature fishery phase. Voluntary measures include MSC certification (both pre-entry and post-entry components) and Fishery Improvement Projects. Government-mandated measures include both stock-level and national/international-level management measures other than rebuilding plans. Predictor variable $\ln(B/B_{REF})$ is the start-of-year value. Stocks are weighted equally. MSLV is maximum sustainable landed value, the product of MSY and mean ex-vessel price. The reference group for overall intercepts is 'single-species fishery', with the categorical 'mixed-species fishery' representing a difference from these intercepts. Thick and thin error bars represent standard errors and 95% confidence intervals, respectively. Circle area is proportional to the absolute *t*-value of the coefficient. Model is based on Eq. (B.2). Coefficient values are reported in Table A.7.

management scenarios were implemented in the 10th year, labelled as year 0 in Fig. 8, changes in stock status trends were observed. Low-intensity scenarios slightly slowed the increase in fishing pressure and slightly slowed the decrease in biomass (left panels); medium-intensity scenarios reversed the fishing pressure trend to a decrease and further slowed the biomass decline (middle panels); and the high-intensity scenarios further strengthened these changes (right panels).

Additional changes in stock status trends were observed when additional measures were also implemented in year 0. In the hypothetical low management intensity scenario, when a 5-year FIP was also implemented, model projections showed opposite-than-expected changes, with an increase in fishing pressure and decrease in biomass (Fig. 8), though these changes were small relative to the large uncertainties in trends. These projections are consistent with the unexpected (though not significant) direction of coefficient estimates associated with the FIP index (Fig. A.5). In the medium management intensity scenarios, when a modelled stock entered MSC pre-assessment in year 0 (for a 5-year period, after which it entered formal assessment and was successfully certified with a condition), biomass was only slightly affected and fishing pressure increased, though again uncertainties in trends were relatively large. In the high management intensity scenario, rebuilding plans rapidly lowered fishing pressure in the first year of implementation, and in remaining years biomass increased substantially compared to the case without rebuilding plans. After 10 years of a modelled rebuilding plan, the average stock was increasing toward target biomass (Fig. 8).

3.4. Sensitivity analyses

Stocks were weighted equally in the main analysis (Fig. 6) and when management indices were disaggregated into component indices (Fig. A.5). In a sensitivity analysis, stocks were instead weighted by economic value, MSLV. Results were generally consistent with those under equal weighting (results for disaggregated indices are shown in Fig. A.6). The immediate influence of rebuilding plans on trends in fishing pressure was weaker, and the influence of the MSC pre-entry

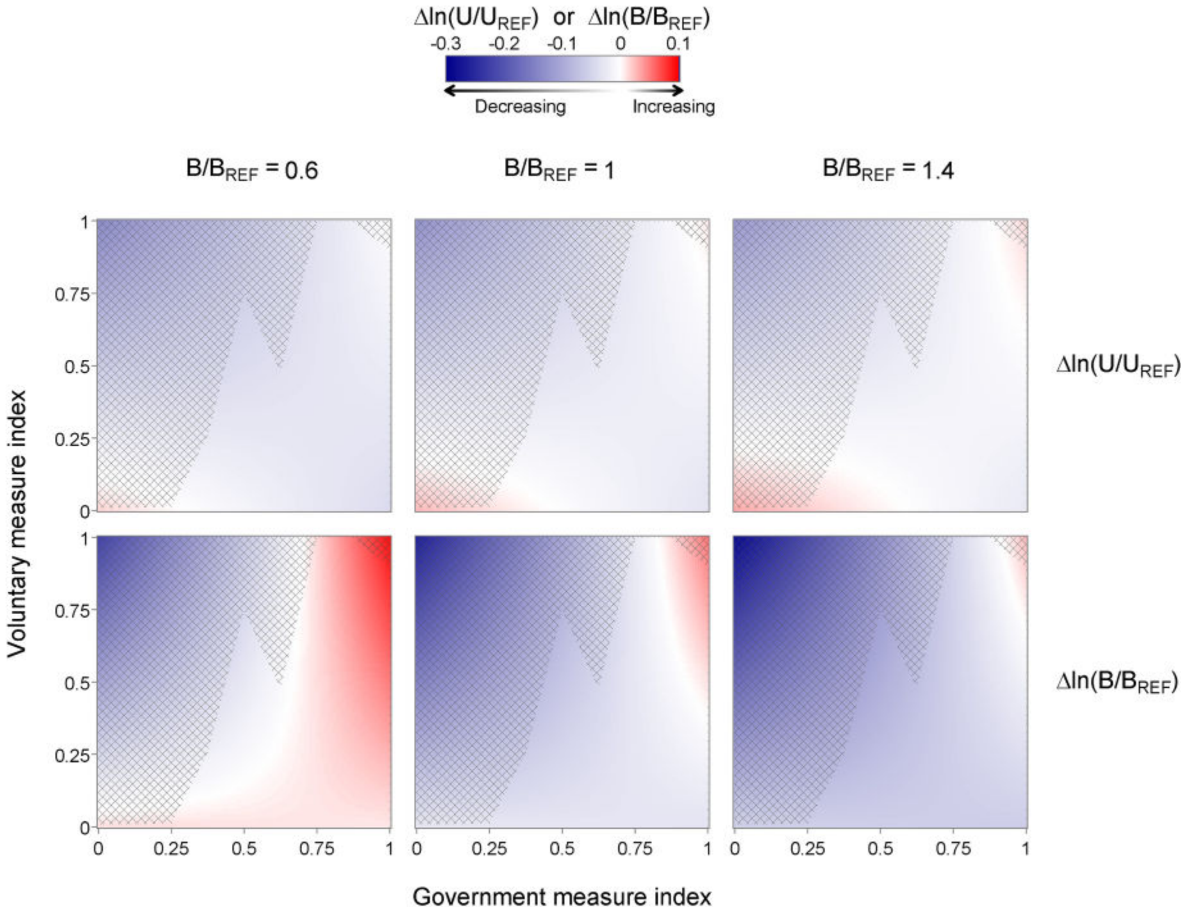

Fig. 7. Annual predicted changes in relative fishing pressure $\ln(U/U_{REF})$ (top panels) and relative biomass $\ln(B/B_{REF})$ (bottom panels) at different combinations of voluntary and government-mandated management measures. Predictions are shown for three start-of-year biomass levels in the absence of rebuilding plans. Regions with hatching show combinations of management indices that are not represented in the data. Model is based on Eq. (B.2) with an additional interaction term between voluntary and government management indices.

index on biomass trends was positive under value-weighting whereas no influence was observed under equal weighting. No notable changes in the effects of other predictors were observed between weighting schemes (Fig. A.5 and Fig. A.6).

Alternative ARIMA model correlation structures (differing in the number of autocorrelation and moving average parameters estimated) were considered, with results presented in Appendix C. Additionally, ARIMA model assumptions of stationarity and temporal causality were verified, and model fit diagnostics showed negligible bias and reasonable predictive performance (Appendix C).

4. Discussion

In this study, we compared the relative influence of voluntary and government-mandated management measures on changes in stock status. We found that government-mandated measures—in particular rebuilding plans (see Fig. 4 as an example)— had stronger overall influence than voluntary measures. Stronger observed effects of mandated measures are to be expected given the degree of direct control over fishing pressure on target stocks. In contrast, voluntary measures primarily operate through incentivizing better performance by fisheries against established standards (Komives and Jackson, 2014), and through incentivizing the strengthening of existing management systems. Additionally, economic investment in government-mandated systems is often substantial (Mangin et al., 2018), so it should not be surprising that government systems are better positioned to drive changes in stock status towards target levels. Previous work in agri-food systems has similarly suggested that mandated measures may be more effective than voluntary measures when the goal is to achieve a minimum level of sustainability-related performance across all firms (Russo et al., 2023). Voluntary measures—specifically, post-certification conditions and suspensions of certification—did show some association with increasing biomass, but because no simultaneous association with decreasing fishing pressure was observed, the biomass increases may be unrelated. Further, strong voluntary measures were only applied when several government measures were already in place (Fig. 5), consistent with previous contentions (Shelton, 2009; Stratoudakis et al., 2015). Sustainability-related incentives associated with voluntary measures may therefore help to promote more desirable conservation outcomes if used in parallel with, rather than as an alternative to, more conventional top-down approaches to management (Shelton, 2009).

Government-mandated and voluntary measures are not independent of one another (Parkes et al., 2016). Voluntary measures have only been applied in recent decades, so for the relatively data-rich stocks considered here, government measures tended to come first, often by several decades (Fig. A.3). A few exceptions were observed for harvest control rules, where MSC pre-assessments, assessments, and FIPs came before the implementation of a few harvest control rules. In these cases, the MSC certification process and FIPs may have helped to incentivise use of harvest control rules (Cannon et al., 2018; Gutteridge et al., 2024; Schiller and Bailey, 2021). In the opposite direction, governments have also helped provide financial or regulatory support to fisheries seeking certification. Any influence of voluntary measures on stock status changes may depend on the magnitude of government measures at the

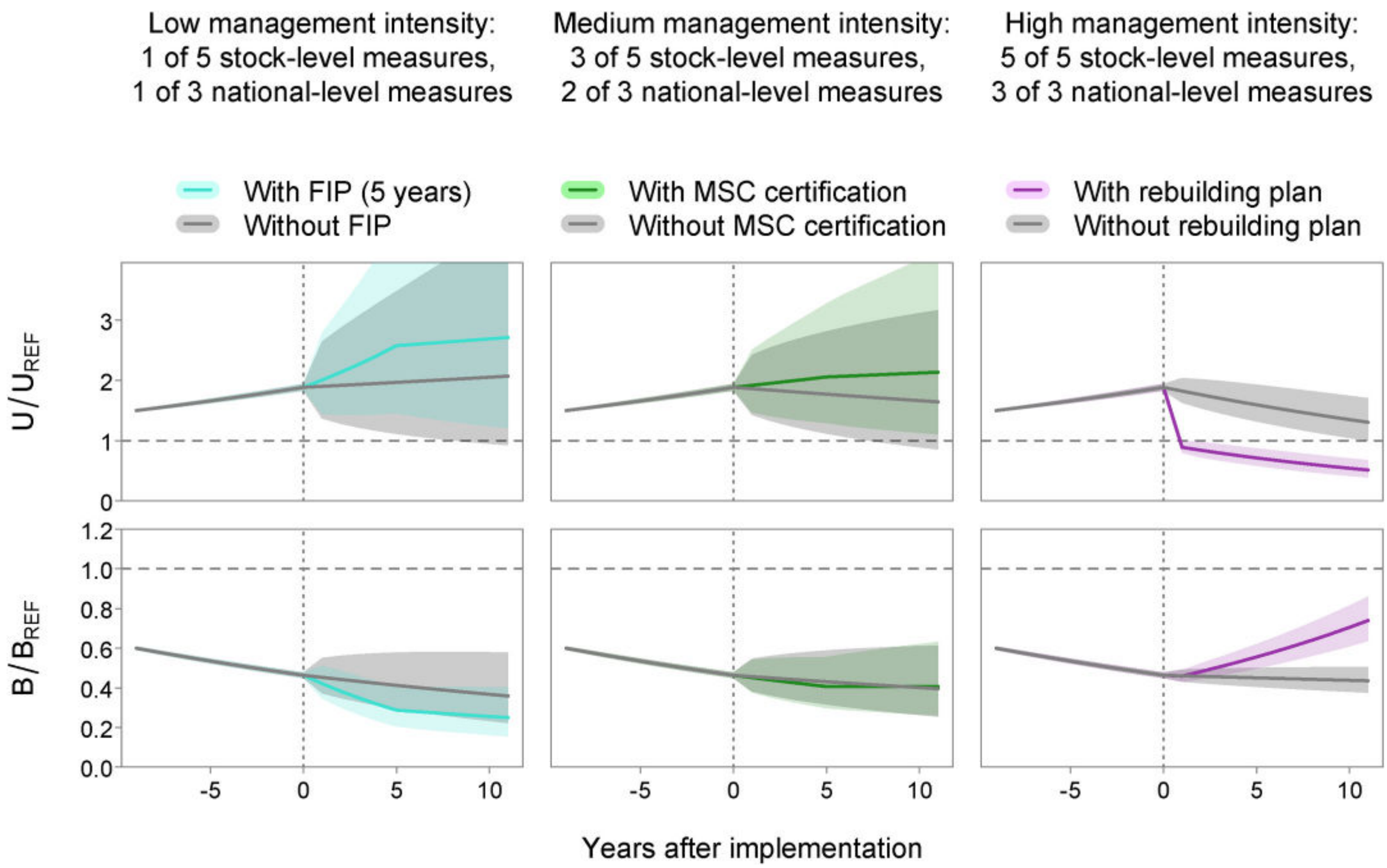

Fig. 8. Predicted effects of voluntary and government-mandated fisheries management interventions on stock status. Predictions are shown for relative fishing pressure (U/U_{REF}) and relative biomass (B/B_{REF}) of an average stock during its 'mature fishery' phase. Year 0 represents when a suite of stock-level measures and national/international-level measures were implemented under six scenarios: low management intensity either with or without a 5-year Fishery Improvement Project with FIP index value 0.5; medium management intensity either with or without MSC certification including a 5-year pre-entry period with index value 0.5 and a 5-year post-entry period with index value 0.375; and high management intensity either with or without a rebuilding plan for the full period. Predicted trends are shown over nine preceding (baseline) years in the absence of management, and over ten subsequent (impacted) years. Shaded regions denote 95% confidence bands. Horizontal dashed lines show management targets. Model is based on Eq. (B.1) without start-of-year biomass as a predictor.

time the voluntary measures were implemented. Voluntary measures may have a limited role if overall management intensity (from government measures) is already high, and we might expect greater influence from voluntary measures when government management intensity is low to begin with (Cannon et al., 2018). However, there were no cases observed where high values of the voluntary measure index coincided with low values of the government measure index (Figs. 5 and 7), and voluntary measures tend to be implemented for stocks that already had reasonably high levels of government measures (Fig. A.7), at least for the set of scientifically-assessed stocks analysed here. In other words, at least for MSC-certified fisheries, there is a self-selection bias where certified fisheries must be already performing well to a certain standard to become certified in the first place. It may be that any influence of voluntary measures—in particular FIPs—is stronger for unassessed stocks which we could not include in our analysis, and for which government management intensity would tend to be lower (Gomez-Gomez et al., 2024; Melnychuk et al., 2020). Recent studies have highlighted that FIPs have contributed to important improvements in contexts of limited capacity, such as the implementation of data collection schemes, stock assessments, and fishery management plans (Crona et al., 2019; García-Rodríguez et al., 2024).

Neither voluntary nor government-mandated management index variables are independent of the response variables, as voluntary or mandated measures are often implemented depending on perceptions of stock status from stock assessments and survey indices of abundance. The observed association between management measures and stock status should be interpreted with caution as these predictor variables are therefore not exogenous (although the changes in response variables are at least evaluated *after* the index values at any given time, providing a before-after study design). Researchers have suggested that exogeneity and endogeneity may be best considered along a continuum rather than as strict alternatives (Stone and Rose, 2011). The index variable that might be closest to being exogenous is the national/international-level government mandated index, because those measures are implemented simultaneously across all or most stocks in a country or region, rather than implemented specifically for individual stocks. In other words, the national/international-level management index does not respond to the perceived status of a single stock specifically. Interestingly, when disaggregated, the influence of national/international-level measures was stronger than the influence of stock-level management measures in leading to reduced relative fishing pressure (Fig. A.5), potentially related to the variable's lesser endogeneity.

The strong observed influence of start-of-year biomass on changes in fishing pressure and biomass implies a negative feedback process. This influence is direct for biomass and may be a density-dependent ecological effect, with greater increases at low starting levels of biomass. For fishing pressure, the influence is indirect, in that increasing fishing pressure associated with high relative biomass would be expected to eventually reduce biomass, and lower fishing pressure associated with low relative biomass would be expected to eventually increase biomass, so this also implies negative feedback on biomass trends. This effect on change in fishing pressure may be in part historical, as early high and decreasing biomass typically coincided with low and increasing fishing pressure. It may in part also result from underlying harvest decisions or other management changes that are not fully captured by the explicit management covariates, especially for government-mandated indices which depended only on the year that measures were first used. Instead, the start-of-year biomass effect on fishing pressure is similar in nature to a harvest control rule, in that if biomass is relatively low, fishing pressure decreases, and if biomass is high, fishing pressure increases, particularly at low levels of both voluntary and government measures. The value of this predictor variable changes over time, providing contrast in the data and opportunities for response variables to track this variability. The strength of the observed effects on changes in stock status may have leveraged this time-varying property of start-of-year biomass, which, unlike the year-of-first-use management measures, provides greater temporal contrast. Previously, Melnychuk et al. (2021) did not include start-of-year biomass as a covariate, and instead observed a stronger signal of stock-level management intensity, suggesting some degree of collinearity with start-of-year biomass.

Among voluntary measures, the MSC post-entry index stood out as having the strongest association with stock status, with an observed increase in biomass. Reasons for opening some conditions or starting some suspensions (those related to Principle 1 of the Fisheries Standard) are often in response to unfavourable levels of stock status detected in recent stock assessments. This result may suggest that these conditions or suspensions of certification are operating as intended, to incentivise fisheries to aid in stock rebuilding when necessary. While there may be some degree of inverse causality present (with conditions being opened and suspensions activated when biomass levels were already increasing), the simultaneous accounting of government measures and start-of-year biomass in the analysis would seem to suggest at least some real influence of these MSC measures. However, we interpret this result with caution, as we did not observe a simultaneous decrease in fishing pressure associated with the MSC post-entry index, which would have been expected if the biomass increase were the result of changes in fishing activity. The closing of conditions of certification has previously been found to be associated with improved institutional management practices such as increased transparency, greater accounting of model uncertainties, and increased monitoring (Longo et al., 2021), suggesting that a stock status effect associated with conditions could occur indirectly through these mechanisms.

A previous study investigated associations between MSC certification and stock status (Gutiérrez et al., 2012), but was based on limited data available at the time. A more recent study used an expanded dataset (Melnychuk et al., 2022), but when comparing MSC stocks and non-MSC stocks, did not control for other factors (such as fisheries management measures) operating simultaneously, nor did it account for autocorrelation in a formal time series framework. Our study is the most comprehensive evaluation of MSC program impacts and FIP impacts on the sustainability status of target fish stocks. While other seafood eco-labelling programs are used regionally or globally, the MSC is the largest and most widely-recognised of such programs.

The indications of higher FIP index values being associated with increasing fishing pressure and decreasing biomass (Fig. 8 and Fig. A.5) was opposite to expectations though not statistically significant. One possible explanation is inverse causality or collinearity. Like rebuilding plans, FIPs have the same "chicken and egg" problem of the independent variable being partly driven by the response variable. The "I" in FIP is for improvement; a FIP might not be activated if there is no perceived need for improvement. If FIPs are implemented during a period of increasing fishing pressure or decreasing biomass, aiming to reverse these trends through improvements, some of those changes could be attributed statistically to the FIP implementation. Time series around FIP implementations were relatively short and thus sample sizes were insufficient to properly evaluate changes in fishing pressure and biomass in years before and after FIP implementation (Fig. A.8a and b). A possible explanation for the lack of expected effect is that some FIPs are narrow in scope with stage-3 indicators that do not necessarily relate to pushing for rebuilding stock biomass or reducing fishing pressure on target stocks. Finally, for cases in which FIPs are implemented when government measures are still under development, new tools may be required and thus the time required to see changes at the stock level may be longer than in higher-intensity management systems (Cannon et al., 2018). To clarify the possible indications of opposite-from-expected associations between FIPs and trends in stock status, more detailed studies should consider the specific objectives of individual FIPs and the extent to which their action plans and indicators play a role in meeting those objectives.

Annual changes in fishing pressure or biomass are most informative in the context of their current magnitude. For example, an increase in biomass has different implications depending on whether that increase is from a low biomass level towards the target or from a high biomass level further away from the target. Overall, baseline changes in the absence of any management measures were an increase in relative fishing pressure (toward the target) and a decrease in relative biomass (toward the target) during the mature fishery phase. With respect to specific management measures, strong changes were associated with rebuilding plans (lowering fishing pressure towards targets and increasing biomass towards targets after implementation), followed by similar but weaker changes associated with harvest control rules (Fig. A.8a and b). In contrast, opposite patterns were observed following EEZ declarations, presumably as national management systems aimed to increase utilization of their fisheries resources. With respect to MSC assessment, on average fishing pressure was already relatively low and biomass already relatively high in the 10 years leading up to formal assessment, and these levels persisted in the 10 years following (Fig. A.8a and b). This supports earlier suggestions that favourable and stable stock status levels are typically a prerequisite for a successful MSC assessment (Melnychuk et al., 2022).

Voluntary measures are a market-driven approach and are therefore expected to be undertaken more commonly for more economically valuable fisheries. In turn, more valuable fisheries tend to receive more attention for conducting stock assessments (Neubauer et al., 2018) and for management (Melnychuk et al., 2023), so it may be expected that voluntary measures would be more influential for more valuable target species. With stocks weighted in proportion to their economic value instead of equally weighted, the positive influence of voluntary measures on biomass trends increased further. When disaggregated, this was attributed to the MSC pre-entry index (Fig. A.6). This may be an indication that fisheries undertaking a pre-assessment were successfully incentivised to contribute to increasing abundance especially for more valuable target stocks. Fisheries with a greater perceived need for improvements at the pre-assessment stage (including improvements in stock status) were assigned higher index values (Fig. 3). The positive coefficient estimate observed for the MSC pre-entry index can only result from these perceived needs being associated with a positive influence on biomass trends, and this result was observed only in the value-weighted analysis.

We did not consider all types of conditions and suspensions related to MSC certification in this study, only those that related to Principles 1 and 3, as these were more strongly hypothesised to potentially influence stock status. It seems this was supported by the results. Other types of conditions, as well as FIPs and certification in general, may be more relevant to a wider range of ecological objectives beyond management aspects and the status of target stocks. Whereas rebuilding plans are designed to do one thing (and do that well), FIPs and improvements following MSC pre-assessments are often designed to do many things, only one of which may be to help improve the status of target stocks. Other objectives outlined in action plans often include bycatch reduction of non-target species and reducing impacts on sensitive habitats (Lees et al. n.d.). If other aims typical of FIPs and MSC pre-assessments had been considered here, greater positive effects may have been observed than those limited to target stock status.

Our sample of fish and invertebrate stocks was not representative of all global fisheries. Although the included stocks were distributed in coastal and high seas waters around the world (Fig. 2; Table A.2), sample size was skewed towards regions and countries in which formal stock assessments are commonly conducted, which tend to be in countries with developed economies (Melnychuk et al., 2017). While our analyses relied on stock assessment outputs, it is important to note that these are not strictly necessary for managing fisheries effectively. Other systems that are instead based on co-management or bottom-up, community-based frameworks may be more effective in some socioeconomic contexts, particularly in countries with developing economies and in small-scale fisheries (Arnason, 2023; Basurto et al., 2025; Evans et al., 2011; Purcell and Pomeroy, 2015). Moreover, while management objectives involving stock sustainability status invariably rely on formal stock assessments, different management objectives and priorities do not to the same extent (Basurto et al., 2025; Bene et al., 2015; Evans et al., 2011; Szuwalski et al., 2016).

In this study, voluntary measures were considered simultaneously with government-mandated management measures for potentially influencing trends in stock status. As such, estimated coefficients for voluntary measures are intended to represent effects above and beyond those of mandated measures and start-of-year biomass. However, this analysis framework does not fully capture the extent of potential MSC or FIP effects, which may instead be indirect. Under the MSC Theory of Change and the overall FIP model, these programs are intended to incentivise best practices in fisheries and to incentivise changes in management, so any indirect influence on fish stock status may be attributed statistically to government-mandated measures. Further, in addition to providing nudges in several key areas of fisheries sustainability, the MSC program in particular is designed to reward fisheries that are already fishing sustainably, so changes in stock status following implementation should not necessarily be expected (i.e., maintaining an already-acceptable state would instead be expected). Science-based voluntary measures should therefore be viewed as potentially valuable tools when used in parallel with, rather than as an alternative to, conventional fisheries management measures. This aligns with how the MSC program is designed, with requirements pertaining to conventional management systems intentionally built into the Fisheries Standard. Although we only considered relatively data-rich stocks in this analysis, in contexts of more limited data availability and governance capacity, voluntary measures and other market-driven approaches may also help to catalyse stronger management and data collection frameworks.

CRediT authorship contribution statement

Michael C. Melnychuk: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Samantha Lees:** Writing – review & editing, Methodology, Investigation, Data curation. **Pedro Veiga:** Writing – review & editing, Methodology, Investigation, Data curation. **Jennifer Rasal:** Methodology, Investigation, Data curation. **Nicole Baker:** Investigation. **Lauren Koerner:** Visualization, Methodology, Investigation, Data curation. **Daniel Hively:** Investigation, Data curation. **Hiroyuki Kurota:** Writing – review & editing, Investigation. **Carryn L. de Moor:** Writing – review & editing, Investigation. **Maite Pons:** Writing – review & editing, Investigation. **Pamela M. Mace:** Writing – review & editing, Investigation. **Ana M. Parma:** Writing – review & editing, Methodology, Investigation. **Alessandro Mannini:** Writing – review & editing, Investigation. **L. Richard Little:** Investigation. **Jilali Bensbai:** Writing – review & editing, Investigation. **Arturo Muñoz Albero:** Writing – review & editing, Investigation. **Beth Polidoro:** Writing – review & editing, Supervision. **Ernesto Jardim:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Ray Hilborn:** Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Catherine Longo:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization.

5. Data statement

All stock status data are contained in the RAM Legacy Stock Assessment Database (extended version 4.66 'model fits'), available at https://doi.org/10.5281/zenodo.14043038 (RAMLDB, 2024). Supplementary data files provide government-mandated management data (Table A.3), MSC fishery data (Table A.4), Fishery Improvement Projects data (Table A.5), and MSC conditions of certification and suspensions (Table A.6) used in analyses. All MSC fishery data are available through 'Track a Fishery' (https://fisheries.msc.org/en/fisheries/). Additional FIP data are available through FIP-DB (https://sustainablefisheries-uw.org/databases/fishery-improvement-projects-database). Stock assessment areas shown in Fig. 2 were primarily drawn from the RAM Legacy Stock Boundary Database (https://github.com/cfree14/ram_boundaries). Code to reproduce statistical analyses and generate figure outputs is available upon request.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ray Hilborn reports financial support was provided by World Wildlife Fund. Ray Hilborn reports financial support was provided by consortium of Seattle fishing companies through the University of Washington. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. None of the authors have any interests to disclose, apart from employment with environmental organisations, government agencies or academic institutions involved with researching and advocating for sustainable fisheries management policies.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.124090. Appendix A contains supplementary tables and figures. Appendix B describes supplementary methods. Appendix C describes ARIMA model structures and diagnostics.

Data availability

Datasets used in this analysis are provided as supplementary files or cited with links. Our Data Statement in the paper details these sources.

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