ANALYSIS
https://doi.org/10.1038/s41893-020-00668-1

nature sustainability

Check for updates

Identifying management actions that promote sustainable fisheries

Michael C. Melnychuk[1]✉, Hiroyuki Kurota[2], Pamela M. Mace[3], Maite Pons[1], Cóilín Minto[4], Giacomo Chato Osio[5,6], Olaf P. Jensen[7,8], Carryn L. de Moor[9], Ana M. Parma[10], L. Richard Little[11], Daniel Hively[1], Charmane E. Ashbrook[1], Nicole Baker[1], Ricardo O. Amoroso[1], Trevor A. Branch[1], Christopher M. Anderson[1], Cody S. Szuwalski[12], Julia K. Baum[13], Tim R. McClanahan[14], Yimin Ye[15], Alessandro Ligas[16], Jilali Bensbai[17], Grant G. Thompson[12], John DeVore[18], Arni Magnusson[19], Bjarte Bogstad[20], Edward Wort[21], Jake Rice[22] and Ray Hilborn[1]

Which management actions work best to prevent or halt overfishing and to rebuild depleted populations? A comprehensive evaluation of multiple, co-occurring management actions on the sustainability status of marine populations has been lacking. Here we compiled detailed management histories for 288 assessed fisheries from around the world (accounting for 45% of those with formal stock assessments) and used hierarchical time-series analyses to estimate effects of different management interventions on trends in stock status. Rebuilding plans, applied less commonly than other management measures (implemented at some point historically for 43% of stocks), rapidly lowered fishing pressure towards target levels and emerged as the most important factor enabling overfished populations to recover. Additionally, the ratification of international fishing agreements, and harvest control rules specifying how catch limits should vary with population biomass, helped to reduce overfishing and rebuild biomass. Notably, we found that benefits of management actions are cumulative—as more are implemented, stock status improves and predicted long-term catches increase. Thus, a broad suite of management measures at local, national and international levels appears to be key to sustaining fish populations and food production.

Well-designed management systems can improve environmental outcomes of renewable resources. In many regions, fisheries management now effectively regulates fishing pressure, either to maintain population biomass within sustainable, productive ranges or to rebuild populations back to more productive levels[1–4]. In other regions, fisheries regulation and enforcement are lacking or insufficient, and as a result many stocks have become overfished[5–7]. Management systems are complex, and it is unclear which specific management measures are most influential because many may be applied simultaneously, in different combinations and with varying impacts on individual fished stocks[7–11]. The numerous measures used to manage fisheries also vary considerably among stocks and regions[1,7,9], and may have stronger effects on some life-history types or fishing fleets than on others[12]. Our limited understanding of the relative effectiveness of different management measures hinders fishery-rebuilding initiatives around the world, impedes progress towards the zero-overfishing target of the United Nations Sustainable Development Goals[13] and diminishes potential global food production from capture fisheries[14].

Here we distinguish between management measures applied to individual stocks from those applied at the country level as mandated by broader legislative policies or commitments in international agreements[15–17]. Previous studies have identified measures such as catch limits[6,18], harvest control rules that specify how catch limits should vary with stock abundance[19] and individual quotas[18], which have helped to meet management targets. Although overall management intensity and comprehensive reforms generally aid in meeting objectives for target species[3,4,7,14], there are also cases where fishing pressure was not reduced, and cases where fishing pressure was reduced but stocks nevertheless did not recover[1,12,20]. To identify the combinations of management actions most consistently effective at reducing overfishing and rebuilding depleted stocks, in this article we collate the multi-level management history of hundreds of individual stocks, and then assess which actions are most influential.

[1]School of Aquatic and Fishery Sciences, University of Washington, Seattle, WA, USA. [2]Fisheries Resources Institute, Japan Fisheries Research and Education Agency, Nagasaki, Japan. [3]Fisheries New Zealand, Wellington, New Zealand. [4]Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, Galway, Ireland. [5]Unit D.02 Water and Marine Resources, Directorate D—Sustainable Resources, Joint Research Centre, European Commission, Ispra, Italy. [6]Unit D.1 Fisheries Conservation and Control in Mediterranean and Black Sea, DG Maritime Affairs and Fisheries, European Commission, Brussels, Belgium. [7]Department of Marine and Coastal Science, Rutgers University, New Brunswick, NJ, USA. [8]University of Wisconsin-Madison, Center for Limnology, Madison, WI, USA. [9]Marine Resource Assessment and Management (MARAM) Group, Department of Mathematics and Applied Mathematics, University of Cape Town, Rondebosch, South Africa. [10]Center for the Study of Marine Systems, CONICET, Puerto Madryn, Argentina. [11]CSIRO Oceans and Atmosphere, Hobart, Tasmania, Australia. [12]Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, Seattle, WA, USA. [13]Department of Biology, University of Victoria, Victoria, British Columbia, Canada. [14]Global Marine Program, Wildlife Conservation Society, Bronx, NY, USA. [15]Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome, Italy. [16]Consorzio per il Centro Interuniversitario di Biologia Marina ed Ecologia Applicata, Livorno, Italy. [17]Institut National de Recherche Halieutique, Casablanca, Morocco. [18]Pacific Fishery Management Council, Portland, OR, USA. [19]ICES Secretariat, Copenhagen, Denmark. [20]Institute of Marine Research, Bergen, Norway. [21]School of Biological and Marine Science, University of Plymouth, Plymouth, UK. [22]Science Branch, Fisheries and Oceans Canada, Ottawa, Ontario, Canada. ✉e-mail: mmel@u.washington.edu

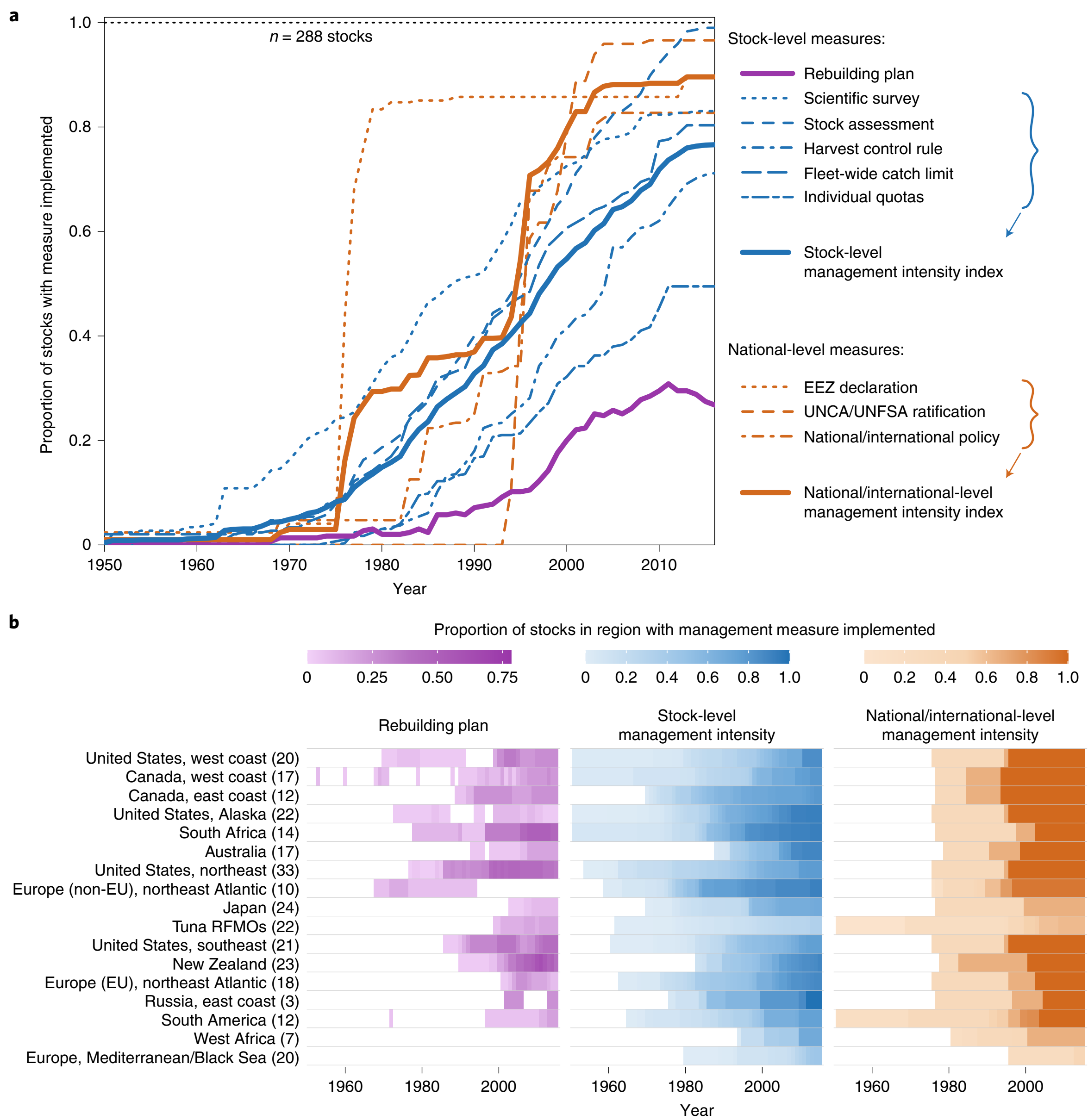

Fig. 1 | Implementation history of fisheries management measures for assessed stocks, showing steady increases globally over the past half century. **a**, Thick solid lines represent the proportion of stocks under a rebuilding plan (purple), and aggregate indices of management intensity at the stock level (blue) or national/international level (orange). Thin dotted/dashed lines show individual measures that comprise these aggregate indices. **b**, Region-specific proportions of stocks for the three thick solid lines in **a**. Numbers in parentheses show the number of stocks in analyses, and regions are ordered top to bottom by median U/U_{REF} of stocks over their last five years of available data (lowest to highest). EEZ, exclusive economic zone; RFMO, Regional Fisheries Management Organization.

Management histories of fished populations

Management histories for 288 well-studied stocks from 17 regions around the world covered a range of measures implemented at the stock level and at national/international levels (Supplementary Table 1). Use of stock-level measures increased steadily from low levels in 1950 (Fig. 1 and Supplementary Figs. 1–3). One of the key measures, rebuilding plans, involves fishery moratoria or substantial reductions in allowable catches for stocks with depleted biomass, typically used as an emergency measure. Rebuilding plans are incredibly diverse across stocks and regions in terms of the criteria that trigger implementation, the specific measures enacted under the plan and the degree to which those measures are enforced[20]. Rebuilding plans became more commonly used after the mid-1980s in most regions (particularly in the northeast and southeast United States, South Africa and New Zealand; Fig. 1b), and for the past two decades have been in place for roughly one-quarter of sampled stocks in any given year (Fig. 1a). Five additional measures have also been increasingly implemented: at least three-quarters of sampled stocks are currently managed using scientific surveys of fish abundance, stock assessments, fleet-wide catch limits and harvest control rules; and half of sampled stocks are managed using individual quotas, where fishing access is divided among vessels or other entities (Fig. 1a).

In contrast to the incremental addition of stock-level measures, nationally and internationally mandated measures are usually applied simultaneously for many stocks in a country or region (Fig. 1 and Supplementary Figs. 2 and 3). These measures include declaration of exclusive economic zones, primarily in the late

1970s[15]; ratification of the Compliance Agreement of the Food and Agriculture Organization of the United Nations (UNCA)[16] or the UN Fish Stocks Agreement (UNFSA)[17], mainly during the 1990s; and major fishery legislation at the country or regional level, implemented mostly during the 1980s–1990s but varying by region (Supplementary Table 2 and Supplementary Discussion).

Treating management changes as policy interventions

We hypothesize that each of the management measures shown in Fig. 1 and described in Supplementary Table 1 should strongly influence the fishing pressure and biomass of stocks. Because the timing of implementation varies by stock and region (Supplementary Figs. 2 and 3 and Supplementary Discussion), each application of a management measure can be modelled as a policy intervention that affects fishing pressure (U, the annual fraction harvested) and, through U, indirectly affects stock biomass (B). Time series of U and B relative to fisheries management target reference points (U_{REF} and B_{REF}, which are usually related to maximum sustainable yield, MSY, or approximations of MSY) were assembled for 288 stocks from the RAM Legacy Stock Assessment Database (RAMLDB)[21,22], with regional representation reflective of all assessed stocks from these regions (Supplementary Table 3). Fisheries on these 288 stocks accounted for 30% (mean, 23.8 million t) of all global marine catch from 1970 to 2017 (Supplementary Table 3). These stocks represent a variety of fish and invertebrate taxa, comprise both large and small populations, and are harvested by diverse gear types and industry structures.

For each stock, we examine the impact of rebuilding plans, an aggregate management intensity index of the other five stock-level measures and an index of the three national-level measures (Fig. 1). The two indices range from 0 to 1 (Supplementary Methods). To quantify influences of management interventions during the most relevant portion(s) of a stock's fishing history, we partition time series of U/U_{REF} and B/B_{REF} into a 'developing' phase (with low fishing pressure and catch) and a 'mature' phase (after development) (Fig. 2). Across stocks, levels of U/U_{REF} and B/B_{REF} varied widely at the start of available time-series data, at the start of the 'mature' phase and when individual management measures were first applied (Supplementary Table 4); analyses integrate over this variability in initial conditions of fishing pressure and biomass status.

Hierarchical autoregressive integrated moving average (ARIMA) time-series models (Methods) allow us to relate changes in U/U_{REF} and B/B_{REF} to the implementation of management measures. For any given stock and intervention, years before the intervention contribute information to the baseline trend, and years after the intervention contribute to the impacted trend. We use these models with verified temporal causality in U/U_{REF} and B/B_{REF} (Supplementary Note 1) to address three questions: (1) How do different types of management measures, fishery attributes and life-history traits affect trends in fishing pressure and biomass? (2) What are the short-term predicted responses in fishing pressure and biomass trends after implementing a combination of management measures? (3) What are the predicted equilibrium levels of fishing pressure, biomass and fishery yield relative to targets under a given set of management conditions?

Results

The three subsections below directly correspond to research questions (1)–(3).

Management measures collectively meet objectives. Strong fisheries management reduced fishing pressure and increased biomass towards their targets. In the absence of any management measures, on average U/U_{REF} increased by 2.9–4.8% annually and B/B_{REF} decreased by 3.1–4.4% annually during the 'mature' fishery phase across three taxonomic groups (Fig. 3). Incrementing either of the two management intensity indices slowed these trends, and if implemented along with a rebuilding plan, reversed these trends to reduce U/U_{REF} (by 56.3–57.0% in the first year of a rebuilding plan and 4.9–6.6% annually thereafter) and increase B/B_{REF} (by 5.2–6.6% annually after the first year of a rebuilding plan). Across stocks, the mean magnitude of U/U_{REF} was >1 and the mean magnitude of B/B_{REF} was <1 during the 'mature' fishery phase; therefore, on average, these directional changes under management imply moving towards target ratios of 1. Rebuilding plans tended to be implemented when several other measures were already in place (Supplementary Fig. 4). With the influence of rebuilding plans separated into immediate (first year) and persistent (all remaining years) components, for U/U_{REF} the immediate effect was strongest, and for B/B_{REF} the persistent effect was strongest (Fig. 1).

Influences of management on stock status were robust to alternative model structures and weighting assumptions. Aside from rebuilding plans, if components of management intensity indices are disaggregated for reanalysis, the individual measures with greatest influence on stock status were enacting the UNCA or UNFSA (negative effect on fishing pressure and positive effect on biomass); and harvest control rules (slight positive effect on biomass; Supplementary Fig. 5). Other management measures considered individually did not significantly affect fishing pressure or biomass trends (Supplementary Fig. 5), but still contributed to influence stock status via their inclusion in aggregate indices of management intensity (Fig. 3). If stocks are instead weighted by their maximum sustainable landed value (the product of MSY and average price, which both drive incentives for fishing[23]), the immediate decrease in fishing pressure from implementing a rebuilding plan was still the greatest effect overall (Supplementary Fig. 6), but was less pronounced than the effect under equal weighting (Fig. 3). The relative influence of the two management intensity indices on stock status differed slightly depending on whether stocks were equally weighted or weighted by landed value, but effects were similar in magnitude (Fig. 3 and Supplementary Fig. 6).

Compared with time-varying management attributes, the static fishery-related attributes and life-history traits generally had weaker associations with fishing pressure and biomass trends. The patterns that did emerge were that stocks in mixed-species fisheries had a slower increase in fishing pressure than stocks in single-species fisheries (Fig. 3), and later-maturing species had faster rates of biomass decline during baseline periods and slower rates of biomass recovery after management measures were implemented. No significant effects of landed value, body size or taxonomic group on trends in fishing pressure or biomass were observed, and other life-history variables were not included as predictors due to collinearity (Supplementary Fig. 7).

Rebuilding plans provide rapid turn-around. To address question (2), estimated parameters from fitted models were used to predict fishing pressure and biomass trends for nine years before and ten years after management interventions (Methods). Shortly before interventions, the modelled stock was overfished ($U/U_{REF} \approx 2$) and biomass was depleted ($B/B_{REF} \approx 0.5$; Fig. 4).

Rebuilding plans rapidly decreased fishing pressure and accelerated the recovery of depleted stocks. By implementing a full suite of five stock-level management measures and a full suite of three national-level measures, the baseline increase in average fishing pressure was reversed, and the baseline decrease in average biomass was slowed (Fig. 4). By also implementing a rebuilding plan simultaneously, the model predicted that fishing pressure would be reduced sharply in the first year after implementation to below target levels ($U/U_{REF} < 1$), and that biomass would increase to near targets within a ten-year projection period (Fig. 4). Scenarios with lower levels of stock-level and national-level management intensity had weaker

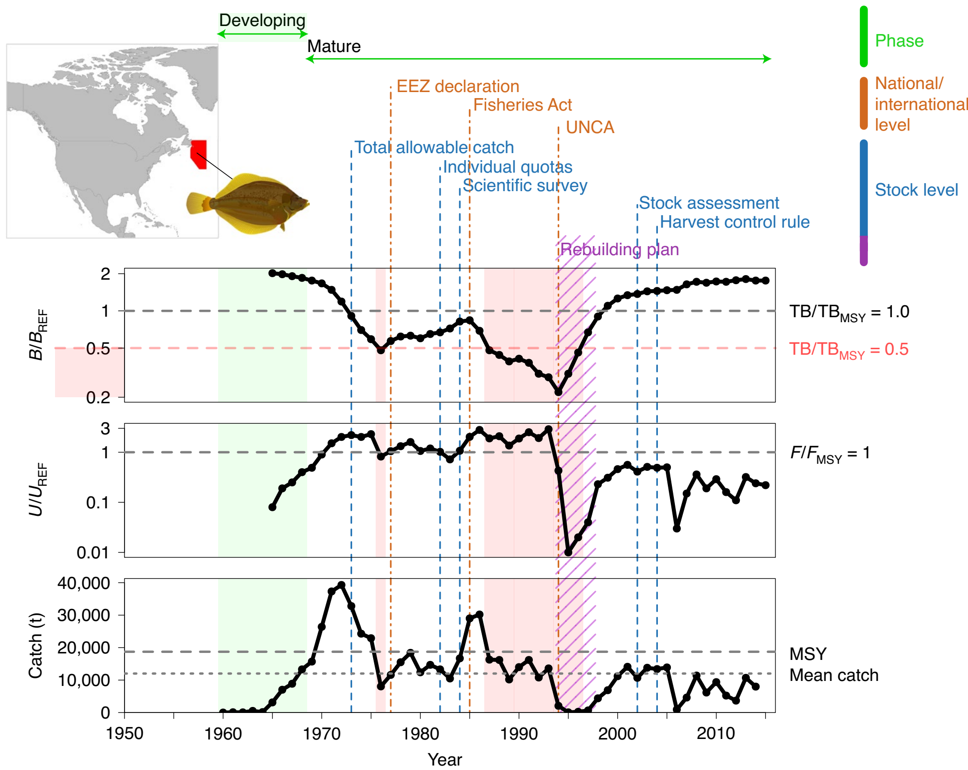

Fig. 2 | Stock status history relative to the timing of fisheries management interventions. Data for yellowtail flounder on the Grand Banks of Newfoundland (statistical area 3LNO) are shown as an example. Similar figures are provided for all 288 stocks in Supplementary Fig. 1. Panels show time series of relative biomass (B/B_{REF}), relative fishing pressure (U/U_{REF}) and catch. For this stock, B/B_{REF} is best represented by total biomass relative to a benchmark based on maximum sustainable yield (TB/TB_{MSY}), and U/U_{REF} is best represented by the fishing mortality rate relative to an MSY-based benchmark (F/F_{MSY}). Stock histories are partitioned into 'developing' (shaded green) and 'mature' fishery phases (Supplementary Methods). Years during which $B/B_{REF} < 0.5$ are shaded light red. Years under a rebuilding plan are shown with purple hatching. Years when other management measures were first implemented are indicated by vertical dashed lines. Flounder image reproduced with permission from Fisheries and Oceans Canada.

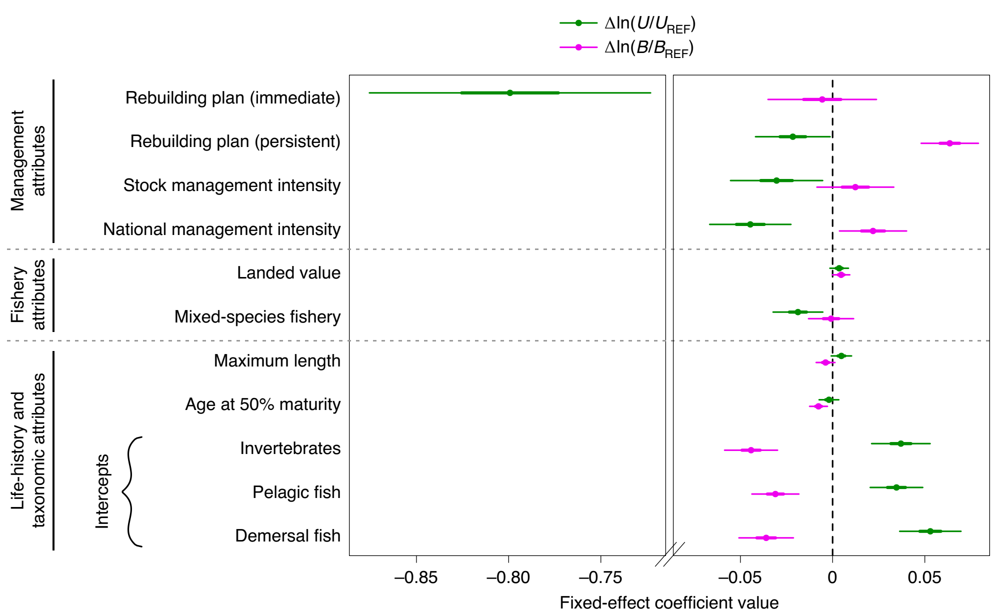

Fig. 3 | Effects of management, fishery and life-history attributes on annual changes in relative fishing pressure and relative biomass. Positive (or negative) coefficients reflect increasing (or decreasing) trends in fishing pressure (U/U_{REF}, in green) and biomass (B/B_{REF}, in purple) during the 'mature' fishery phase. The horizontal axis is broken for visual clarity because one coefficient differs substantially in magnitude from the others. 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.

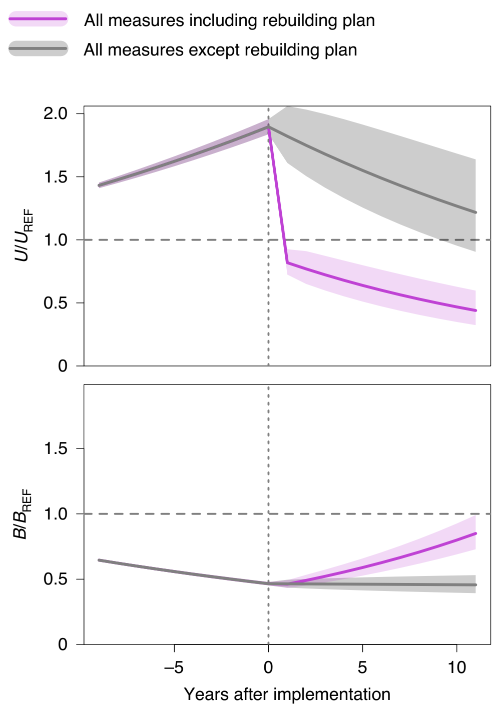

Fig. 4 | Predicted effects of fisheries management interventions on stock status. Predictions are shown for relative fishing pressure (U/U_{REF}) and relative biomass (B/B_{REF}) of an average stock during its 'mature' fishery phase. Year 0 represents when a full suite of five stock-level measures and three national/international-level measures were implemented, either with or without a rebuilding plan. 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.

responses, but the effect of rebuilding plans on stock status trends remained strong across scenarios (Supplementary Fig. 8).

If the fitted model is based on stocks weighted by landed value instead of weighted equally, the immediate decrease in fishing pressure following a rebuilding plan intervention was less pronounced, but the persistent increase in biomass under a rebuilding plan was stronger (Supplementary Fig. 8). There is considerable variability in the raw data around these mean predictions (Supplementary Fig. 9); nevertheless, among the nine individual management measures, the implementation of rebuilding plans had the strongest association with reduced fishing pressure and increased biomass (Supplementary Fig. 9).

Necessity of multi-level management approaches. To address question (3), long-term predictions of biomass and fishing pressure under a given management regime were obtained by additionally using B/B_{REF} as a predictor for change in U/U_{REF}, and U/U_{REF} as a predictor for change in B/B_{REF}, and then projecting U/U_{REF} and B/B_{REF} forward together to equilibrium (Methods). At this equilibrium, expected catch relative to MSY is given by $B/B_{REF} \times U/U_{REF}$. During projections, rebuilding plans were assumed to activate when B/B_{REF} fell to <0.5, and to deactivate when B/B_{REF} increased to >1.

We found that strong fisheries management at both stock and national levels was required to prevent overfishing and maintain stocks at their most productive levels. Equilibrium predictions of biomass, fishing pressure and catch were sensitive to both stock-level and national-level management intensity (Fig. 5). At the highest levels of management intensity (index values ≥0.75), equilibrium biomass was greater than targets, fishing pressure was lower than targets and catches were near targets; rebuilding plans were unnecessary because mean biomass did not decline below activation levels. As one or both management indices decreased towards intermediate levels, equilibrium biomass and catch dropped to less than targets and fishing pressure increased to greater than targets. As the combined management intensity dropped further and crossed a threshold (into the shaded region of the right-most panel in Fig. 5), the equilibrium switched from a stable point to a cycle of periodic rebuilding plans (Supplementary Fig. 10), with biomass occasionally dropping below the activation threshold of $0.5B_{REF}$ and then, under active rebuilding, increasing to $>B_{REF}$ at which point the rebuilding plan was deactivated.

The predicted proportion of time spent under rebuilding plans varied inversely with management intensity (Fig. 5; in practice, use of rebuilding plans usually coincides with moderate to high values of management intensity, Supplementary Fig. 4). During these cycles, average catch remained relatively high, ~0.75MSY, but this was obtained only by applying high average fishing pressures ($U/U_{REF} \approx 1.5$) to low average biomass ($B/B_{REF} \approx 0.5$), through cycles of alternating overfishing and rebuilding periods. In the absence of rebuilding plans at low to moderate levels of management intensity, stocks would be depleted and average catches would be lower.

Discussion

Among commonly used management measures, rebuilding plans had the strongest effect overall on changes in stock status. Implementing a rebuilding plan resulted in rapid drops in fishing pressure, from overfishing in one year to below targets in the next, and accelerated the rebuilding process of depleted stocks in our short-term projections. While previous studies have described the effectiveness of rebuilding plans in specific regions[20,24], our global analysis revealed the great extent to which they outperformed other individual management actions. This stronger response compared to other measures might be expected given that rebuilding plans are typically implemented when fishing pressure is high and biomass is depleted (Supplementary Table 4), leaving much room for improving stock status. Specific criteria for implementing a rebuilding plan, and targets for recovery, vary among fisheries and regions. Rebuilding plans have usually been implemented when levels of management intensity were already moderate or high (Supplementary Fig. 4), and multiple measures may be incorporated into a rebuilding plan that includes sharp reductions in catch or effort limits; setting and enforcement of bycatch limits for the species; expansion of temporal or spatial closures; and gear restrictions to reduce discards. As part of a rebuilding plan 'package', these and other measures have usually resulted in depleted stocks recovering. Biomass increased for over three-quarters of the stocks in our dataset for which rebuilding plans were in place for at least five of the last ten years of available data ($n = 69$ of 88; Supplementary Fig. 1). When stocks did not show signs of biomass increase despite being under rebuilding plans ($n = 19$), this was typically because the rebuilding plan had failed to halt overfishing ($n = 14$; that is, fishing pressures were $>U_{REF}$ targets in most or all years during this period), supporting previous findings[12,20]. Although rebuilding plans have not always led to populations recovering to target levels[20], in most cases they have succeeded through reductions in fishing pressure that stemmed from substantial reductions in catch or effort limits[2,6,25]. Indeed, the two regions in our dataset with greatest median U/U_{REF} recently (Mediterranean/Black Seas and West Africa) are also the only two regions without any history of rebuilding plans implemented (Fig. 1b and Supplementary Discussion). Some of the failures of depleted stocks to recover can also result from changes in environmental conditions[26,27].

Apart from rebuilding plans, other stock-level and national-level measures contributed to regulating fishing pressure and rebuilding biomass. Notably, when multiple measures were implemented

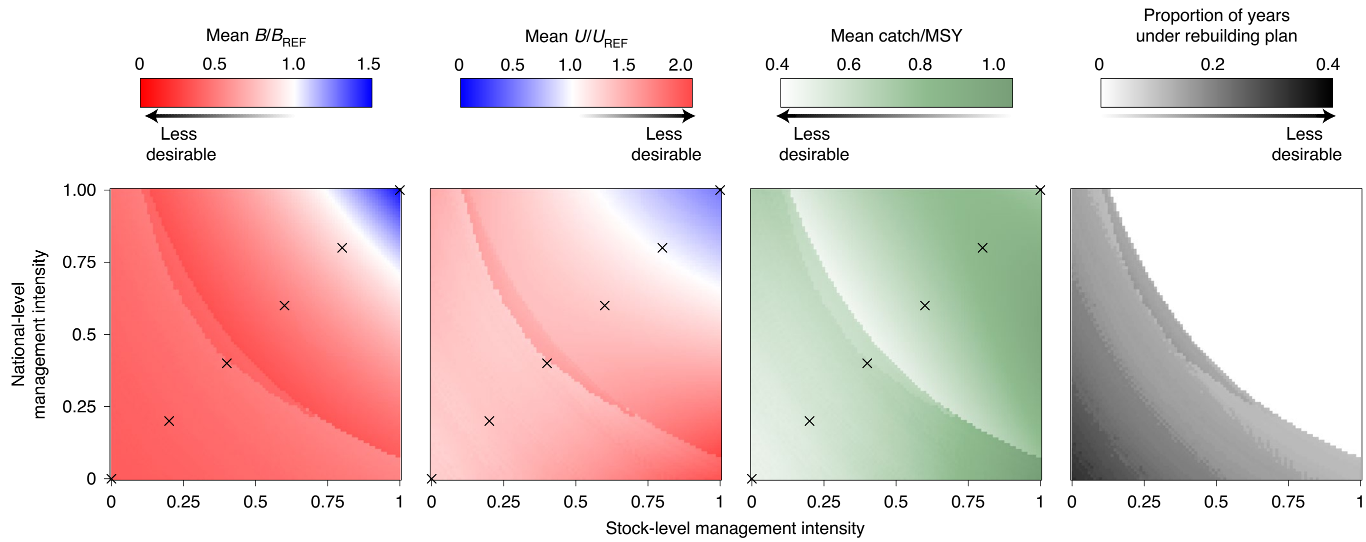

Fig. 5 | Equilibrium predictions at different combinations of stock-level and national-level management intensity. Predictions are shown for mean scaled relative biomass (B/B_{REF}), mean relative fishing pressure (U/U_{REF}), mean relative catch (catch/MSY) and the proportion of years spent under rebuilding plans for an average stock. White isoclines in the first two panels represent management target ratios of 1. For each panel, conditions generally considered as less desirable with respect to management targets are indicated. Crosses show combinations of stock-level and national-level management intensity at which representative equilibrium time series were extracted for Supplementary Fig. 10.

together to strengthen overall management intensity, the need for rebuilding plans was avoided (because the modelled stock at equilibrium was never overfished), consistent with previous suggestions for avoiding strict fishing moratoria[24,28]. The effect on stock status was particularly strong from enacting either the UNCA or the UNFSA (Supplementary Fig. 5). This was surprising because these agreements do not apply directly to the many stocks in our dataset that are caught entirely within the waters of a single country, whereas the agreements address illegal and unreported fishing on the high seas and management of transboundary stocks. The observed influence of the UN agreements might reflect countries generally intensifying their fisheries management approaches as they simultaneously instituted changes for transboundary or high-seas stocks in the mid-1990s. The non-binding Food and Agriculture Organization Code of Conduct for Responsible Fisheries was also introduced around the same time, embodying many of the same principles as the UNFSA and the UN Convention on the Law of the Sea[15], and further encouraged the strengthening of fisheries management in domestic waters. In turn, the engagement of countries in these international agreements was enabled by their management capacity, which had already been gradually developing over preceding decades.

Effects of management measures on stock status trends were stronger when considered in aggregate (Fig. 3) than individually (Supplementary Fig. 5), as found previously[29]. This suggests that comprehensive management systems with multiple measures in place provide greater opportunities and mechanisms for meeting objectives. This result further implies that of the many individual measures available to fisheries managers, there is no one-size-fits-all solution, underscoring the need for local management approaches to be tailored to each fishery's biological and socioeconomic context.

In the long term, a wide range of combinations of stock biomass and fishing pressures will often produce annual yield near MSY[30]. Likewise, equilibrium projections showed that during cycles of overfishing and rebuilding, a wide range of management intensity levels produced similar levels of equilibrium catch on average, ~0.75MSY (Fig. 5), at the cost of low biomass and high interannual variability in catch (Supplementary Fig. 10). Although fluctuations in stock biomass and catch due to environmental changes are unavoidable for some species[26,27], large fluctuations that result from controllable management policies increase the risk of stock collapse and result in poorer socioeconomic outcomes due to their boom-and-bust nature. Our equilibrium projections suggest that strong management at both stock and national levels (for example, four of five stock-level measures and all three national-level measures implemented) can avoid these unnecessary cycles, generate higher average annual yield and also reduce interannual variability in yield, consistent with previous findings[8–10,18].

The regions included in our analysis tend to contain well-studied stocks and have high management capacity compared with others around the world, yet even in these regions there are many stocks that could not be included because they lack scientific estimates of biomass or fishing pressure. Larger and more valuable stocks are disproportionately fished[23], scientifically studied[31] and managed, and therefore smaller or less valuable stocks were less likely to be included here. Furthermore, over half the world's landings from capture fisheries come from regions with more limited capacity for research and management, in which formal stock assessments are rarely conducted[7,13,14]. These regions, which lacked the status estimates to be included in our analysis, are typically of greater concern for poor and worsening stock status[7,13].

The management approaches that can attain the best possible outcomes in a given fishery depend on goals and on resources, which differ especially among regions varying in management capacity[29]. The intensive measures that have proven successful in attaining stock status objectives within our sample may not be feasible in regions without the infrastructure to conduct surveys or monitor stock-level catch by fleet or by individual vessel[13]. In those regions, typical measures include fleet size controls, area-based regulations of access for different fleets and seasonal closures. These are usually not tailored to individual stocks, and may better align with objectives of maintaining multi-species aggregate catches rather than the status of any constituent stock. Nevertheless, the insights of this study extend to aggregate catch measures: limiting fishing effort is expected to maintain fishery resources at productive levels, or to rebuild them back to these levels. Effective fisheries management requires engaging at national, stock and fleet levels, and responding to changes in stock status or relative abundance with appropriate interventions.

Methods

This section describes model specifications and procedures for fitting ARIMA models to stock status and fisheries management data. ARIMA models, a form of time-series analysis, have been commonly used in fisheries applications to forecast landings or abundance[32,33]. Implementing a management measure can be considered a policy intervention that potentially affects stock status, that is, fishing pressure and biomass relative to target reference points (U/U_{REF} and B/B_{REF}). These possible effects were evaluated using ARIMA models, in this case not for forecasting but for attributing changes over time in stock status to management actions. The models are hierarchical, integrating effects across stocks while assuming stock-level random effects, and account for autoregressive and moving-average components in their correlation structures.

Management measures are not implemented randomly, but typically when undesirable trends are detected[6,25,34] or as social context changes[35]. Although temporal causality in the response variables was verified (Supplementary Note 1), our analysis does not account for the non-random implementation of management measures, that is, for self-selection bias. Propensities for implementing single measures have been quantified in other studies to account for non-random implementation[18,31]. For multiple measures analysed simultaneously, however, identifying suitable control stocks without management is prohibitive; stocks with less-intensive management also tend to have unknown trends in biomass and fishing pressure. Instead, information about the absence or presence of a management measure is provided by the pre- or post-intervention periods, respectively.

The following three subsections below directly correspond to research questions (1)–(3), and directly correspond to the three Results subsections. The Supplementary Methods describes the input data, data preparation procedures, pre-modelling diagnostics and sensitivity analyses conducted. Supplementary Tables 5 and 6 provide additional details for pre-modelling diagnostics, Supplementary Table 7 summarizes model fit diagnostics, while Supplementary Table 8 and Supplementary Note 2 provide additional details for sensitivity analyses.

Base model for stock status trends. To address question (1), a base model was constructed to evaluate the relative influence of management, fishery and life-history attributes on stock status trends. Response variables $y_{t,j}$ are first-order differenced time series of $\ln(U/U_{REF})_{t\to t+1,j}$ or $\ln(B/B_{REF})_{t\to t+1,j}$ representing the change from year t to year $t+1$ for stock j. Positive values reflect increases over time in U/U_{REF} or B/B_{REF}, and negative values reflect decreases. Response variables were modelled as:

$$\begin{aligned} y_{t,j} &= \beta_0 + b_{1,\mathrm{Taxon}_j} + b_{2,\mathrm{SingMix}_j} + b_3 A_{\mathrm{M50}_j} + b_4 L_{\mathrm{MAX}_j} \\ &\quad + b_5 \mathrm{MSLV}_j + b_6 \mathrm{Reb}_{\mathrm{immediate}_{t,j}} + b_7 \mathrm{Reb}_{\mathrm{persistent}_{t-1,j}} \\ &\quad + b_8 \mathrm{Mgmt}_{\mathrm{stock}_{t,j}} + b_9 \mathrm{Mgmt}_{\mathrm{national}_{t,j}} + \beta_j + \varepsilon_{t,j} \\ \beta_j &\sim N(0, \sigma^2_{\mathrm{stock}}) \\ \varepsilon_{t,j} &= \sum_{m=1}^{p} \phi_m y_{t-m,j} + \sum_{n=1}^{q} \theta_n \epsilon_{t-n,j} + \epsilon_{t,j} \\ \epsilon_{t,j} &\sim N(0, \sigma^2) \end{aligned} \tag{1}$$

Among fixed-effect coefficients (first line of equation (1)), life-history or fishery-related variables (b_1–b_5) are static quantities, and management variables (b_6–b_9) are time varying. Taxon_j is the three-level categorical variable of broad taxonomic groups, with two estimated parameters representing differences from the overall intercept. (For plotting in Fig. 3, these were instead shown as three overall intercepts.) $\mathrm{SingMix}_j$ is the single or mixed-species fishery categorical variable, with 'mixed-species' representing a difference from the overall intercept which represents the reference category 'single-species'. The life-history variables included are age at 50% maturity (A_{M50_j}) and maximum body length (L_{MAX_j}). MSLV_j is the maximum sustainable landed value, the product of MSY and average ex-vessel price.

In actuality, any management action lies on a continuum ranging from weak to strong, but for tractability in our analysis, we treat one management measure (rebuilding plans) as a binary category in any given year and other management measures as binary categories that increment a persistent management intensity index. Predictor variables for rebuilding plans assume a value of 1 only during the years in which rebuilding plans were active, and 0 in other years. Rebuilding plan effects (b_6 and b_7) are separated into a component that operates only in the year of implementation, $\mathrm{Reb}_{\mathrm{immediate}_{t,j}}$, and a component that operates in all years after the first year while the rebuilding plan is still active, $\mathrm{Reb}_{\mathrm{persistent}_{t-1,j}}$. With annual timesteps, $y_{t,j}$ is affected by $\mathrm{Reb}_{\mathrm{immediate}_{t,j}}$ in year t and by $\mathrm{Reb}_{\mathrm{persistent}_{t-1,j}}$ from previous years (in other words, there is a ≥1 year lag in the effect of $\mathrm{Reb}_{\mathrm{perisistent}}$ on y). This approach for rebuilding plans differs from the approach used for management intensity index variables $\mathrm{Mgmt}_{\mathrm{stock}_{t,j}}$ and $\mathrm{Mgmt}_{\mathrm{national}_{t,j}}$, for which only persistent effects were assumed to occur, beginning in the year of implementing a management measure and persisting thereafter.

The random effect term β_j (second line of equation (1)) represents stock-specific differences from the overall intercept β_0. The correlation structure function is specified by $\varepsilon_{t,j}$ (third line of equation (1)): the first term represents the autoregressive component, with number of lag terms equal to p; the second term represents the moving average component, with number of propagating noise terms equal to q; and the third term $\epsilon_{t,j}$ is a homoscedastic noise term centred at zero[36,37]. In an ARIMA(1,1,1) structure (Supplementary Methods), there is one ϕ autocorrelation parameter and one θ moving-average correlation parameter to estimate, applying the same grouping structure as assumed for the random effect terms[37]. Within-group error $\epsilon_{t,j}$ in the natural-log-transformed ratios (fourth line of equation (1)) is assumed to be normally distributed and independent of the random effects. After applying filters for surplus production fits and time-series duration, sample sizes were 284 stocks for U/U_{REF} and 280 stocks for B/B_{REF}.

The above model structure (equation (1)) was used for the results shown in Fig. 3. An alternative model formulation was also considered, in which the five components of the stock-level management intensity index and the three components of the national-level management intensity index were considered as predictor variables individually instead of including the two aggregated indices of management intensity. This required estimating 17 instead of 11 fixed-effect parameters, as eight management measures replaced the two indices b_8 and b_9. The results for this alternative structure are shown in Supplementary Fig. 5.

Two weighting schemes were considered. In the main text results and Fig. 3, stocks were equally weighted. In Supplementary Fig. 6, stocks were weighted by MSLV in millions of US dollars, giving greater weight to more valuable fisheries. Additionally, two regional-level weighting schemes were considered, with sample weights proportional to the number of stocks with available stock assessments in each region (Supplementary Note 2).

Model diagnostics were checked to ensure proper model fitting. These included plotting histograms of response variables ($\ln(U/U_{REF})_{t\to t+1}$ and $\ln(B/B_{REF})_{t\to t+1}$) after calculating first-order differences, to assess assumptions of normality; plotting residuals of model fits for response variables to identify possible non-linear patterns or heteroscedastic variances; and calculating variance inflation factors to assess potential collinearity of predictors[38]. Diagnostics were generated for both the 'mature' fishery phase and the full time series. Based on the variance inflation factor results, only two life-history variables were included in analyses (Supplementary Methods and Supplementary Fig. 7). Other diagnostics showed little reason for concern about possible violations of model assumptions.

All ARIMA(1,1,1) models (equation (1) above, as well as equations (2) and (3) outlined below) were fit to data by maximizing the restricted maximum likelihood[37]. The lme() function from the R package 'nlme'[39] was used for all model fits, using first-order differenced time series as the response variables and specifying an ARMA(1,1) correlation structure (which is equivalent to an ARIMA(1,1,1) structure with undifferenced time series). 'Stock' was treated as a grouping variable for both the correlation structure and random intercepts β_j. In all analyses, a minimum of ten years of data for a given stock and response variable were required for inclusion in analyses.

Predicting short-term responses to management. To predict short-term changes in U/U_{REF} and B/B_{REF} following the implementation of management measures, a model similar to the base model in research question (1) was fit to data, and estimated coefficients were subsequently used to project baseline trends (before intervention) and impacted trends (after intervention). The model, requiring eight fixed-effect parameters to be estimated, was identical to equation (1) without terms b_{1,Taxon_j} and $b_{2,\mathrm{SingMix}_j}$:

$$\begin{aligned} y_{t,j} &= \beta_0 + b_1 A_{\mathrm{M50}_j} + b_2 L_{\mathrm{MAX}_j} + b_3 \mathrm{MSLV}_j + b_4 \mathrm{Reb}_{\mathrm{immediate}_{t,j}} \\ &\quad + b_5 \mathrm{Reb}_{\mathrm{persistent}_{t-1,j}} + b_6 \mathrm{Mgmt}_{\mathrm{stock}_{t,j}} + b_7 \mathrm{Mgmt}_{\mathrm{national}_{t,j}} + \beta_j + \varepsilon_{t,j} \\ \beta_j &\sim N(0, \sigma^2_{\mathrm{stock}}) \\ \varepsilon_{t,j} &= \sum_{m=1}^{p} \phi_m y_{t-m,j} + \sum_{n=1}^{q} \theta_n \epsilon_{t-n,j} + \epsilon_{t,j} \\ \epsilon_{t,j} &\sim N(0, \sigma^2) \end{aligned} \tag{2}$$

This modification allowed us to predict changes in stock status trends for an average stock across all three taxonomic groups and both fishery types. Like the base model, this model assumes that aggregate management intensity indices have a persistent effect on stock status for all years during and following the intervention, whereas the effect of rebuilding plans is separated into immediate and persistent components. Similar to analysis of the base model, two weighting schemes were evaluated: stocks weighted equally and stocks weighted by MSLV.

After fitting the model to time-series data during the 'mature' fishery phase, estimated coefficients from equation (2) were used to project U/U_{REF} and B/B_{REF} forward 20 years. For the first nine years of projections, no management measures were active, representing a baseline scenario. In the tenth year (labelled as year 0 in Fig. 4 and Supplementary Fig. 8), a set of management measures was implemented and remained in place for the following ten years. Three scenarios were considered to represent low, medium or high levels of management intensity. These scenarios involved implementing one, three or five (of five possible) stock-level management measures along with one, two or three (of three possible) national/international-level measures, all implemented in year 0. For each of these three levels of management intensity, a rebuilding plan is either also implemented, or not implemented, in year 0 (Supplementary Fig. 8). The high-intensity scenario, either with or without rebuilding plans, is shown in Fig. 4.

Initial values of U/U_{REF} and B/B_{REF} used in projections were specified to represent typical states of overfishing and biomass depletion. These were calculated as the mean values across all stocks of U/U_{REF} and B/B_{REF} observed during years when stocks were under rebuilding plans. Means were first calculated for each stock, and the mean of means was then calculated across stocks. These overall means were calculated as $U/U_{\mathrm{REF}} = 1.45$ and $B/B_{\mathrm{REF}} = 0.65$, which were used as initial values, shown in year −9 in Fig. 4 and Supplementary Fig. 8.

After the initial year, values for following years were obtained by adding the predicted annual change in the variable, y_t, to the value from the preceding year. In the first nine years of projections, values of all management variables were set to 0 to calculate y_t, producing the baseline trends seen in Fig. 4 and Supplementary Fig. 8. By the end of this pre-management period, U/U_{REF} had increased to nearly 2, and B/B_{REF} had decreased to below 0.5. Management intensity variables were activated in year 0 and remained in place thereafter. By activating, the values of the stock-level management index switched from 0 to 0.2, 0.6 or 1 in the low-, medium- and high-intensity scenarios, respectively. Likewise, in year 0 the values of the national-level index switched from 0 to 1/3, 2/3 or 1 in the three scenarios. For rebuilding plans specifically, $\mathrm{Reb}_{\mathrm{immediate}_t}$ affects stock status in year $0 \rightarrow 1$, so the variable's value switched from 0 to 1 in year 0, and then switched back to 0 after the first year. Similarly, $\mathrm{Reb}_{\mathrm{persistent}_{t-1}}$ affects stock status in years after the first year, so the variable's value remained at 0 in year 0, and then switched to 1 in year 1 and remained at a value of 1 thereafter.

Total uncertainty around projected trends was estimated from the variances of four individual components. The first two were constant over the 20 year projection, the third was constant at one value for the first ten years and constant at a different value for the last ten years and the fourth component increased gradually over time because annual predicted changes y_t are cumulative over the projection period, updating values of U/U_{REF} and B/B_{REF} each year:

(1) One thousand random draws of fixed-effect parameters were resampled from a multivariate normal distribution of the covariance matrix for fixed-effect coefficients, accounting for covariances among fixed effects. Predicted values of y_t were generated for each sampled set of parameter values, and the variance across y_t predictions was calculated. Only applicable fixed effects were considered; for scenarios without rebuilding plans, parameter values for $b_4\mathrm{Reb}_{\mathrm{immediate}_t}$ and $b_5\mathrm{Reb}_{\mathrm{persistent}_{t-1}}$ were omitted.
(2) The variance of the random effect, $\sigma^2_{\mathrm{stock}}$ (stock-level differences from the overall intercept for y, β_0), was extracted from model fit outputs.
(3) Variances and covariances of fixed effects were extracted from the covariance matrix of the fitted model and summed. For the first ten years, only variances corresponding to non-management parameters (β_0, b_1, b_2, b_3) were included in the sum. For the last ten years, terms corresponding to applicable management parameters were also included in the sum.
(4) Annual variances over the 20 year period were assumed to increase because values of U/U_{REF} and B/B_{REF} in each year incremented with the added y_t. This incremental variance began at 0 in the year (−9) of initial conditions. For the next nine years of the pre-management period, the estimated variance of the overall intercept β_0 was added to the previous year's incremental variance component. For the last ten years, in the post-intervention period, the estimated variance associated with applicable management parameters was also added incrementally each year along with the variance of the overall intercept.

The largest variance component was the post-implementation period of (3). Variances of the four individual components were summed, and 95% confidence limits were calculated from the resulting total variance. These confidence limits were back-transformed from log space and are shown in Fig. 4 and Supplementary Fig. 8.

While Fig. 4 and Supplementary Fig. 8 show predictions resulting from the above fitted model (equation (2)), Supplementary Fig. 9 shows raw data for individual stocks in a similar format. Time series of U/U_{REF} and B/B_{REF} for each stock are shifted so that the year in which a given management measure was implemented aligns with year 0.

Predicting equilibrium responses to management. To predict long-term equilibrium states in U/U_{REF} and B/B_{REF} under a specified set of management conditions, a model similar to the base model in research question (1) was fit to data, estimated coefficients were used to predict annual changes in these variables and coupled projections of these predicted changes were together run out to equilibrium.

Changes in fishing pressure and biomass are influenced not only by management measures, but also by one another[40], as fishing pressure (that is, exploitation rate) is a proportion of the biomass, and biomass responds to fishing. The magnitude of B/B_{REF} was considered as another predictor of $\ln(U/U_{\mathrm{REF}})_{t\rightarrow t+1}$, and the magnitude of U/U_{REF} was considered as another predictor of $\ln(B/B_{\mathrm{REF}})_{t\rightarrow t+1}$. Predictions for annual change in U/U_{REF} feed into the function for predicting annual change in B/B_{REF}, which in turn feed back again into the following year's predictions for annual change in U/U_{REF}. This proceeds until equilibrium is reached. Coupling these functions for change allows for generating equilibrium (*) predictions of $(U/U_{\mathrm{REF}})^*$, $(B/B_{\mathrm{REF}})^*$, and their product, (catch/MSY)*. Predicted equilibrium values depend on the selected values for stock-level and national-level management intensity, which were held fixed. We assume stationarity in stock-recruitment and production relationships throughout these projections.

Coefficients were estimated from the following model, which builds on equation (2):

$$\begin{aligned} y_{t,j} = {} & \beta_0 + b_1 A_{\mathrm{M50}_j} + b_2 L_{\mathrm{MAX}_j} + b_3 \mathrm{MSLV}_j + b_4 \mathrm{Reb}_{\mathrm{immediate}_{t,j}} \\ & + b_5 \mathrm{Reb}_{persistent_{t-1,j}} + b_6 \mathrm{Mgmt}_{\mathrm{stock}_{t,j}} + b_7 \mathrm{Mgmt}_{national_{t,j}} + b_8 \tfrac{B}{B_{\mathrm{REF}_{t,j}}} \\ & + b_9 \left(\tfrac{B}{B_{\mathrm{REF}_{t,j}}}\right)^2 + b_{10} \mathrm{Mgmt}_{\mathrm{stock}_{t,j}} : \mathrm{Mgmt}_{\mathrm{national}_{t,j}} + \beta_j + \varepsilon_{t,j} \\ \beta_j \sim {} & N(0, \sigma^2_{\mathrm{stock}}) \\ \varepsilon_{t,j} = {} & \sum_{m=1}^{p} \phi_m y_{t-m,j} + \sum_{n=1}^{q} \theta_n \epsilon_{t-n,j} + \epsilon_{t,j} \\ \epsilon_{t,j} \sim {} & N(0, \sigma^2) \end{aligned} \tag{3}$$

The above model for $\ln(U/U_{\mathrm{REF}})_{\mathrm{t}\rightarrow\mathrm{t+1,j}}$ (with predictor terms B/B_{REF}) was coupled with the similar model for $\ln(B/B_{\mathrm{REF}})_{t\rightarrow t+1,j}$ (with predictor terms for U/U_{REF} instead of B/B_{REF}). Quadratic predictor terms (b_9) were included to allow for non-linearities in the values below and above target levels of 1. Again, the categorical fixed effects Taxon (taxonomic group) and SingMix (single or mixed-species fishery) used in the base model were omitted here, which allowed for making equilibrium predictions for an average stock across these groups. Combinations of stock-level and national-level management intensity values between 0 and 1 were selected and held fixed throughout projections, and the interaction between these two indices was included in the model (b_{10}) to allow for possibilities of redundancy between them. This model is most suitable for the full time series of each stock, including the 'developing' phase, because this allows for a greater range of U/U_{REF} and B/B_{REF} magnitudes and thus more reliable model fits with the greater contrast provided. The dataset for fitting equation (3) included 277 stocks that had B/B_{REF} and U/U_{REF} data both available (the remaining 11 of 288 stocks had one or the other time series missing).

Presence/absence of a rebuilding plan was not held fixed during projections, but was instead modelled as responding to predicted biomass, activating when B/B_{REF} decreased below 0.5, and deactivating when B/B_{REF} increased to above 1. Equilibrium may thus consist of a stable cycle during which rebuilding plans alternate between periods of activity and inactivity. In practice, it would be unlikely that rebuilding plans would be implemented at stock-level management intensity ~0 or national-level management intensity ~0 (Supplementary Fig. 4), but for consistency, we did not impose additional restrictions on the conditions under which rebuilding plans would activate. Once activated, the term $\mathrm{Reb}_{\mathrm{immediate}}$ affected predictions in the first year of the rebuilding plan and $\mathrm{Reb}_{\mathrm{persistent}}$ affected predictions in years thereafter (with one exception, see next paragraph).

Because $(U/U_{\mathrm{REF}})^*$ and $(B/B_{\mathrm{REF}})^*$ were generated from coupled statistical models and not from a population dynamics model, there are no inherent negative feedback mechanisms operating, so three adjustments were made to ensure more realistic projections of these variables. First, if the decrease in U/U_{REF} in the first year of a rebuilding plan was insufficient to reduce $U/U_{\mathrm{REF}} < 1$, then $\mathrm{Reb}_{\mathrm{immediate}}$ was applied for a second year to ensure U/U_{REF} fell to <1. This avoided unrealistic scenarios in which U/U_{REF} increased without limit while under a rebuilding plan, never falling to <1, because the estimated coefficient for $\mathrm{Reb}_{\mathrm{persistent}}$ was slightly positive.

Second, a logistic growth adjustment was applied to predicted biomass to prevent unrealistically high biomass increases in cases where biomass might approach carrying capacity:

$$\frac{B}{B_{\mathrm{REF}_{t+1}}} = e^{\left(\ln\left(\frac{B}{B_{\mathrm{REF}\,t}}\right) + y_t\right)} + r_{\mathrm{MAX}} \left(\frac{B}{B_{\mathrm{REF}_t}}\right) \left(1 - \frac{\frac{B}{B_{\mathrm{REF}_t}}}{2}\right) \tag{4}$$

The first term represents the updated relative biomass from the statistical model, in which y_t is the predicted annual change in ln-biomass under the given management regime and magnitude of $(U/U_{\mathrm{REF}})_{\mathrm{t}}$. The second term is the logistic growth model applied, assuming the carrying capacity is $2B_{\mathrm{REF}}$ (hence 2 in the denominator) and average intrinsic growth rate $r_{\mathrm{MAX}} = 0.0437$. This value for r_{MAX} was estimated across stocks over their full time series by calculating the change in B from a fitted model while fixing U/U_{REF} to 0 and omitting management variables. After reaching equilibrium, $\ln((U/U_{\mathrm{REF}})^*)$ and $\ln((B/B_{\mathrm{REF}})^*)$ were exponentiated.

Third, the equilibrium value of $(B/B_{\mathrm{REF}})^*$ was scaled to ensure closer correspondence with $(U/U_{\mathrm{REF}})^*$, as small $(U/U_{\mathrm{REF}})^*$ are typically associated with large $(B/B_{\mathrm{REF}})^*$ and vice versa. The scaling factor simultaneously incorporated the maximum value of $(B/B_{\mathrm{REF}})^*$ paired with the minimum value of $(U/U_{\mathrm{REF}})^*$, and the minimum value of $(B/B_{REF})^*$ paired with the maximum value of $(U/U_{REF})^*$, across all possible combinations k of stock-level and national-level management intensity:

$$\frac{B^*}{B_{REF_{scaled}}} = \frac{B^*}{B_{REF}}\left(\max_k\left(\frac{B^*}{B_{REF}}\right)\times\min_k\left(\frac{U^*}{U_{REF}}\right)\right)\left(\max_k\left(\frac{U^*}{U_{REF}}\right)\times\min_k\left(\frac{B^*}{B_{REF}}\right)\right) \quad (5)$$

Equilibrium values of (catch/MSY)* were calculated as the product of $(U/U_{REF})^*$ and $(B/B_{REF})^*_{scaled}$. The above model structure (equations (3)–(5)) was used for the results shown in Fig. 5; asterisks are omitted in the main text and figures.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

Stock assessment data are compiled in RAMLDB (version 4.491-mdl-fits)[22], which is publicly available at https://zenodo.org/record/3877545.

Code availability

All data input files and code to reproduce analyses are publicly available at https://github.com/mcmelnychuk/MCM-NatSust_2020-12-05.

Received: 23 July 2020; Accepted: 20 November 2020;
Published online: 11 January 2021

References

1. Worm, B. et al. Rebuilding global fisheries. *Science* **325**, 578–585 (2009).
2. Fernandes, P. G. & Cook, R. M. Reversal of fish stock decline in the northeast Atlantic. *Curr. Biol.* **23**, 1432–1437 (2013).
3. Costello, C. et al. Global fishery prospects under contrasting management regimes. *Proc. Natl Acad. Sci. USA* **113**, 5125–5129 (2016).
4. Hilborn, R. et al. Effective fisheries management instrumental in improving fish stock status. *Proc. Natl Acad. Sci. USA* **117**, 2218–2224 (2020).
5. Osio, G. C., Orio, A. & Millar, C. P. Assessing the vulnerability of Mediterranean demersal stocks and predicting exploitation status of un-assessed stocks. *Fish. Res.* **171**, 110–121 (2015).
6. Pons, M. et al. Effects of biological, economic and management factors on tuna and billfish stock status. *Fish. Fish.* **18**, 1–27 (2017).
7. Melnychuk, M. C., Peterson, E., Elliott, M. & Hilborn, R. Fisheries management impacts on target species status. *Proc. Natl Acad. Sci. USA* **114**, 178–183 (2017).
8. Essington, T. E. et al. Catch shares, fisheries, and ecological stewardship: a comparative analysis of resource responses to a rights-based policy instrument. *Conserv. Lett.* **5**, 186–195 (2012).
9. Melnychuk, M. C., Banobi, J. A. & Hilborn, R. Effects of management tactics on meeting conservation objectives for western North American groundfish fisheries. *PLoS ONE* **8**, 1–15 (2013).
10. Melnychuk, M. C. et al. Which design elements of individual quota fisheries help to achieve management objectives? *Fish. Fish.* **17**, 126–142 (2016).
11. Pons, M., Melnychuk, M. C. & Hilborn, R. Management effectiveness of large pelagic fisheries in the high seas. *Fish. Fish.* **19**, 260–270 (2018).
12. Neubauer, P., Jensen, O. P., Hutchings, J. A. & Baum, J. K. Resilience and recovery of overexploited marine populations. *Science* **340**, 347–349 (2013).
13. Ye, Y. & Gutierrez, N. L. Ending fishery overexploitation by expanding from local successes to globalized solutions. *Nat. Ecol. Evol.* **1**, 0179 (2017).
14. Costello, C. et al. The future of food from the sea. *Nature* https://doi.org/10.1038/s41586-020-2616-y (2020).
15. *Convention on the Law of the Sea* (UN General Assembly, 1982).
16. *Agreement to Promote Compliance with International Conservation and Management Measures by Fishing Vessels on the High Seas* (Food and Agriculture Organization of the United Nations, 1995).
17. *Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks* (Food and Agriculture Organization of the United Nations, 1995).
18. Melnychuk, M. C. et al. Can catch share fisheries better track management targets? *Fish. Fish.* **13**, 267–290 (2012).
19. Deroba, J. J. & Bence, J. R. A review of harvest policies: understanding relative performance of control rules. *Fish. Res.* **94**, 210–223 (2008).
20. Murawski, S. A. Rebuilding depleted fish stocks: the good, the bad, and, mostly, the ugly. *ICES J. Mar. Sci.* **67**, 1830–1840 (2010).
21. Ricard, D., Minto, C., Jensen, O. P. & Baum, J. K. Examining the knowledge base and status of commercially exploited marine species with the RAM Legacy Stock Assessment Database. *Fish. Fish.* **13**, 380–398 (2012).
22. RAM Legacy Stock Assessment Database, version 4.491-mdl-fits. *Zenodo* https://doi.org/10.5281/zenodo.3877545 (2019).
23. Sethi, S. A., Branch, T. A. & Watson, R. Global fishery development patterns are driven by profit but not trophic level. *Proc. Natl Acad. Sci. USA* **107**, 12163–12167 (2010).
24. Benson, A. J., Cooper, A. B. & Carruthers, T. R. An evaluation of rebuilding policies for US fisheries. *PLoS ONE* **11**, e0146278 (2016).
25. Cardinale, M. et al. Rebuilding EU fish stocks and fisheries, a process under way? *Mar. Policy* **39**, 43–52 (2013).
26. Bell, R. J. et al. Rebuilding in the face of climate change. *Can. J. Fish. Aquat. Sci.* **75**, 1405–1414 (2017).
27. Britten, G. L., Dowd, M., Kanary, L. & Worm, B. Extended fisheries recovery timelines in a changing environment. *Nat. Commun.* **8**, 15325 (2017).
28. Hillary, R. M. et al. A scientific alternative to moratoria for rebuilding depleted international tuna stocks. *Fish. Fish.* **17**, 469–482 (2016).
29. Gutierrez, N. L., Hilborn, R. & Defeo, O. Leadership, social capital and incentives promote successful fisheries. *Nature* **470**, 386–389 (2011).
30. Hilborn, R. Pretty good yield and exploited fishes. *Mar. Policy* **34**, 193–196 (2010).
31. Neubauer, P., Thorson, J. T., Melnychuk, M. C., Methot, R. & Blackhart, K. Drivers and rates of stock assessments in the United States. *PLoS ONE* **13**, e0196483 (2018).
32. Lloret, J., Lleonart, J. & Solé, I. Time series modelling of landings in northwest Mediterranean Sea. *ICES J. Mar. Sci.* **57**, 171–184 (2000).
33. Gutiérrez-Estrada, J. C., Sanz-Fernández, V., Pulido-Calvo, I. & Gil-Herrera, J. Improving the interpretability of the effects of environmental factors on abundance of fish stocks. *Ecol. Indic.* **117**, 106533 (2020).
34. Methot, R. D., Tromble, G. R., Lambert, D. M. & Greene, K. E. Implementing a science-based system for preventing overfishing and guiding sustainable fisheries in the United States. *ICES J. Mar. Sci.* **71**, 183–194 (2014).
35. Pascoe, S. et al. Developing harvest strategies to achieve ecological, economic and social sustainability in multi-sector fisheries. *Sustainability* **11**, 644 (2019).
36. Hyndman, R. J. & Athanasopoulos, G. *Forecasting: Principles and Practice* (OTexts, 2018).
37. Pinheiro, J. C. & Bates, D. M. *Mixed-effects Models in S and S-PLUS* (Springer, 2000).
38. Zuur, A. F., Ieno, E. N. & Elphick, C. S. A protocol for data exploration to avoid common statistical problems. *Methods Ecol. Evol.* **1**, 3–14 (2010).
39. Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D. & R Core Team nlme: linear and nonlinear mixed effects models. R package version 3.1-149 (2019).
40. Szuwalski, C. S. & Thorson, J. T. Global fishery dynamics are poorly predicted by classical models. *Fish Fish.* **18**, 1085–1095 (2017).

Acknowledgements

Fisheries experts who graciously provided management-related information are listed in Supplementary Note 3. Many other scientists generously contributed data to RAMLDB. C. Costello provided helpful comments on the manuscript. J. Sanders, D. Ovando, H. Bassett, A. Faraj, S. Segurado and J. Wilson provided valuable feedback. Fisheries and Oceans Canada granted permission to reproduce the flounder illustration in the Fig. 2 inset. This work was supported by the Science for Nature and People Partnership programme (working group 'Fisheries Measures') from the National Center for Ecological Analysis and Synthesis, which was funded by the Nature Conservancy and the Wildlife Conservation Society. RAMLDB has been supported by funding from the Walton Family Foundation and a consortium of Seattle fishing companies. T.A.B. was funded in part by the Richard C. and Lois M. Worthington Endowed Professorship in Fisheries Management. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the authors and do not necessarily reflect those of NOAA or the US Department of Commerce.

Author contributions

Specific contributions made by each author are listed by role, following the Contributor Roles Taxonomy (CRediT) model. Conceptualization: M.C.M., H.K., P.M.M., C.M., O.P.J., C.L.d.M., A.M.P., T.A.B., C.M.A., C.S.S., J.K.B., T.R.M., Y.Y., R.H. Data curation: M.C.M., D.H. Formal analysis: M.C.M., C.M., D.H. Funding acquisition: R.H. Investigation: M.C.M., H.K., P.M.M., M.P., C.M., G.C.O., O.P.J., C.L.d.M., A.M.P., L.R.L., D.H., C.E.A., N.B., R.O.A., J.K.B., T.R.M., A.L., J.B., G.G.T., J.D., A.M., B.B., E.W., J.R. Methodology: M.C.M., C.M., O.P.J., A.M.P., T.A.B., C.S.S., R.H. Project administration: M.C.M., R.H. Resources: R.H. Software: M.C.M., C.M., D.H. Supervision: M.C.M., R.H. Validation: M.C.M., H.K., P.M.M., M.P., C.M., G.C.O., O.P.J., C.L.d.M., A.M.P., L.R.L., D.H., R.O.A., C.M.A., Y.Y., J.R. Visualization: M.C.M., C.M., T.A.B. Writing (original draft): M.C.M. Writing (review and editing): M.C.M., H.K., P.M.M., M.P., C.M., G.C.O., O.P.J., C.L.d.M., A.M.P., L.R.L., D.H., C.E.A., N.B., T.A.B., C.M.A., C.S.S., J.K.B., T.R.M., Y.Y., A.L., G.G.T., J.D., B.B., J.R., R.H.

Competing interests

Most authors are involved in fisheries management or provide fisheries advice in ways that can be viewed by some as competing interests. Many are employed by national fisheries agencies or non-governmental organizations that advocate for specific fisheries policies. The academic scientists have received funding from sources that include government fisheries agencies, fishing companies and environmental non-governmental organizations.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-00668-1.

Correspondence and requests for materials should be addressed to M.C.M.

Peer review information *Nature Sustainability* thanks J. C. Gutierrez-Estrada, A. Tsikliras and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2021

nature research

Corresponding author(s): Michael Melnychuk

Last updated by author(s): Nov 11, 2020

Reporting Summary

Nature Research wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Research policies, see our Editorial Policies and the Editorial Policy Checklist.

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☐	☒	A description of all covariates tested
☐	☒	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒	A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☒	☐	For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☐	☒	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☐	☒	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Stock assessment data are compiled in the publicly-available RAM Legacy Stock Assessment Database, which is hosted on a cited Zenodo repository. Data from this version 4.491 are available for download either as .RData files for use in R, or as .xlsx files for use in Excel.
Data analysis	All data analyses for this study were conducted using R version 3.6.3. Key R packages used are cited in the reference list with version numbers. All data input files and code to reproduce analyses are publicly available (https://github.com/mcmelnychuk/MCM-NatSust_2020-07-08).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
- A description of any restrictions on data availability

Stock assessment data are compiled in RAMLDB (version 4.491-mdl-fits), which is publicly available (DOI 10.5281/zenodo.3877545).

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study uses time series of stock biomass (B) and fishing pressure (U) relative to their biological reference points (Bref and Uref), collated for 288 fish and invertebrate stocks worldwide. Interannual changes in the trends of these variables are used as response variables in ARIMA models. These ARIMA models incorporate management, life-history, and fishery-related variables as predictor variables potentially influencing changes in B/Bref and U/Uref. Interactions among these predictor variables are included in some models. The models are hierarchical, incorporating random intercepts for each population. Treatments are neither controlled nor randomised; information about the influence of predictors on responses in these observational data is based on differences between the pre- and post-intervention periods in the time series for each individual stock, with overall effects across stocks estimated.
Research sample	Biomass and fishing pressure time series for individual stocks are estimated from stock assessments, typically carried out by governmental fisheries agencies. Biological reference points are also estimated within the assessment framework of most stock assessments, or otherwise are estimated post-hoc with previously-developed methods. These estimates are compiled in the publicly-available RAM Legacy Stock Assessment Database, from which data for the response variables was drawn. A variety of marine fish and invertebrate stocks are included in the analysis.
Sampling strategy	We primarily focussed on stocks that at some point in their fishing history had high levels of relative fishing pressure and/or low levels of relative biomass, i.e. stocks that at some point had undergone overfishing or been overfished to some degree. We prioritized stocks on this basis and targeted our collection of management attribute data accordingly. In the end, we included 288 stocks in the analysis that had both sufficient data for one or the other response variable, as well as sufficient management attribute data used as predictor variables. As the focus is on overall effects across stocks (in a hierarchical model), this number of sampled stocks is sufficient for estimating effects of management interventions and other influences on changes in response variables.
Data collection	Data for response variables were drawn from the RAM Legacy Stock Assessment Database, a publicly-available compilation of stock assessment outputs for assessed marine fish and invertebrate stocks around the world. Assessment data are entered into the database from a variety of sources: some contributed by government agencies, some by a network of scientists around the world (including several co-authors), and others by staff at the University of Washington. Data for management attributes were collected by co-authors in their contries or regions of familiarity; some regional experts collected the necessary information themselves, others co-ordinated data collection in their region, drawing on the expertise of people familiar with individual stocks.
Timing and spatial scale	The duration of time series of estimated biomass and fishing pressure vary by stock, as stock assessments are conducted for stocks individually and are limited by available information. The full time series for each stock is contained in the RAM Legacy Stock Assessment Database, with varying dates of earliest data availability among stocks. There were few stocks with data available for years after 2016, so time series were capped at 2016 for analyses. Stock assessments are carried out for individual defined stocks, which are typically considered to be biological populations but are also based on considerations of statistical fishing areas. We used the same spatial definitions of stocks as used in stock assessments.
Data exclusions	No samples (i.e. individual stocks) were excluded from analyses. For some analyses, earlier years of the time series ('Developing fishery' phase, as described in the paper) were excluded for some stocks to focus on the years in which the fishery had already matured. Pre-established rules for distinguishing 'developing' from 'mature' phases, based on values of estimated biomass, fishing pressure, and catch, were described in the paper. In other analyses, the 'developing' and 'mature' phases of stock time series were both included, to provide greater contrast.
Reproducibility	All input data and code for analyses are cited and publicly available. These provide the ability to reproduce all figures presented in the main text and Supplementary Information.
Randomization	Individual stocks were allocated into one of 17 regions around the world for presentation of management histories by region (Fig. 1 and Supplementary Figures 2 and 3). This allocation was based on geographical location and/or management authority for each stock. This allocation has no impact on analyses because random intercepts were specified for individual stocks, not regions.
Blinding	Blinding is not relevant here, as there were no controlled or randomised treatments. Stock status data were drawn from published sources, and management attribute data were collected for specified stocks.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging