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Global status of groundfish stocks

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Abstract

We review the status of groundfish stocks using published scientific assessments for 349 individual stocks constituting 90% of global groundfish catch. Overall, average stock abundance is increasing and is currently above the level that would produce maximum sustainable yield (MSY). Fishing pressure for cod-like fishes (Gadiformes) and flatfishes (Pleuronectiformes) was, for several decades, on average well above levels associated with MSY, but is now at or below the level expected to produce MSY. In contrast, fishing pressure for rockfishes (Scorpaeniformes) decreased from near MSY-related levels in the mid-1990s, and since the mid-2000s has remained on average at only one third of MSY-related levels. Regions with the most depressed groundfish stocks are the Northwest Atlantic and the Pacific coast of South America, while stocks from the Northeast and Eastern Central Pacific, Northeast Atlantic, Southeast Atlantic and Southwest Pacific tend to have greatest average abundance relative to MSY-based reference points. In the most recent year available for each stock, the catch was only 61% of MSY. Equilibrium yield curves indicate that 76% of global potential groundfish yield could be achieved using current estimates of fishing pressure. 15% of this is lost by excess fishing pressure, 67% results from lower than optimal fishing pressure on healthy stocks and 18% is lost from stocks currently overfished but rebuilding. Thus, there is modest opportunity to increase catch of global groundfish fisheries by reducing overfishing on some stocks, but more by increasing harvest on others. However, there may be other reasons not to fully exploit these stocks.

KEYWORDS

abundance, cod, fisheries management, overfishing, pollock, sustainable fishing

1 | INTRODUCTION

Groundfish is an umbrella term generally applied to demersal fishes from temperate and northern latitudes. Regional fisheries management councils of the United States, and national management agencies of Canada and Europe, commonly identify groundfish as a distinct group of fish in their research and management plans.

The most abundant groundfish are from the taxonomic order Gadiformes and include Atlantic pollocks (*Pollachius virens* and *Pollachius pollachius*), Pacific pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus microcephalus*), Atlantic cod (*Gadus morhua*), hakes (family Merlucciidae) and haddock (*Melanogrammus aeglefinus*). Other species generally considered groundfish are flatfishes of the order Pleuronectiformes, and rockfishes and their relatives of the order Scorpaeniformes. While these orders of groundfishes share some strong commonalities, there are also differences among them in life-history characteristics and in how they are fished.

Groundfish are found almost exclusively in the temperate and higher latitudes of both the Northern and Southern hemispheres and all continents, but stocks in the Northern hemisphere are typically much larger. Since 2000, groundfish landings reported to FAO (FAO, 2020a) have averaged 10.5 million metric tons (mmt) and constituted about 12% of annual global landings of all marine species. Of these groundfish landings, 85% comprise stocks of the order Gadiformes. While similar numbers of stocks of the orders Pleuronectiformes and Scorpaeniformes are assessed, those stocks are on average smaller in their contribution to global food production.

Groundfish have featured prominently in discussions about fisheries sustainability in recent decades. Declines of cod are perhaps the best known examples of overfishing and stock depletion (Hutchings & Myers, 1994; Kurlansky, 2011; Myers et al., 1997b), Almost all groundfish are managed by agencies that conduct fisheries stock assessments to estimate trends in abundance and fishing pressure, so compared to most fish stocks worldwide, groundfish stocks tend to be data-rich with relatively well-known status. Despite their commercial importance and concerns around non-sustainable fishing, there has not yet been a comprehensive synthesis of the global status of groundfish stocks, nor their management intensity.

Many agencies report on the status of fish stocks. The Food and Agriculture Organization of the United Nations (FAO) publishes a bi-annual estimate of the proportion of stocks that are overfished according to the criterion of whether biomass is less than or greater than 80% of the biomass that would produce maximum sustainable yield (B_{MSY}) (FAO, 2020b). In the United States, the National Marine Fisheries Service reports how many stocks are overfished (default threshold is 50% of B_{MSY}) or subject to overfishing ($U > U_{MSY}$, i.e. fishing pressure is greater than the fishing pressure expected to generate MSY) (NMFS, 2019). ICES reports on the status of individual fish stocks in the Northeast Atlantic, including European Union, Norway, Iceland and Faroe Islands, and many other governments provide some summary of their fisheries status.

There have been a number of papers on the status and trends in European Atlantic fisheries (Cardinale et al., 2013; Cook et al., 1997; Fernandes & Cook, 2013; Froese et al., 2018; Zimmermann & Werner, 2019) and Mediterranean fisheries (Fernandes et al., 2017; Vasilakopoulos et al., 2014). Two papers have examined the status of global tuna fisheries (Juan-Jorda et al., 2011; Maite et al., 2016), and a third paper (Pons et al., 2017) explored the relationship between various management measures and stock abundance. Trends in the abundance and management of groundfish stocks off the West Coast of the United States. (Hilborn et al., 2012; Keller et al., 2012) and North America (Melnychuk et al., 2013) have also been examined. Atlantic cod have been of particular interest both because of the dramatic declines seen in many of the stocks (Myers et al., 1996, 1997a) and the differential recovery of different stocks (Hilborn & Litsinger, 2009; Rothschild, 2007; Sguotti et al., 2019).

Recently, Hilborn et al., (2020) reviewed what is known from scientific stock assessments about the status and management of fisheries from different regions around the world and highlighted regional differences in management, showing that countries which managed their fish resources more intensively tended to have better stock status. Follow-up work evaluated the influence of individual management attributes on changes in the time series of fishing pressure and biomass, showing that rebuilding plans had particularly strong effects on reversing overfishing (Melnychuk et al., 2021). However, neither of these studies focused on specific types of species or fisheries in their analyses. Given the differences in biology and the fisheries between tunas, groundfish, small pelagics and invertebrates we might expect major differences in status and influences of management.

Although only constituting 12% of global catch, groundfish have had outsized importance in the development of fisheries management measures and are particularly well studied. The prominence of groundfish in fisheries science and management may have resulted from their being the mainstay of many fishery-dependent communities in the North Atlantic where much of current fisheries management theory was developed. Because they are distributed primarily in the waters of countries and regions that regularly undertake scientific stock assessments, and because most stocks in these regions are assessed, an analysis of groundfish stocks in well-studied regions essentially represents a global analysis of groundfish.

There is an ongoing desire to increase food from the sea as evidenced by the recent high-level report to a number of heads of state (Costello et al., 2020). Thus, as part of this analysis, we examine the extent to which global groundfish production could be increased by either reducing overfishing or more fully exploiting currently underexploited stocks.

The purpose of this paper is to: (1) synthesize the results of stock assessments which quantify the current status and history of groundfish stocks around the world; (2) compare stock status among groundfish orders of Gadiformes, Pleuronectiformes and Scorpaeniformes and for different regions; (3) evaluate the potential for sustained production or increases in production; and (4) understand the relationship between the nature of the management systems and the outcomes for the stocks with respect to biological reference points based on maximum sustainable yield (MSY) or other targets.

2 | MATERIALS AND METHODS

In this paper, we consider all available catch and stock status estimates for populations of species from the orders Gadiformes, Pleuronectiformes and Scorpaeniformes, with one exception. We excluded one gadid species, North Atlantic blue whiting (*Micromesistius poutassou*), which is a very large fishery but is used primarily for fishmeal and oil.

2.1 | RAMLDB

The RAM Legacy Stock Assessment Database (RAMLDB; www.ramlegacy.org) is a compilation of stock assessments that contain time series of stock abundance, catch, fishing pressure and recruitment, as well as a range of biological and management parameters (Ricard et al., 2012). Version 4.493 (RAM Legacy Stock Assessment Database, 2021) contains data for over 1,200 stocks, which together constitute almost 50% of fish catch reported to FAO (FAO, 2019). The RAM Legacy Database includes coverage of 80% of the landings reported to FAO from North America, Europe, Peru, Chile, Argentina, Australia, New Zealand, Japan, Russia and South Africa and thus covers most of the major countries catching groundfish (Figure 1).

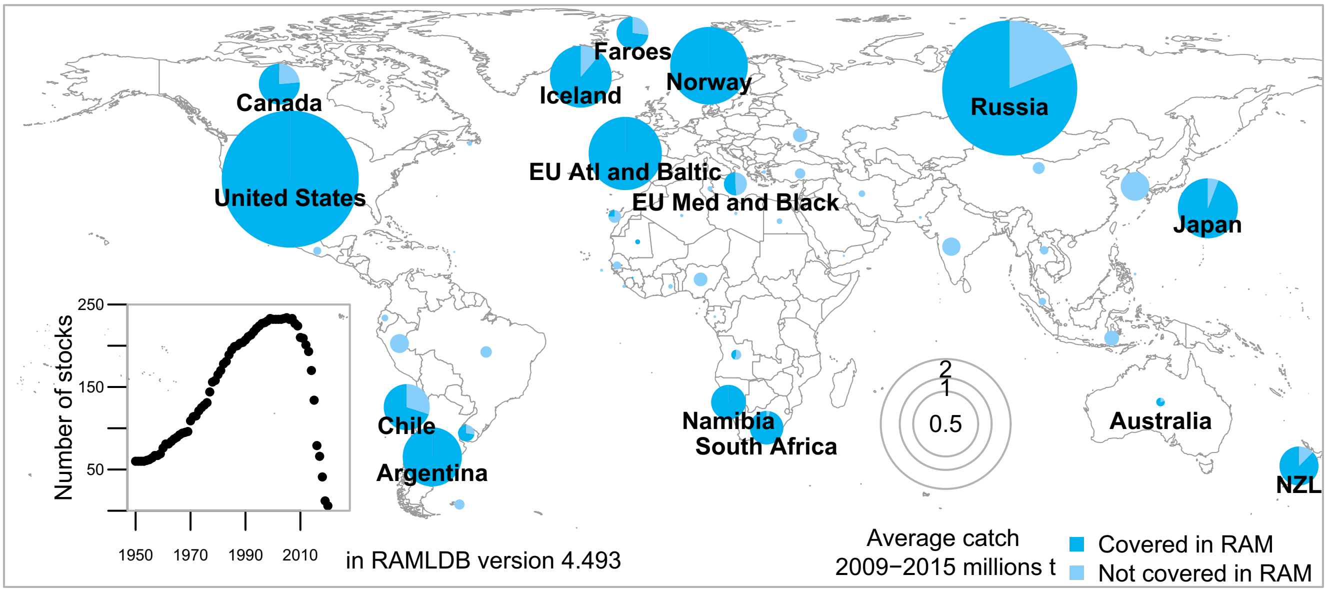

FIGURE 1 Coverage by country or aggregated region of assessed groundfish stocks contained in RAMLDB. Circle area is proportional to the country or region's average annual catch of groundfish from 2009 to 2015 (orders Gadiformes, Pleuronectiformes and Scorpaeniformes) as reported to FAO. Dark blue shading represents the fraction of the country's groundfish catch covered by stocks in RAMLDB. Circles are plotted for the following regions instead of individual countries: the Mediterranean and Black Sea (European Union countries), Atlantic and Baltic waters (EU countries). Inset panel is number of groundfish stocks contained in RAMLDB with abundance data for each year. The total number of groundfish stocks in the dataset is 349 but only 237 have estimates of biomass and fishing pressure relative to MSY-based reference points

2.2 | FAO landings data

Global landings data are reported by individual countries to FAO (FAO, 2019) and contain the country, FAO statistical area, scientific name or species group and landings in metric tons. The data base we used covers years 1950–2017. To link FAO landings data with biological stocks contained in RAMLDB, all species in the FAO database that were from Gadiformes, Pleuronectiformes or Scorpaeniformes were included except North Atlantic blue whiting. A few species from other orders are often called groundfish, including Patagonian toothfish, orange roughy and monkfish, but these are not large fisheries and we have chosen to include for analysis in this paper only species in the three primary orders.

Figure 1 shows the total tonnage of groundfish landings reported to FAO by country, represented by the area of circles, showing the greater overall abundance of stocks at temperate and northern latitudes. The shading of circles represents the proportion of the catch reported to FAO that is represented by stocks contained in RAMLDB. Many countries or regions have stock assessments covering nearly all of the groundfish landings, including the EU, Russia, USA, Iceland, Norway, Japan, New Zealand, Argentina, Chile, Faroe Islands, Namibia and South Africa.

2.2.1 | Trends in abundance and fishing pressure

Stock assessments from different government fisheries agencies and for individual stocks do not cover the same ranges of years. Some go back as far as 1950, but most assessments tend to begin between 1960 and 1980, so years are unbalanced with respect to the number of stocks covered. Reconstructing the average abundance or fishing pressure in any year must therefore account for these "ragged ends" of unequal data coverage. The inset panel in Figure 1 shows the number of groundfish stocks with abundance estimates available for each year. The data coverage is most complete between the late 1990s and 2012. After 2012, RAMLDB includes fewer and fewer stocks with assessments covering those years. For some stocks, the most recent available assessments are several years out of date; for other stocks, there is a lag between an assessment's publication and it being entered into RAMLDB.

To estimate the trend in abundance or fishing pressure in years with low stock coverage, we used the state-space model approach used in Hilborn et al., (2020) to estimate the mean trends in abundance and fishing pressure across stocks, treating time series of individual stocks as observations around the group mean, which is constrained to follow a random walk. Groups consistent of FAO Major Fishing Areas in some analyses, and taxonomic order in other analyses.

We assume that the group trend in an index follows a random walk in time:

$$x_t = x_{t-1} + \eta_t,\;\; \eta_t \sim \mathrm{N}(0, \sigma_\eta^2) \tag{1}$$

where x_t is the mean index at time t, η_t is a process deviation, assumed normally distributed with zero mean and standard deviation σ_η. Observations consist of estimates for $j = \{1,\ldots,m\}$ stocks, which we assume follow the overall trend via

$$y_{j,t} = x_t + a_j + \varepsilon_{j,t},\;\; \varepsilon_{j,t} \sim \mathrm{N}(\varphi \varepsilon_{j,t-1}, \sigma_\varepsilon^2) \tag{2}$$

where $y_{j,t}$ is the observation for a given stock (e.g. $\ln(B_{j,t}/B_{MSY,j})$), x_t is the mean index from Equation (1), a_j is a fixed effect deviation from the overall trend for stock j (we constrain $\sum a_j = 0$ such that x_t represents the overall mean and not that of a baseline stock), $\varepsilon_{j,t}$ is the measurement error assumed to follow an autoregressive (AR(1)) process with autoregressive coefficient φ and innovation standard deviation σ_ε. Equations (1) and (2) are the process and measurement equations of the state-space model.

Assuming a random walk ensures strong autocorrelation in the mean trend so that if the only stocks assessed in a year had typically higher or lower values than the stocks not assessed, the predicted mean trend only slightly "chases" these values, and instead largely propagates forward (or backward) from the mean in years of high coverage. When coverage is high, meaning most stocks in the group had estimated values in that year, the state-space estimates converge to the median values across stocks, and our conclusions about current status in the most recent years (of lower coverage) will be influenced by earlier years when coverage was greater. The mean trend is re-scaled to median values using a calculated scaling factor during years of >90% coverage.

Our state-space analysis is related to methods of Zuur et al., (2003) and Conn (2010) in extracting hierarchical trends from component series. Our method differs from dynamic factor analysis in Zuur (2003) in that we do not standardize the series a priori but include a sum-to-zero constraint on the stock effects such that the mean trend is output, and we allow for autocorrelated process errors. Autocorrelated process errors are particularly important as stock coverage at the beginning and ending years is often low. Differences from Conn include autocorrelated within-stock process errors (a possibility noted in Conn, 2010) and our year effects follow a random walk, whereas year effects in Conn (2010) are independent and therefore subject to domination by remaining stocks in the ragged ends.

In addition to unequal temporal coverage across stocks, geographic coverages of groundfish landings and abundance are not uniformly distributed worldwide. Because of the regional variation in groundfish yield, some of our analyses below are stratified by major FAO statistical area. Other analyses are stratified taxonomically, by groundfish orders of Gadiformes, Pleuronectiformes and Scorpaeniformes, to evaluate possible differences among these taxa.

2.3 | Estimation of stock status relative to MSY or target reference points

The most common way to assess the status of fish stocks is by comparing time series of estimated biomass (B) and fishing pressure (U) to their respective biological reference points. Depending upon the assessment biomass may be measured as spawning stock biomass or biomass of all fish above a certain age. Fishing pressure may be measured as an instantaneous rate or a discrete rate. These reference points are commonly based on quantities associated with MSY, that is B_{MSY} and U_{MSY}, or may also be based on other specified management targets which are often proxies for B_{MSY} and U_{MSY}. Following the example of Worm et al., (2009) and Hilborn et al., (2020) we preferentially used MSY-based reference points when available for calculating ratios of B/B_{MSY} and U/U_{MSY}; these ratios represent current or historical stock status. If no MSY-based reference points were available, but management targets were provided we used those. If no reference points were available from the assessment agency as part of the published assessment, they were estimated *post hoc* by fitting surplus production models to time-series data from assessments as described in Hilborn et al., (2020). However, estimation of reference points was not possible for 112 stocks (the estimates did not pass a series of filters designed to guard against poor estimates). Thus, from the 349 groundfish stocks in the database, only 237 have stock status estimated relative to reference points. Groundfish stocks with reference points constitute over 94% of the total groundfish landings in RAMLDB, and 81% of the total groundfish landings reported to FAO, thus most of the world's largest groundfish landings come from stocks for which we have biomass and fishing pressure reference points, consistent with Neubauer et al., (2018). The stocks without reference points tended to be small stocks (median landings 2000–2010 was 1,500 MT). Table S1 lists all stocks included in our analysis and summarizes values of landings and the stock status relative to reference points.

2.4 | Fisheries management

Melnychuk et al., (2021) collected data on 288 individual fish stocks in the RAMLDB, determining in what year the following actions were first implemented (1) stock assessment of current status, (2) scientific surveys of stock abundance, (3) total landings limits for the stock, (4) a harvest control rule that specifies how the landings will be adjusted in relation to stock abundance and (5) individual vessel quotas. These data were available for 109 of the groundfish stocks in our dataset and are assumed to be the key elements of modern single-stock fisheries management. For each stock and year, a management intensity index is constructed that is 0.0, 0.2, 0.4, 0.6, 0.8 or 1.0 depending how many of the 5 actions are in place in any year. We can then compare the changes in abundance and fishing pressure in relation to management intensity either globally, regionally or on a stock by stock basis.

2.5 | Lost yield

A key question we wished to ask is how much yield are stocks providing, relative to potential long-term maximum yield? We explore this in two ways. First, we simply compare current harvest to estimated MSY. The difference is an empirical estimate of lost yield if we could manage that stock to produce MSY. An alternative approach is to compare long-term yield at current fishing pressure or at current biomass. If a stock is fished at U_{MSY}, its equilibrium yield is predicted to be MSY, and therefore, it has no lost potential yield. If we fish harder than U_{MSY}, we obtain less yield than we could if we fished at U_{MSY}. Similarly, if we fish with a rate lower than U_{MSY} we also forego potential yield that could have been caught. This amount "lost" for each stock is the difference between what could be realized by fishing at U_{MSY} (with biomass equilibrating at B_{MSY}, and annually landing MSY) and the expected equilibrium yield under current U. The magnitudes of lost yield and value increase the further away that U is from U_{MSY}. This is known as a yield curve and is simply a curve that rises from 0 (with $U/U_{MSY} = 0$) to 1 (achieving MSY) as U/U_{MSY} increases from 0 to 1, and then declines as U/U_{MSY} increases beyond 1. Using such equilibrium yield curves, for any stock we can calculate the fractions of potential yield lost due to fishing pressure being either above U_{MSY} or below U_{MSY}, and the equilibrium yield obtained at the current U (Hilborn, 2018). The same basic rules apply for current biomass; yield can be lost because biomass is below B_{MSY} or because it is above B_{MSY}.

We used the Pella–Tomlinson model (Pella & Tomlinson, 1969) as the basis for the relationship between the current status of the stock (using separate calculations for U/U_{MSY} and B/B_{MSY}) and the fraction of potential yield that is obtained. The model's shape parameter value was based on a global meta-analysis (Thorson et al., 2012). This produced a loss relationship nearly identical to the logistic growth model (Hilborn, 2018). The total equilibrium yield predicted at the U/U_{MSY} or at the B/B_{MSY} in the final year of each stock assessment was summed across all stocks. This gives large stocks greater weight (as their potential MSY is higher). This approach ignores age/size structure and many other stock-specific details, but figure 3a of Hilborn et al., (2020) demonstrated that biomass and fishing pressure on average explain changes in abundance and thus sustainable yield. This means that our method of estimating lost yield should produce, on average, reliable results.

3 | RESULTS

3.1 | Trends in landings

Aggregate landings of major groundfish groups, and amount of landings from stocks assessed in each year in RAMLDB, are shown in Figure 2. Worldwide groundfish catches are dominated by order Gadiformes, represented by four of the six panels. Summed catches of pollocks and cods show declines between 1970 and 2000, with recent increases since 2010. Catches of hakes have been reasonably stable since 1980. Landings of other gadids peaked around 2000, declined over the following decade, and then rebounded since 2010. Catches of flatfishes (Pleuronectiformes) have been largely stable since 1970, while those of scorpionfishes (Scorpaeniformes), consisting primarily of rockfishes (family Sebastidae) have decreased slightly since 1990. The coverage of these groundfish in RAMLDB is reasonably complete between 1990 and 2010 but poorest for the flatfishes and scorpionfishes. The assessment coverage during earlier

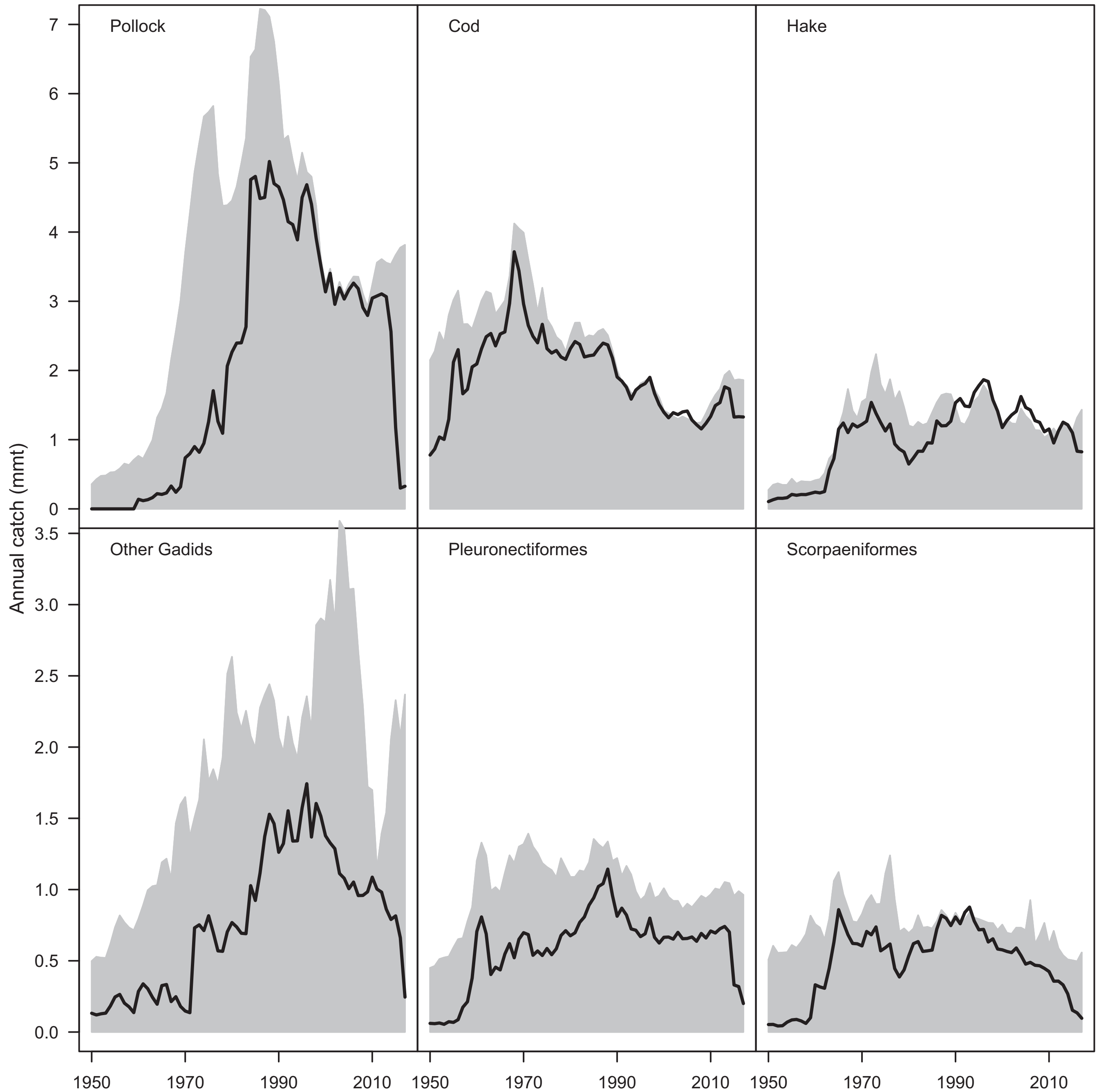

FIGURE 2 Trends in total global catch (as reported to FAO) of six major taxonomic groups of groundfish (filled area) and catch in RAMLDB (solid line) from the same groups. Assignments of individual groundfish stocks into these six groups are listed in Table S1

years before 1990 is lower for most of these groundfish groups because some stock assessments do not include historical landings. Russian pollock assessments do not extend back into the 1980s, and Argentine hakes are also limited in temporal coverage, which reduces the aggregate catch of assessed stocks in RAMLDB relative to the aggregate catch for these groups in the FAO landings database.

Separating trends in landings by FAO region (Figure 3), we see that groundfish catch is currently dominated by three regions: the Northeast Atlantic, the Northwest Pacific and the Northeast Pacific. The Northwest Atlantic was also a significant producer until the collapse of the Canadian and American cod stocks in the early 1990s. The Southwest Atlantic landings are mainly from Argentine hake stocks, the Southwest Pacific landings are primarily hoki (=blue grenadier) and Southern blue whiting stocks from New Zealand, and the Southeast Atlantic landings are mainly from hake stocks from Namibia and South Africa.

3.2 | Mean trends in stock status

Mean relative abundance trends across groundfish stocks from all FAO areas are shown in the top row of Figure 4 for years

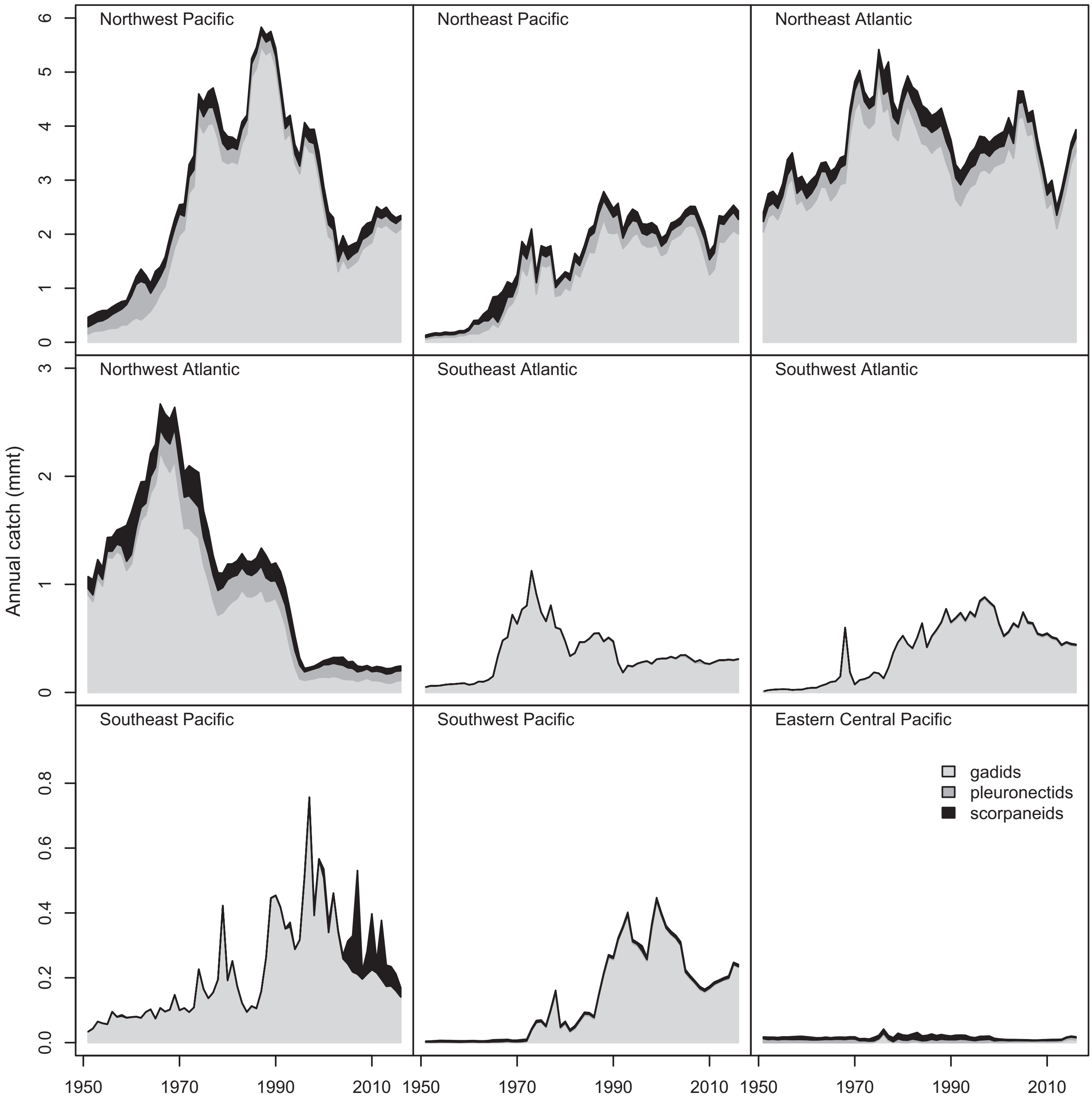

FIGURE 3 Trends in total global catch of groundfish by major FAO area, as reported to FAO. Assignments of individual groundfish stocks into these areas are listed in Table S1. Stacked areas are shown for orders Gadiformes (light grey), Pleuronectiformes (medium grey) and Scorpaeniformes (black)

1970–2018, separated by taxonomic order. These show an overall pattern of decline to just below B_{MSY} levels in the 1990s and 2000s, and then a recent increase to above B_{MSY} levels for all three orders (Figure 4). This pattern is clear in both the state-space model and median of assessed stocks. For flatfishes and scorpaenids, the medians of assessed stocks in the last few years have been greater than the mean trend estimates from the state-space model, in part because the assessed stocks in those years had higher than average B/B_{MSY}, and in part because the mean trend follows a random walk with constrained change from one year to the next. While some assessments consider years before 1970, coverage was generally lower in earlier years (Figure 2), so only trends since 1970 are shown. By 1970, mean relative abundance of flatfishes was on average already near B_{MSY} levels, lower than the medians of included stocks in these years, again because the assessed stocks in those years tended to have higher B/B_{MSY} values than they did in later years of higher coverage. While the exact timing differs slightly among the three orders of groundfish, the general pattern of mean stock decline and later recovery is observed across these taxonomic groups.

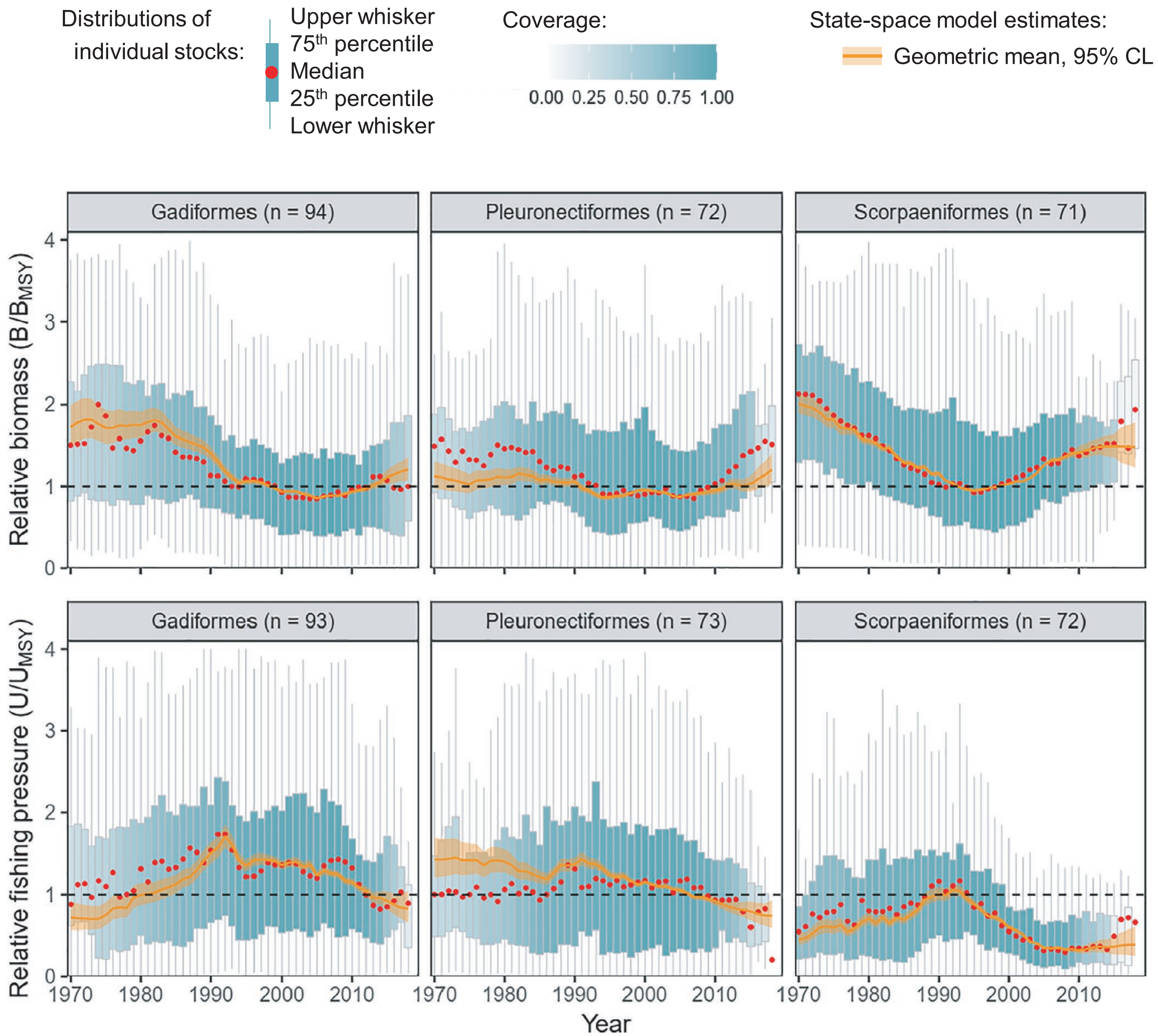

FIGURE 4 Trends in groundfish global means of: (top row) relative abundance, B/B_{MSY}; and (bottom row) relative fishing pressure, U/U_{MSY} from 1970 to 2018. Distributions and mean trends across stocks are shown separately by order. Estimates are generated from a state-space model (Hilborn et al., 2020) treating time series of individual stocks as observations. Shaded bands around mean denote 95% finite population-corrected confidence bounds (applicable to all years with <100% coverage). Boxplots with medians as red circles show distributions of individual stocks in each year, with shading reflecting the fraction of stocks with assessments covering that year. The horizontal line at 1.0 is the MSY value. Stocks are equally weighted

Average fishing pressure generally showed opposite trends to the abundance trends (bottom row of Figure 4). Mean fishing pressure in 1970 was predicted to be about 0.5, 1 and 1.5 of U_{MSY} for scorpaenids, gadids and pleuronectids, respectively. For flatfishes, similar to the difference between medians and state-space mean abundance in earlier years, the estimated mean trends in fishing pressure were greater than medians across included stocks in earlier years. By the 1990s, average fishing pressure for gadids and pleuronectids was high, around 1.5 U_{MSY}, after which it was reduced, and has steadily declined to current levels near or slightly below U_{MSY} on average. Even though mean fishing pressure for scorpaenids was near U_{MSY} in the 1990s, fishing pressure was also reduced for these stocks, even more sharply than for gadids and pleuronectids. Since the mid-2000s, mean fishing pressure for scorpaenids has been well below half of U_{MSY}. Overall, there appears to be a general reduction in the variability of fishing pressure in recent decades as more regions have enacted stricter fishing pressure.

3.3 | Individual stock status

Stock status is commonly expressed visually in co-plots of relative fishing pressure plotted against relative abundance, as shown in Figure 5 for individual groundfish stocks in the last year of their

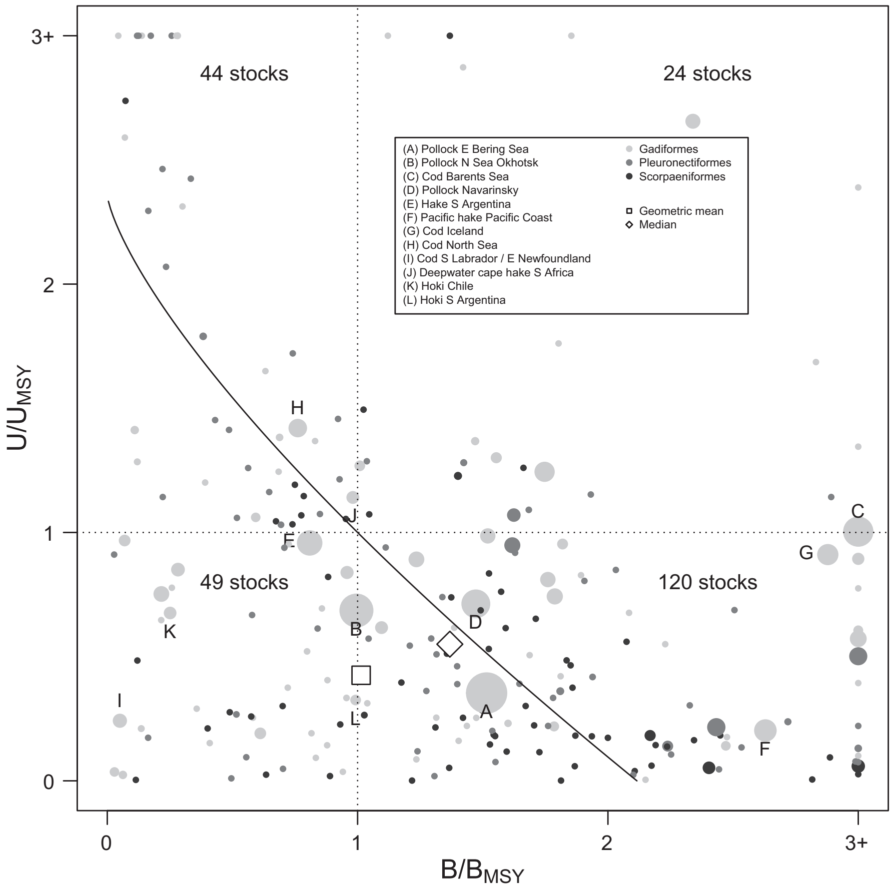

FIGURE 5 Status of individual groundfish stocks in their most recent year of joint available estimates of relative fishing pressure (U/U_{MSY}) and relative biomass (B/B_{MSY}). Circles represent individual stocks, with shading distinguishing taxonomic orders. Vertical and horizontal dotted lines represent traditional MSY-based targets of 1. The solid isocline going from upper left to lower right is the predicted equilibrium abundance for a given level of fishing pressure. Area of circles is proportional to MSY of the stock, or if an estimate of MSY was not available, to the average catch from 2000 to 2012. Open square represents the geometric mean and open diamond the median across stocks

most recent assessment. The upper left quadrant is the area of most management concern; stocks have abundance currently below B_{MSY} and are being harvested at levels above U_{MSY}. The one large stock in this quadrant is North Sea cod (H). The once-large stock that stands out in the lower left quadrant is the Canadian S. Labrador E. Newfoundland cod stock ("Northern cod" I), for which fishing pressure has been reduced to around 25% of U_{MSY} but biomass has not yet recovered from severe depletion. The large pollock stocks in the North Pacific (A,B,D) are estimated to be at or above target abundance, with fishing pressure near or below MSY targets. Stock status is summarized in Table S1 for all groundfish populations.

3.4 | Differences in regional trends

There are strong regional differences in abundance trends of groundfish stocks (Figure 6). Pooling together the three taxonomic orders, stocks in the Northeast Atlantic (Europe), Northeast Pacific (mainly from Alaska), Southwest Pacific (mainly New Zealand) and Southeast Atlantic (South Africa and Namibia) have been consistently above or near B_{MSY} on average, and in the last few years have shown increases in biomass on average. The Northwest Atlantic (Canada and USA) has shown slow recovery since the major declines in stock abundances during the 1980s and early 1990s. On average, groundfish stocks in the Northwest Pacific (Japan and Russia), Southeast Pacific (Chile) and Southwest Atlantic (Argentina) have had abundances below B_{MSY} on average for several decades (Figure 6) although the Northwest Pacific and Southwest Atlantic stocks are now close to B_{MSY} on average.

Mean trends in U/U_{MSY} (Figure 7) are equally diverse among regions. The Southeast Atlantic (South Africa and Namibia), Northeast Pacific (mainly Alaska) and Southwest Pacific (New Zealand) have consistently had mean fishing pressure near or well below U_{MSY}. Both North Atlantic regions, the Northwest Pacific and the Eastern Central Pacific all had high average fishing pressure throughout the 1970s and 1980s; the Northeast Atlantic at more than twice the level expected to provide MSY. There was a sharp decline in harvest rate in the Northwest Atlantic in the early 1990s associated with the Canadian cod collapse and ensuing fishing moratoria on several groundfish stocks and substantial reductions in allowed days at sea in New England fisheries, whereas in the Northeast Atlantic fishing pressure declined more gradually since that time, and is currently at U_{MSY} (Figure 7). Declines in mean U/U_{MSY} of stocks in the Northwest Pacific have been gradual in recent years, and fishing pressure is now also at U_{MSY}. More pronounced declines in mean U/U_{MSY} have occurred more recently in the Southwest Atlantic where all assessed stocks show fishing pressure below U_{MSY}. Most estimates for the Southwest Atlantic are only available since the late 1980s or early 1990s. Later-developing fisheries in the Southeast Pacific (Chile) had low mean fishing pressure before 1990, but fishing pressure increased to well above U_{MSY} around 2010 but now appear to be declining. The Eastern Central Pacific (US portion, off

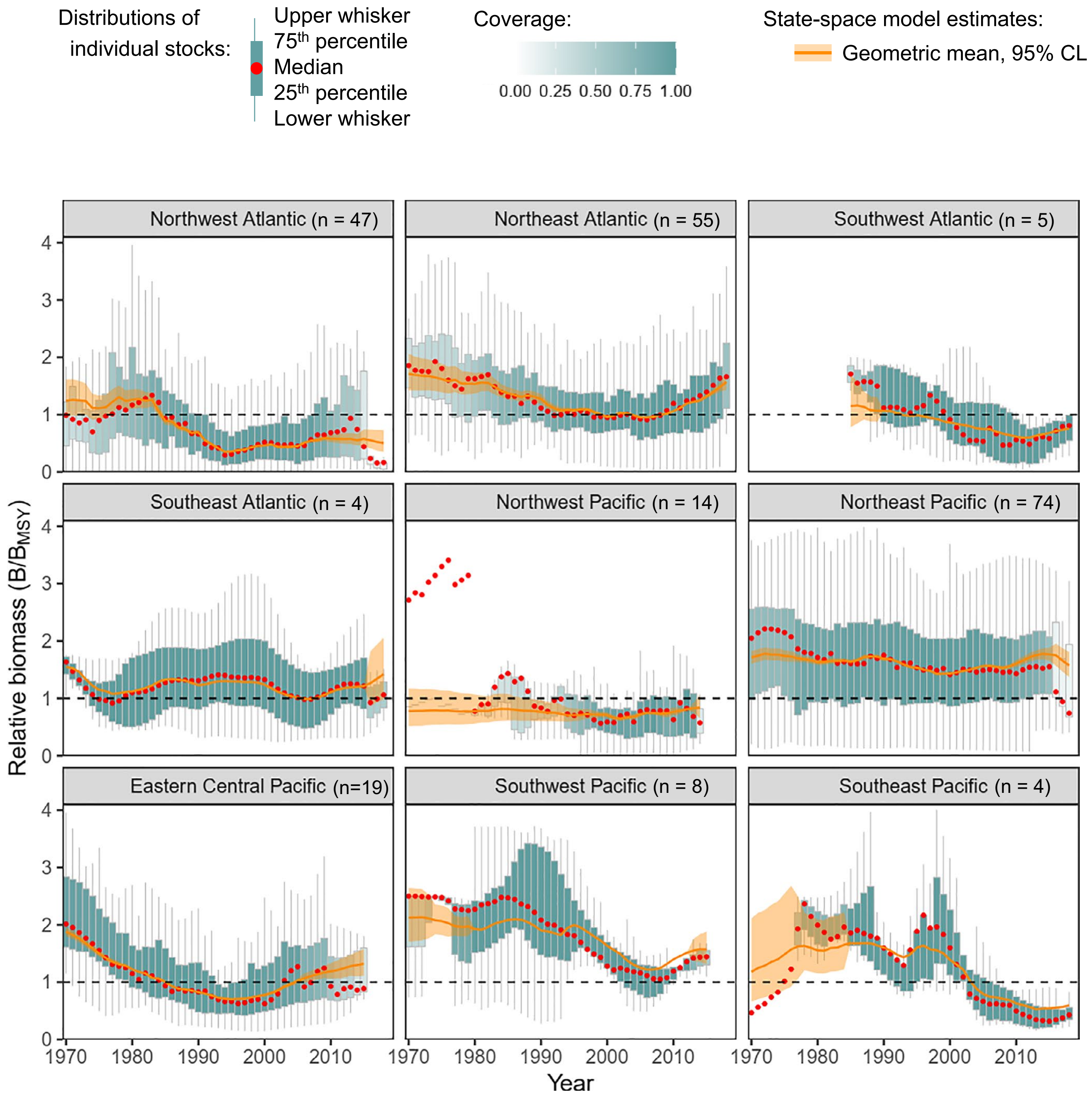

FIGURE 6 Trends in groundfish mean relative abundance, B/B_{MSY}, by major FAO area. Shaded bands around mean denote 95% finite population-corrected confidence bounds (applicable to all years with <100% coverage). Boxplots with medians as red circles show distributions of individual stocks in each year, with shading reflecting the fraction of stocks with assessments covering that year. The horizontal line at 1.0 is the MSY value. Stocks are equally weighted

the coast of California) saw a major decline in U/U_{MSY} beginning in the late 1990s as a result of mandatory rebuilding requirements for several depleted rockfish stocks (McQuaw & Hilborn, 2020; Warlick et al., 2018) and continues to have the lowest fishing pressure among all regions.

The joint relationship of trends in mean U/U_{MSY} and B/B_{MSY} further shows that transitions in groundfish stock status over four decades have strongly differed by region (Figure 8). All regions show the general (and expected) counter-clockwise pattern of rising U/U_{MSY} leading to declining B/B_{MSY}, then as U/U_{MSY} was lowered B/B_{MSY} began to increase. The solid isocline in each panel shows the boundary between when B/B_{MSY} is expected to decrease based on U/U_{MSY} (at combinations up and right of the line) and where B/B_{MSY} is expected to increase (at combinations down and to the left of the line). All regions with the exception of the Northeast Atlantic are roughly consistent with this.

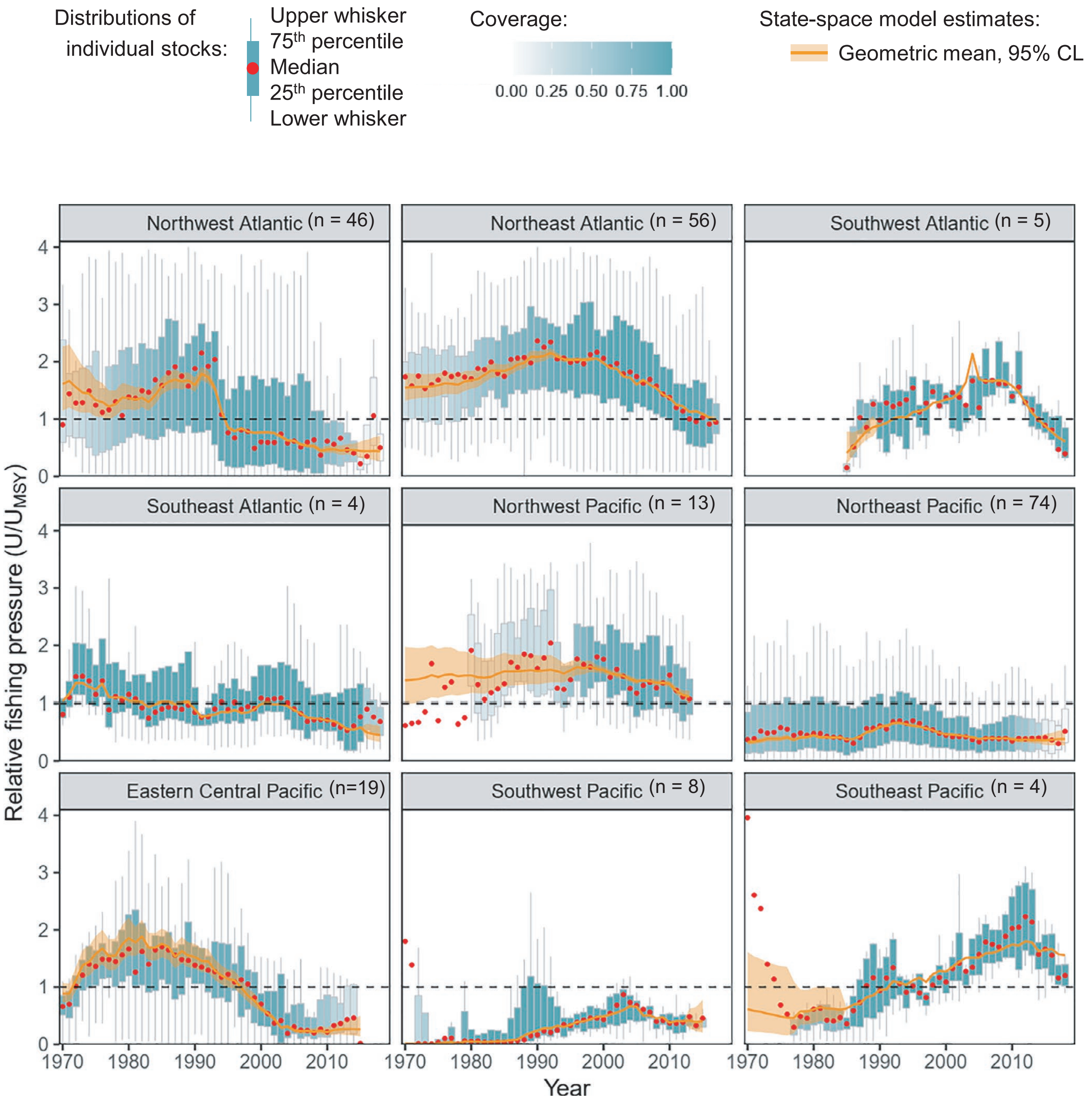

FIGURE 7 Trends in groundfish mean fishing pressure, U/U_{MSY}, by major FAO area. Shaded bands around mean denote 95% finite population-corrected confidence bounds (applicable to all years with <100% coverage). Boxplots with medians as red circles show distributions of individual stocks in each year, with shading reflecting the fraction of stocks with assessments covering that year. The horizontal line at 1.0 is the MSY value. Stocks are equally weighted

Mean trends in some regions (Southeast Atlantic, Northeast Pacific, Southwest Pacific) have rarely been outside of the lower right quadrant, with high abundance and low fishing pressure. In the Northwest Pacific the mean trends has remained in the upper left quadrant throughout the years covered by stock assessments, where fishing pressure remains high despite average abundance being low, below B_{MSY}. Seven of the nine regions have had mean bivariate trends crossing the equilibrium biomass isocline, moving from the region of expected biomass decrease to the region of expected biomass increase. In the other two regions (Northeast Atlantic and Northwest Pacific), mean trends have remained above the isocline for most or all of the time series. In the Northeast Atlantic, the classic counter-clockwise pattern is seen, but the stocks started rebuilding at a higher fishing pressure and biomass than would be expected.

Mediterranean groundfish stocks are all heavily fished (Colloca et al., 2013; Tsikliras et al., 2013; Vasilakopoulos et al., 2014), with U/U_{MSY} estimates in stock assessments averaging well above 5.

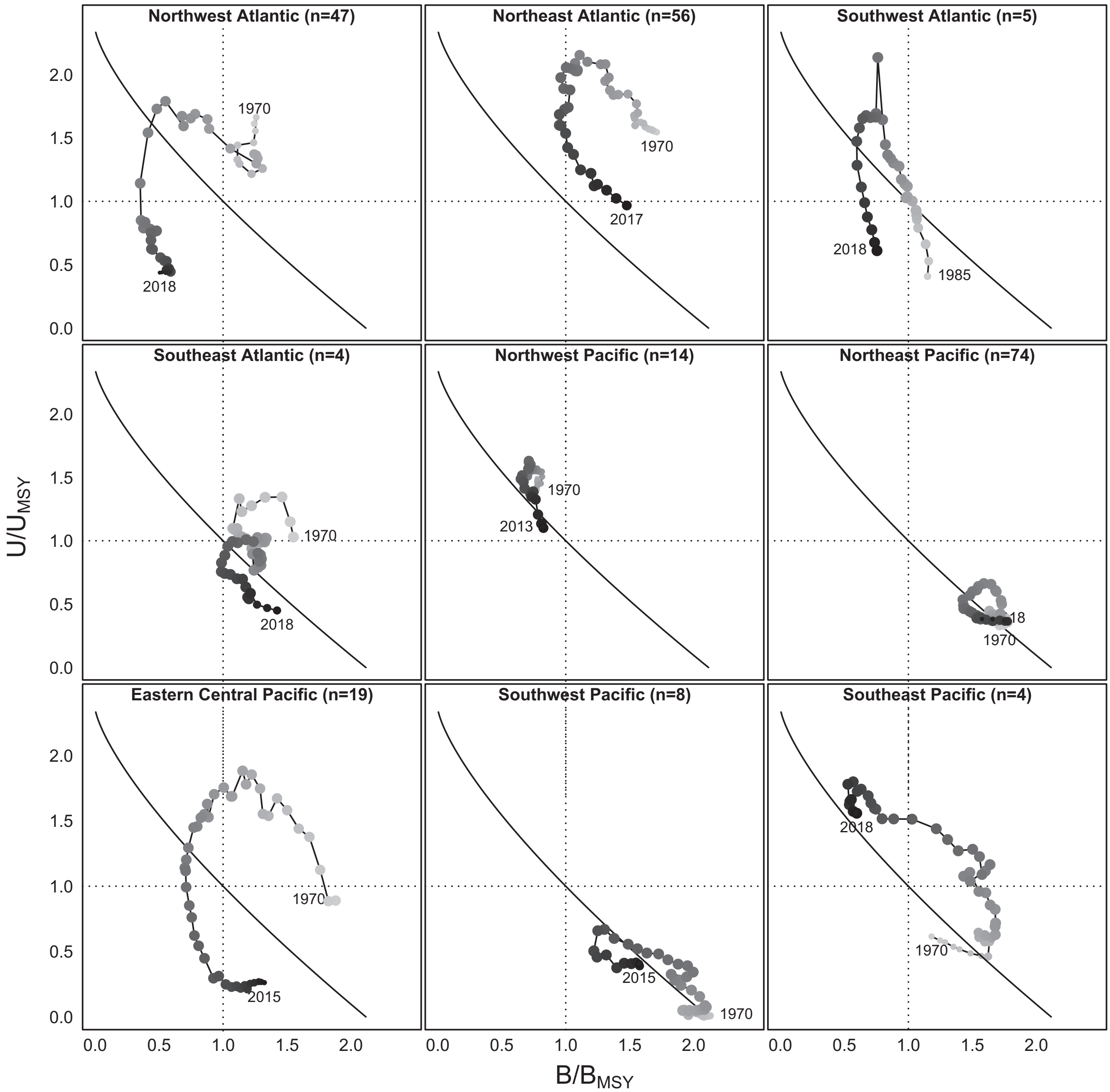

FIGURE 8 Bivariate mean trends in B/B_{MSY} and U/U_{MSY} by major FAO area. Values of geometric mean stock status are estimates from the state-space model, the same values as shown in the univariate trends in Figures 6 and 7. Shading transitions from earlier (light) to later (dark) years, with different year ranges among regions. Area of circles is proportional to the number of stocks with data available in that year; scaling is applied within each area not across areas. The solid isocline going from upper left to lower right is the predicted equilibrium abundance for each level of fishing pressure; for stocks above and to the right of this line, abundance is predicted to decrease whereas abundance is predicted to increase in the region below and to the left of the line

However, the assessments generally cover a very short period of time, and reliable B/B_{MSY} estimates are not available because most assessments only cover the period during which stocks were heavily fished, not earlier years. State-space model fits for FAO area 37 did not converge for U/U_{MSY}, so trends are not shown individually for this group of stocks from the Mediterranean (these stocks are still included in the worldwide trends shown in Figure 4).

3.5 | Lost yield

The number of stocks and the summed MSY of stocks are listed by status categories of current relative biomass and current relative fishing pressure (Table 1). For each stock, the magnitude of foregone equilibrium yield was calculated and summed across stocks in each category (Table 1). For each stock, the foregone yield estimates were

TABLE 1 Number of stocks, total potential MSY and foregone potential yield and landed value of groundfish stocks in different status categories of fishing pressure (U/U_{MSY}) and biomass (B/B_{MSY})

Status category	Number of stocks	Sum of MSY (t)	% of stocks in status category	% of total MSY in status category	Foregone potential equilibrium yield (t)	Foregone potential equilibrium value ($m)	Foregone equilibrium yield as % of MSY	% of foregone equilibrium yield in status category	Sum of differences, MSY - current catch (t)
$1.5 < U/U_{MSY}$	26	376,332	7%	3%	331,352	455	88%	11%	196,375
$1 < U/U_{MSY} < 1.5$	42	2,327,407	12%	17%	104,793	195	5%	4%	716,767
$U/U_{MSY} < 1$ & $1 < B/B_{MSY}$	120	6,244,846	34%	47%	1,961,737	1,167	31%	67%	2,261,384
$U/U_{MSY} < 1$ & $B/B_{MSY} < 1$	49	3,202,279	14%	24%	538,522	539	17%	18%	1,364,264
U/U_{MSY} unknown	112	1,197,537	32%	9%	Unknown	Unknown	Unknown	Unknown	Unknown
Total for U/U_{MSY}	349	13,348,401	100%	100%	2,936,403	2,355	22%	100%	4,538,789
$B/B_{MSY} < 0.5$	41	1,112,355	12%	8%	739,791	1,120	67%	14%	897,109
$0.5 < B/B_{MSY} < 1$	52	2,891,765	15%	22%	99,661	184	3%	2%	850,154
$1 < B/B_{MSY}$	144	8,146,744	41%	61%	4,551,837	5,429	56%	84%	2,791,527
B/B_{MSY} unknown	112	1,197,537	32%	9%	Unknown	Unknown	Unknown	Unknown	Unknown
Total for B/B_{MSY}	349	13,348,401	100%	100%	5,391,289	6,733	40%	100%	4,538,789

Note: Foregone yield estimates are based on the most recent year of assessment. Stocks with $U/U_{MSY} < 1$ are separated into status categories of under rebuilding ($1 < B/B_{MSY}$) or lightly exploited ($B/B_{MSY} < 1$).

also multiplied by average ex-vessel price to estimate the magnitude of foregone landed value across stocks.

While 32% of assessed groundfish stocks have unknown B/B_{MSY} and U/U_{MSY}, these only constitute 9% of the potential MSY (using average catch as a surrogate for MSY when MSY is not included in the assessment; Table 1). This supports observations across a wide range of species groups that larger (and more valuable) stocks receive more management attention and therefore are more likely to have estimates of B/B_{MSY} and U/U_{MSY} available (Neubauer et al., 2018). The quantities of foregone yield by status category under the alternative empirical measure of foregone yield (based on differences between estimated MSY and current catch) are roughly proportional to the quantities of foregone yield from equilibrium yield curves in the same categories (Table 1).

Of the groundfish stocks that have estimates of B/B_{MSY} or U/U_{MSY}, the majority (71% of stocks) are harvested at less than U_{MSY} and have biomass greater than B_{MSY} (61% of stocks); in terms of potential yield, these stocks represent 78% and 67% of the total MSY, respectively. Estimating total lost yield and value on the basis of fishing pressure, 2.9 million tons and 2.4 billion US$ of potential yield are lost from not fishing at U_{MSY} (Table 1). Of these quantities foregone, only 15% in tonnage is lost from fishing too hard; the loss in value is roughly the same. If lost yield and value are instead estimated on the basis of biomass, again far more yield and value are foregone from stocks at $B > B_{MSY}$ (84% of yield and 81% of value) than from stocks at $B < B_{MSY}$. Because fisheries agencies control the fishing pressure and do not directly control biomass, we emphasize the estimated lost yield and value based on U/U_{MSY}.

The stocks that are in the lower left quadrant of the Kobe plot, with $B/B_{MSY} < 1$ and $U/U_{MSY} < 1$, deserve special attention. In general, these stocks have seen reduced U due to their poor status and we would expect U to rise once stocks rebuild to or above B_{MSY}. While these stocks only account for 18% of the total lost yield at equilibrium based on U/U_{MSY}, a much larger yield loss (2.5 times as large in weight) is estimated from the alternative empirical measure landings (Table 1). This is because the equilibrium method applies the current $U < U_{MSY}$ to a predicted biomass that is higher than current B and higher than B_{MSY}.

3.6 | Management influences on stock status

Management intensity for the groundfish stocks, averaged across all stocks, increased steadily from near 0 in 1950 to 0.9 by 2016. As we saw in Figure 4 average abundance of groundfish declined up until the mid-1990s to early 2000s and then increased, while average fishing pressure increased up to the mid1990s and then declined. Figure 9 shows the year to year rate of change in average biomass and average fishing pressure across all groundfish stocks plotted against the global groundfish fisheries management intensity in the same year. Panel a shows that fishing pressure increased annually while management intensity was relatively low (up to levels of about 0.45, i.e. in early years). As management intensity gradually increased further, average fishing pressure switched to decreasing annually. Panel b shows that average biomass decreased during years of low management intensity (up to index values of about 0.5), again which occurred in earlier years. As management intensity increased in later years, average biomass also increased.

4 | DISCUSSION

Since 2000, total groundfish catch has fluctuated around 10 mmt and overall, the catch of groundfish appears to have stabilized across most major taxa. Analysis of lost yield (Table 1) suggests that there is some potential to increase long-term yields; for some stocks, this would involve decreasing fishing pressure (if $U > U_{MSY}$ currently), and for other stocks, this would involve fishing them harder (if $U < U_{MSY}$ currently). This potential yield that could be gained is roughly 22% of estimated maximum possible long-term yield or 33% of current yield, so if maximum long-term yield is indeed an objective in global groundfish fisheries, a total catch of 14 mmt could be obtainable with perfect management. Thus while much of the discussion of fisheries status and performance in the popular media has tended to focus on the costs of overfishing, it appears for global groundfish stocks that overfishing is not a major source of lost yield.

There are a number of reasons why fisheries management agencies may choose to manage more conservatively than MSY-based levels, maintaining $F < F_{MSY}$ and $B > B_{MSY}$. Annex 2 of the United Nations Fish Stocks Agreement (FAO, 1995) recommends that "the fishing mortality rate which generates maximum sustainable yield should be regarded as a minimum standard for limit reference points". In addition, the US National Research Council (NRC, 1998) advocated for an explicitly conservative approach and recommended that "a moderate level of exploitation might be a better goal for fisheries than full exploitation, because full exploitation tends to lead to overexploitation". These and subsequent developments have led many fisheries management agencies and entities to opt to set biomass targets that exceed B_{MSY} and/or fishing mortality targets that treat F_{MSY} as a limit. There are at least three reasons governments and mangers may choose to forgo some potential yield. First, because groundfish are often caught in mixed stock fisheries, it is not possible to harvest each stock at its optimum rate and thus the theoretical yield cannot be obtained for all stocks. Second, when fishing pressure is consistently lower than F_{MSY} biomass will be higher and costs of fishing lower as a result of greater harvesting efficiencies. Third, ecosystem considerations including explicit recognition of the needs of other marine animals that forage on fish species, the presence of vulnerable species in assemblages of marine species, the effects of fishing effort on bottom habitats in some fisheries, the need to maintain food webs and species diversity, and the need for resilience of both individual species and ecosystems are all arguments for reducing fishing pressure below the level that would maximize yield. Thus the estimates in Table 1 are very much an aspirational goal rather than an expectation of what would be achieved with better

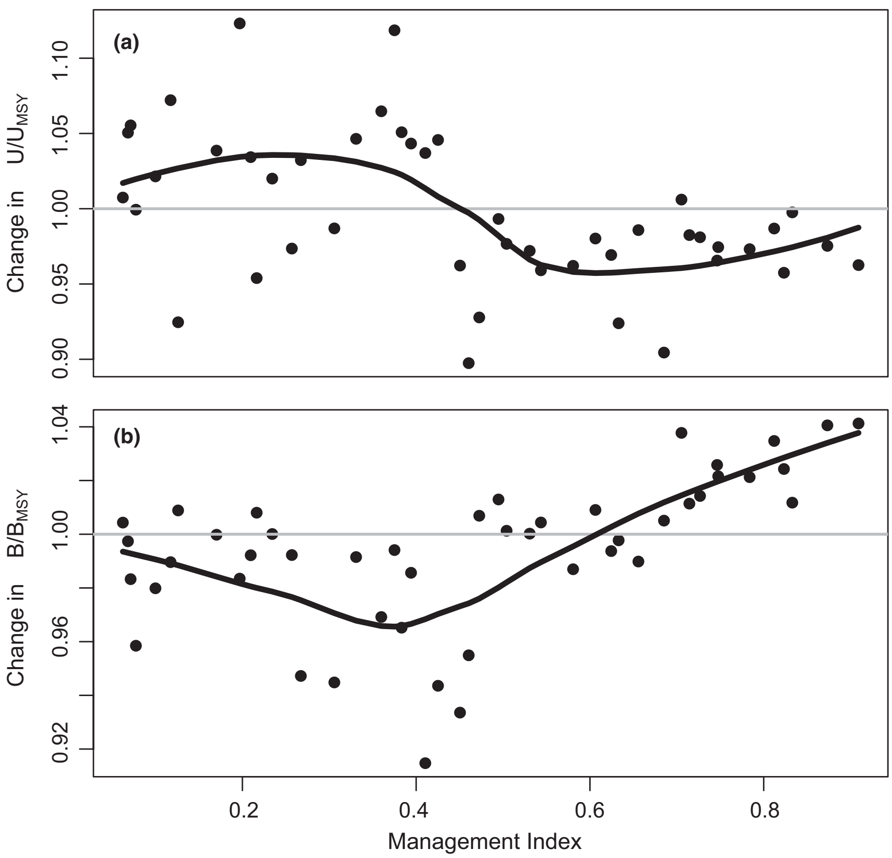

FIGURE 9 Relationship between mean stock-level management intensity index for groundfish stocks and mean annual change in either relative fishing pressure (a) or relative stock abundance (b). Data points represent individual years. Solid line is lowess smoother and grey horizontal line at 1 shows the boundary between increasing and decreasing mean values

management, but they do suggest that excessive fishing pressure is not the major cause of lost potential yield.

Regions that continue to have average fishing pressure above U_{MSY} (or have a considerable portion of individual stocks with $U > U_{\mathrm{MSY}}$) are the Northeast Atlantic, Southeast Pacific and Northwest Pacific. Their current mean U/U_{MSY} are all near 1, so as shown in Table 1, there is not much lost yield globally from this excess fishing pressure. Five regions have fishing pressure well below U_{MSY}: Northeast Pacific (mainly Alaskan stocks), Southeast Atlantic (Southern African stocks), Southwest Pacific (mainly New Zealand stocks), Eastern Central Pacific (US stocks) and Northwest Atlantic (Canadian and US stocks). The first four of these regions should theoretically have some potential to increase long-term yields by fishing harder, if given sufficient market demand, while for the Northwest Atlantic, biomass of most stocks has still not recovered despite reduced fishing pressure since the 1990s. The largest single potential for increased yield is from the Eastern Bering Sea pollock stock, for which annual landings continue to be well below the scientific advice because of an overall regional cap on allowable multi-species catch of 2 mmt (Witherell & Pautzke, 1997). Indeed there are several cases like this where adjusting harvest rates closer to U_{MSY} may not be possible because the stocks are caught in mixed stock fisheries, and catch limits for other species may limit the landings of primary target groundfish stocks (Crowder & Murawski, 1998; Hilborn et al., 2012; Laurec et al., 1991; Melnychuk et al., 2013; Murawski, 1991; Ulrich et al., 2011).

Abundance trends showed clear correlation with changes in fishing pressure: for most regions, as fishing pressure increased, stocks declined, and when fishing pressure was reduced, abundance increased. Similar patterns have been observed for assessed stocks in other taxa (Hilborn et al., 2020; Walters et al., 2008). For groundfish, the most striking anomalies are the Northwest and Northeast Atlantic. In the Northwest Atlantic, stocks have not rebuilt to levels approaching their targets after fishing pressure was dramatically reduced around 1990. For some stocks, this has been the case despite being placed under formal rebuilding plans (Melnychuk et al., 2021). Some of the failures to rebuild are due to changes in productivity that occurred in the late 1980s and 1990s (Frank et al., 2005; Hilborn & Litsinger, 2009; Rothschild, 2007; Shelton et al., 2006) which has meant that Canadian and US stocks have been much slower to recover despite low fishing pressure. The change in productivity occurred at both low abundance (2J3KL cod) and at high abundance (4TVn cod, 4VsW cod, 3Ps cod) (Hilborn & Litsinger, 2009).

In contrast, in the Northeast Atlantic, as others have shown, most stocks are rebuilding (Cardinale et al., 2013; Fernandes & Cook, 2013; Froese et al., 2018; Zimmermann & Werner, 2019) and European stocks have generally responded more quickly to changes in fishing pressure. The Northeast Atlantic stock mean trend has been increasing since 2000 despite the fact that fishing pressure appears to have been greater than U_{MSY} (Figures 6 and 8). This suggests that there may be a systematic bias with either B_{MSY} or U_{MSY} underestimated. Sparholt et al., (2020) have suggested that ICES assessments of U_{MSY} are biased low (about 2/3 of the actual) because they ignore density-dependent somatic growth and natural mortality. Alternatively, B_{MSY} is not estimated in the assessments of many ICES stocks, and the management target $B_{trigger}$ is instead used as a proxy by ICES (ICES, 2019) and in our analysis. $B_{trigger}$ may well be significantly below the biological B_{MSY} and is indeed lower on average than B_{MSY} estimated post hoc from production models for the same stocks. Relative trends in abundance are not affected, but the status relative to true B_{MSY} would be too optimistic. Overall our trends showing the decline and then rebuilding of Northeast Atlantic groundfish stocks are consistent with the pattern shown by Zimmermann and Werner (2019) for all taxa, and our conclusion that reduced fishing pressure was responsible for this biomass rebuilding is consistent with their conclusion.

While we present results for regional status as a whole, there are often large differences within a region, so that even when the average stock status is above target biomass and fishing pressure is below target, some stocks may be at low abundance or subject to excess fishing pressure. Fernandes and Cook (2013) as well as Froese et al., (2018) highlighted the differences in stock status among regions in the EU, and similar differences are seen in US regions (Hilborn et al., 2020). The impact of excess fishing pressure is accounted for in the lost yield analysis and is only a few hundred thousand tons for groundfish globally (Table 1). Nevertheless, losses from depleted stocks may still be important locally even if the overall regional average status of stocks is healthy.

Groundfish management approaches have been diverse among regions (Melnychuk et al., 2021; Melnychuk et al., 2017). The majority of large groundfish stocks from Europe, New Zealand, Russia, South Africa, Namibia and the United States are certified by the Marine Stewardship Council which indicates a high degree of management intensity and health of stocks. Groundfish fleets are primarily industrial fisheries with fleet-wide quota or effort limits. In some regions, these involve individual allocations among vessels, while in others the fisheries remain largely competitive (Melnychuk et al., 2013; Melnychuk et al., 2021). Other attributes of groundfish management systems include harvest control rules, fishery-independent surveys and ratification of international agreements to reduce illegal fishing and jointly manage transboundary stocks (Melnychuk et al., 2021). These attributes can be seen as incremental, each contributing to strengthening overall management intensity, and thereby aiding in meeting stock-level management objectives.

We saw in Figure 9 that higher management intensity has been associated with increasing biomass and decreasing fishing pressure, but we cannot assert this is necessarily a causal relationship. A major focus of fisheries after WWII was on fisheries development, finding new stocks, developing fishing methods and overall expanding fishing pressure (Grainger & Garcia, 1996), thus it is not surprising that fishing pressure was increasing. With the increasing concern about overfishing in the 1990s, we saw management intensity continue to increase, fishing pressure decline and stocks stop their decline and start to rebuild. In addition to the fisheries management intensity measures included in this analysis, the 1990s saw the advent of seafood certification and labelling schemes, and major expansion in marine conservation efforts by environmental NGOs. All of these factors are interrelated, and thus, we cannot be certain that it was the changes in fisheries management that led to the decline in fishing pressure and increase in abundance, though they do support the results of formal time-series intervention analyses which used these same management intensity data (Melnychuk et al., 2021). Of course harvest is not the only influence groundfish stocks—they are subject to environmental changes, which may intensify due to climate change. Vert-pre et al., (2013) estimated that almost 70% of fish stocks are subject to periodic changes in productivity and Figure 1 of that paper shows the analysis for Icelandic cod which showed a dramatic drop in productivity about 1990.

Compared to the tuna and billfish, the other major group of fishes that has been evaluated, groundfish show some striking differences. The major tuna fisheries all had high biomass and low fishing pressure rates in the 1970s and saw increases in fishing pressure and declining biomass with stocks stabilizing at or near B_{MSY} in recent decades. In contrast, groundfish stocks in two regions (Norwest Atlantic, Northwest Pacific) were already fully harvested by 1950 or soon after (B near B_{MSY}) and the Northeast Atlantic already had harvest rates well above U_{MSY}.

The data and analysis in this paper focus on the status and management of groundfish stocks. We do not explore ecosystem-wide impacts of fishing even though many marine ecosystems have been greatly impacted by fishing. Christensen et al., (2014) estimated that predatory fish have declined 60%–70% in global oceans and that lower trophic level fishes have more than doubled in abundance. Mazor et al. (2020) and Amoroso et al., (2018) have documented the global impact of bottom trawling on benthic biota, showing that the impact is highly variable by region and by benthic habitat structure. As mentioned previously, one reason many groundfish stocks may be not fully exploited is concern about the impact of fishing on other species and ecosystem structure.

Many groundfish stocks are among the best-studied and highly targeted stocks worldwide of any fished taxa. While single-species management aiming to meet MSY-based management objectives has generally been the dominant form of management in many regions, some jurisdictions opt to set reference points based on using MSY-related metrics as minimum standards or to maintain stocks at levels above B_{MSY} either to account for potential assessment uncertainties, to add an element of precaution into fisheries management or to provide for other components of the ecosystem. Regardless of the target employed, mixed stock fisheries may involve constraints in achieving single-species objectives. Future work could evaluate the degree to which groundfish fishing fleets are able to target individual stocks while avoiding stocks that may be of greater conservation concern and thus present bycatch restrictions. Certain gear types or fishing patterns may be more selective in catching primary target species. Reducing the incidental catch of non-target or secondary-target species will allow for targeted groundfish stocks to be maintained near their most productive levels, providing more fish on our plates.

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CONFLICT OF INTEREST

RH receives research funding from many groups that have interests in fisheries outcomes including environmental NGOs, foundations, governments and fishing industry groups.

DATA AVAILABILITY STATEMENT

Data used in this paper are available at in the following places: (1) FAO landings data are available from the FAO web site (http://www.fao.org/fishery/statistics/global-capture-production/en) (2) the RAM Legacy Stock Assessment Database (www.ramlegacy.org, and https://zenodo.org/record/4458275) and (3) stock-level management intensity index data are available at https://github.com/mcmelnychuk/MCM-NatSust_2020-12-05.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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