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Original Article

Coherence and potential drivers of stock assessment uncertainty in Northeast US groundfish stocks

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Failure to account for the impacts of climate and ecosystem change on stock dynamics can introduce uncertainty to stock assessments that can make meeting the objective of sustainable fisheries management challenging. The increased prevalence and magnitude of uncertainty in New England groundfish stock assessments (i.e. retrospective patterns) in recent years suggest that there may be common drivers impacting these stocks that are currently unaccounted for in the stock assessment. We examined the coherence in retrospective patterns across groundfish stock assessments and evaluated candidate drivers of retrospective patterns, including large-scale climate and ecosystem change, as well as significant management and monitoring changes. We found high coherence in moving window Mohn's rho time series for groundfish within the Gulf of Maine and Georges Bank areas. Fluctuations in Gulf of Maine groundfish Mohn's rho values were most strongly related to lagged bottom temperature and spiny dogfish biomass time series, whereas fluctuations in Georges Bank groundfish Mohn's rho values were strongly related to lagged time series of warm core rings formation from the Gulf Stream. Our identification of coherence in retrospective patterns across groundfish stocks by region supports the idea of common regional drivers with climate and ecosystem changes emerging as the leading contributing factors.

Keywords: climate change, fisheries management, groundfish, retrospective patterns, stock assessment.

Introduction

Ensuring that fisheries are ecologically and economically productive over the long term requires setting harvest levels that are appropriately scaled to the current and future conditions in the ocean (Holsman *et al.*, 2019). Stock assessments underpin US fishery management decisions and provide estimates of the current biomass of fish and short-term projections of future biomass that are used in setting catch advice. Accurate stock assessment is critical to setting appropriate harvest levels and determining effective rebuilding plans for stocks. Our understanding of fish life history and drivers of population abundance are codified in these models and any misperceptions or omissions can influence their accuracy. In most cases, these statistical models assume that species–ecosystem relationships are stationary over time and do not account for time-varying processes (e.g. natural mortality and survey or fishery catchability; Wilberg *et al.*, 2010; Skern-Mauritzen *et al.*, 2015; Holsman *et al.*, 2019). Directional changes in marine resource productivity and distribution, such as those associated with climate change, can introduce non-stationarity that violates this underlying assumption (Szuwalski and Hollowed, 2016; Chen *et al.*, 2022). This can result in large uncertainties in stock assessment that can cause misperceptions of stock status that directly impact catch advice and challenge the ability to achieve the goal of sustainable fisheries management.

There are several diagnostics used to evaluate the uncertainty of a stock assessment model, but one of the most common approaches is the characterization of retrospective patterns. Retrospective patterns in fish stock assessment are consistent directional changes in estimated quantities (e.g. spawning stock biomass, SSB) as additional years of data are added to an assessment (Szuwalski *et al.*, 2018). These systematic patterns can be induced when time-varying processes are not accounted for in an assessment resulting in a model misspecification (Legault, 2009; Hurtado-Ferro *et al.*, 2015). Some of the candidate causes include (1) ecosystem change and its impact on population processes (e.g. time-varying natural mortality), (2) changes in fishing behaviour and misreporting of catch (e.g. unreported or underestimated discards), or (3) changes in survey or fishery catchability and selectivity. In addition, more than one of these processes can be at play at once, particularly in the case of climate impacts that may simultaneously influence population productivity as well as distribution (Karp *et al.*, 2018).

New England groundfish

Groundfish fisheries in New England have been historically valuable and culturally important to the region. In recent decades, several groundfish stocks have declined to historic low levels (NEFSC, 2019), and this has resulted in dramatic reductions in annual catch limits for these stocks and even broader constraints due to the mixed stock nature of the fishery and choke species issues. With declines in stock biomass, the revenue of the groundfish fishery has declined with losses of ∼$60 million since the mid-2000s (NEFSC, 2021), threatening the future of New England fishing communities (Scyphers *et al.*, 2019). Declines in stock biomass have also coincided with the rise of retrospective patterns in many groundfish stocks, the majority of which exhibit a similar trend of overestimation of stock size and underestimation of fishing mortality (Wiedenmann and Jensen, 2018; NEFSC,

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2019). In 2019, eight stocks had retrospective patterns large enough to require the application of post-hoc adjustment factors to the estimated SSB. For example, in the case of Georges Bank haddock, this equated to imposing a nearly 40% reduction in the SSB estimated from the stock assessment as the basis for setting catch advice (NEFSC, 2019). Retrospective patterns represent a large source of uncertainty in the assessment of Northeast groundfish stocks. These patterns of overestimation of SSB and underestimation of fishing mortality can lead to unintentional overfishing that can undermine efforts to sustainably manage the groundfish fishery.

New England groundfish stocks are managed as a multispecies complex due to similarities in life history and their spatial co-occurrence, which leads to mixed stock catches. Despite the common ecology of many of these species and technical interactions of these stocks, assessments are conducted individually without connections made across stocks regarding common drivers and trends in the dynamics for this group. The fact that multiple groundfish stock assessments have retrospective patterns and the number of stocks with retrospective patterns is on the increase does not factor into management. The presence of retrospective patterns across groundfish stocks suggests there may be common drivers impacting these stocks that are currently unaccounted for or misspecified in the stock assessment. To date, there has been no conclusive diagnosis of this problem; however, unaccounted for natural mortality and underreported catches have been identified as likely contributors (Wiedenmann and Legault, 2022).

We identified large-scale climate and ecosystem change, as well as significant management and monitoring changes, as likely contributors to the observed retrospective patterns across stocks of New England groundfish. In recent decades, the Northeast US Shelf ecosystem has warmed four times faster than the global average rate and groundfish are characterized as exhibiting high sensitivity to changing ocean conditions (Hare *et al.*, 2016), with impacts of warming on productivity and distribution already documented for species such as Atlantic cod (Pershing *et al.*, 2015). In addition to changes in ocean conditions, there have been shifts in relative abundance of both groundfish predators and prey in the region, with increases in known predators such as grey seals and spiny dogfish (NOAA, 2021). There have also been large-scale changes in fisheries management in the region during recent decades, including changes in effort regulations (i.e. days at sea) and a switch to quota-based management for the groundfish fishery in 2010, which may have altered fishing behaviour and discarding practices. Furthermore, there have been changes in the primary fishery-independent survey used in the assessment of these stocks (i.e. Northeast Fisheries Science Center's bottom trawl survey) over the years, most notably a switch of survey vessels in 2009, and associated changes in catchability.

We used retrospective analysis as a tool to aid in diagnosing potential drivers of change in groundfish stock dynamics that are currently unaccounted for in the context of the stock assessment. We examined the degree of coherence in retrospective patterns across groundfish stocks and explored associations between metrics of retrospective inconsistency and potential drivers with the aim of identifying common drivers of these systematic problems in groundfish stock assessments. To date, these issues have been dealt with through *ad hoc* adjustments to stock assessment outputs or outright rejections of assessments and use of data-limited approaches to determine catch advice. However, identifying contributing factors to retrospective patterns in stock assessments provides a pathway to develop an integrated approach to understanding and resolving retrospective patterns across groundfish assessments and informing appropriate management responses. The goals of this study were to (1) characterize the timing and magnitude of retrospective patterns across a range of groundfish stocks, (2) examine the degree of coherence in retrospective patterns across groundfish stocks, and (3) evaluate candidate factors responsible for driving retrospective patterns in Northeast US groundfish stock assessments.

Methods

Characterizing retrospective patterns

We characterized the timing and magnitude of retrospective patterns in New England groundfish stock assessments with major retrospective patterns, including (1) Georges Bank Atlantic cod, (2) Georges Bank haddock, (3) Georges Bank winter flounder, (4) Georges Bank yellowtail flounder, (5) Gulf of Maine cod, (6) Gulf of Maine haddock, (7) Cape Cod/Gulf of Maine yellowtail flounder, (8) American plaice, (9) pollock, (10) Southern New England/Mid-Atlantic winter flounder, (11) Southern New England/Mid-Atlantic yellowtail flounder, (12) white hake, and (13) witch flounder. Characterization of retrospective patterns was conducted using the most recently applied analytical stock assessment models that were accepted for providing management advice. Five of the stocks we examined (i.e. Georges Bank haddock, Georges Bank winter flounder, American plaice, witch flounder, and Cape Cod/Gulf of Maine yellowtail flounder) were assessed using virtual population analysis (i.e. VPA), specifically the ADAPT model, and the remaining eight were assessed using a statistical catch-at-age model (i.e. SCAA), specifically the age structured assessment programme (i.e. ASAP; Legault and Restrepo, 1999). The ADAPT and ASAP software programs used in these assessments are available for download through the NOAA Fisheries Toolbox (https://www.nefsc.noaa.gov/nft/). Assessments were conducted using the data inputs (i.e. catches, catch-at-age, and indices of abundance) and model specifications used in the most recent assessment for each stock. This information is available online through NOAA's Stock Assessment Support Information website (https://www.nefsc.noaa.gov/saw/sasi/sasi_report_options.php). For ten stocks, we used the assessment model that was conducted in 2017 or 2019 (Table 1, NEFSC, 2017, 2019). The remaining three stocks (i.e. Georges Bank cod, Georges Bank yellowtail flounder, and witch flounder) had recent assessments rejected due to severe retrospective patterns. In these cases, we used the most recent assessments available (Georges Bank cod; NEFSC, 2015a, and witch flounder; NEFSC, 2015b). For Georges Bank yellowtail flounder, we obtained an updated ASAP formulation from the lead stock assessment scientist (C. Legault, pers. comm.) but acknowledge that this assessment model has not undergone peer review.

We characterized the timing and magnitude of retrospective patterns in groundfish stock assessments using an extension of the moving window approach to calculate the Mohn's rho retrospective statistic (see Supplementary Material for full description of approach; Boenish and Chen, 2020). Application of a moving window approach has been recommended as a useful means of identifying the timing of retrospective pattern development in stock assessments (Legault, 2009). Typically,

Table 1. Northeast US groundfish stocks examined in characterizing the timing and magnitude of retrospective patterns in stock assessments.

Full stock name	Abbreviated name	Model type	Assessment period	Rho period	Assessment years with rho adjustment	Source
Georges Bank Atlantic cod	GBC	SCAA	1978–2014	1990–2013	2012, 2013	NEFSC (2015)
Gulf of Maine Atlantic cod	GOMC	SCAA	1982–2018	1990–2017	2019*	NEFSC (2019)
Georges Bank haddock	GBH	VPA	1931–2018	1990–2017	2015, 2017, 2019	NEFSC (2019)
Gulf of Maine haddock	GOMH	SCAA	1977–2018	1998–2017	2019	NEFSC (2019)
Gerges Bank yellowtail flounder	GBYF	SCAA	1973–2018	1990–2017	2011, 2012, 2013	
Cape Cod/Gulf of Maine yellowtail flounder	GOMYF	VPA	1985–2018	2000–2017	2012, 2015, 2017, 2019	NEFSC (2019)
Southern New England/Mid-Atlantic yellowtail flounder	SNEYF	SCAA	1973–2018	2001–2017	2017, 2019	NEFSC (2019)
Georges Bank winter flounder	GBWF	VPA	1982–2018	1990–2017	2015, 2017, 2019, 2020	NEFSC (2019)
Southern New England/Mid-Atlantic winter flounder	SNEWF	SCAA	1981–2018	1997–2017		NEFSC (2017)
Witch flounder	WITCH	VPA	1982–2014	1998–2013	2015	NEFSC (2015)
American plaice	PLAICE	VPA	1980–2018	1990–2017	2008, 2012, 2015, 2017, 2019	NEFSC (2019)
Pollock	POL	SCAA	1970–2018	1990–2017	2015, 2017, 2019	NEFSC (2019)
White hake	WHAKE	SCAA	2018	1990–2017	2017, 2019	NEFSC (2019)

Model type was classified as statistical catch-at-age (SCAA) or virtual population assessment (VPA). Assessment period indicates the years of data in the assessment model and rho years indicate the years for which annual Mohn's rho values were estimated using the moving window approach. The rho adjustment years are years in which abundance estimates were adjusted to account for the retrospective pattern. The abbreviated names listed here are used in Figure 3.

analysts remove the most recent 5–7 years of data to calculate an average Mohn's rho value and characterize the retrospective pattern in a stock assessment (e.g. NEFSC, 2019). A moving window Mohn's rho extends these calculations further back in time for each window of years. The extension of the moving window Mohn's rho (Boenish, 2018; Boenish and Chen, 2020) requires the specification of two values: (1) the interval of the moving window, and (2) the number of peels. In our analysis, both the window and number of peels were defined as one, which sequentially decreased the terminal year of the assessment by one year and then recalculated Mohn's rho based on a 1-year peel. While rho is often calculated using a multiyear average of the relative error in estimates, we focused on calculating annual values to understand the long-term behaviour of model deviations. Using this approach, we developed a moving window Mohn's rho time series for SSB for each groundfish stock.

For each stock, we attempted to sequentially remove years of data back to 1990, but for some stocks, the removal of this many years of data resulted in a stock assessment model that did not converge. We only used assessment estimates from model runs that converged to calculate Mohn's rho, so for five stocks the rho time series started after 1990 (i.e. Gulf of Maine haddock [1998–2017], Cape Cod/Gulf of Maine yellowtail flounder [2000–2017], Southern New England/Mid-Atlantic yellowtail flounder [2001–2017], Southern New England/Mid-Atlantic winter flounder [1997–2015], and witch flounder [1998–2013]; Table 1). For all the remaining assessments that converged through 1990, the starting year of data in the model was 1982 or earlier, resulting in a minimum of 9 years of data in the assessment model (Table 1). We assessed the degree of coherence in trends of Mohn's rho values across groundfish stock by calculating the Spearman rank correlation for pairwise comparisons of stocks.

Potential drivers of retrospective patterns

We explored candidate drivers of retrospective patterns, including (1) changes in the ecosystem that impact fish population dynamics, (2) changes in fishery management and fishery behaviour, and (3) changes in survey catchability. Table 2 summarizes potential drivers of retrospective patterns, their hypothetical impact, and supporting evidence relevant to groundfish stocks. We selected time series representative of these drivers to serve as predictor variables of retrospective patterns.

For metrics representing ecosystem changes, we included biotic and abiotic measures that have been linked with changes in natural mortality that could lead to retrospective patterns. Studies have linked changes in natural mortality of New England groundfish with annual sea surface temperature (Pershing *et al.*, 2015) and related indicators, including the Atlantic Multidecadal Oscillation (AMO; Jiao *et al.*, 2012) and the Gulf Stream Index (GSI; O'Leary *et al.*, 2019). We characterized the annual average bottom temperature for the Gulf of Maine and Georges Bank regions (Figure 1) based on the validated Finite Volume Community Ocean Model (Chen *et al.*, 2006). AMO and GSI indices were annual averages of these basin-wide measures (Joyce and Zhang, 2010). In addition, recent work has shown that periodic, rapid changes in temperature (i.e. marine heatwaves; Hobday *et al.*, 2016; Mills *et al.*, 2013) can also lead to fish mortality events (Genin *et al.*, 2020), but the magnitude of such events may not be well reflected in an annual temperature measure. As a proxy for such disruptive events, we used the annual number of warm core rings that meander off the Gulf Stream and move northwards, bringing warm, salty water over the continental shelf (Gangopadhyay *et al.*, 2019). It is important to note that these indicators are not all independent. AMO integrates sea surface temperature across the North Atlantic, so it will include variations in the GSI, especially on decadal scales, and is linked with bottom temperature.

For biotic factors affecting mortality, we used a time series of grey seal pup counts across four islands in the Gulf of Maine and Southern New England regions (i.e. Muskeget, Monomoy, Seal, and Green Islands; Wood *et al.,* 2020) as a proxy for adult seal abundance. Grey seal abundance has increased dramatically in the region since the early 1990s (Hayes *et al.*, 2019) and has been linked with increased natural mor-

Table 2. Potential sources of retrospective patterns in Northeast US groundfish stocks, description of mechanism, supporting examples from fish stocks in the region, and source of time series explored in this study.

Source of positive retrospective pattern	Mechanism	Examples from fish stocks in the region	Time series explored in this study (sources)
Increased natural mortality (post recruitment) through thermal stress	Higher temperatures lead to increased metabolic demands in heterotherms, and lower oxygen saturation in the water, which can lead to increases in starvation- or stress-induced mortality (e.g. Klein *et al*., 2017).	Increasing *M* for GOM cod with increasing temperature (Pershing *et al*., 2015). Increasing *M* for weakfish as the Atlantic Multidecadal Oscillation (AMO) became more positive (Jiao *et al*., 2102). Dome-shaped relationship between summer flounder *M* and the Gulf Stream Index (GSI; O'Leary *et al*., 2019)	Modeled average annual bottom temperature (Finite Volume Community Ocean Model; Chen *et al*., 2006) Gulf stream index (GSI; Joyce and Zhang, 2010; NOAA ecodata portal—https://noaa-edab.github.io/ecodata/articles/ecodata.htmll) Frequency of warm core ring formation (Gangopadhyay *et al*., 2019; NOAA ecodata portal)
Increased natural mortality (post recruitment) through increased predation	Increased abundance or exposure to marine mammal predators leads to greater consumption. Grey seals have increased in abundance in the region since the early 1990s (Hayes *et al*., 2019).	Many examples from nearby Canadian ecosystems linking higher *M* in Atlantic cod with increased abundance of grey seals (Benoit *et al*., 2011 ; O'Boyle and Sinclair, 2012; Swain and Benoît 2015)	Grey seal time series of pup counts on four islands in New England region (Wood *et al*., 2020)
Increased natural mortality (post recruitment) through competition/predation	Dogfish are very abundant in the region (http://www.asmfc.org/species/spiny-dogfish) and are generalist predators with high spatio-temporal and dietary overlap with many groundfish species (Link *et al*., 2002; Link and Auster, 2013).	Ecosystem modelling suggests that the high abundance of dogfish could be limiting the recovery of other groundfish species (Morgan and Sulikowski, 2015)	Spiny dogfish female spawning biomass time series (https://www.st.nmfs.noaa.gov/stocksmart)
Misreported catch (landings and/or discards)	There may be incentives and opportunities for misreporting of landings or discards. Large management changes aimed at reducing fishing effort and mortality following Amendments 5 and 13 (NEFMC, 1993, 2003) and a move to sector-based management with Amendment 16 (NEFMC, 2009) may have resulted in such behaviour.	A 2007 survey of managers, enforcement officers, and participants in the groundfish fishery indicated that noncompliance is a serious issue and has been for decades (King and Sutinen, 2010). Large scale mislabeling of groundfish stocks on Georges Bank by the largest owner of quota in the region (Van Beveren *et al*., 2017).	Four time blocks representing the different periods between implementation of regulations specified in amendments to the Northeast Multispecies Fishery Management Plan (1990–1993; 1994–2003; 2004–2009; 2010-present).
Changes in survey catchability	Changes in catchability that are unaccounted for in the stock assessment could result in retrospective patterns.	A new survey vessel with new gear began in 2009. The new survey estimates are calibrated based on a study of paired trawls between the old and new vessel (Miller *et al.*, 2010).	Two time blocks (1990–2008; 2009-present) representing the transition between NOAA survey vessels Albatross and Bigelow.

tality for a number of groundfish stocks in neighbouring regions (e.g. O'Boyle and Sinclair, 2012). We did not include harbor seal abundance in our analysis due to the limited continuous time series of pup or adult abundance and the fact that the available evidence suggests that their population size has been relatively stable over the years of our analysis of retrospective patterns (Hayes *et al*., 2019; Johnston *et al*., 2015). In addition, we used annual estimates of coastwide spiny dogfish biomass from the most recent stock assessment (NEFSC, 2018) as a predictor. Spiny dogfish are generalist predators that have high spatio-temporal and dietary overlap with many groundfish species (Link *et al*., 2002; Link and Auster, 2013). They may be important competitors with certain groundfish stocks, as well as predators of juvenile groundfish (Morgan and Sulkowski, 2015).

There are technical interactions in the groundfish fishery and evidence of some issues with noncompliance where landings or discards may be unreported or misreported for a number of stocks (King and Sutinen, 2010; Van Beveren *et al*., 2017; Holland *et al*., 2019). However, we do not have an accurate understanding of the magnitude of underreporting and how it has changed over time. As a proxy for issues with catch reporting, we created management time blocks representing major management changes to the groundfish fishery management plan that could have resulted in changes in fishing behaviour and compliance. We created four management periods (pre-1995, 1995–2003, 2004–2009, and 2010 to present) that are separated by significant changes or amendments to the Northeast Multispecies (Groundfish) Fishery Management Plan (i.e. Amendments 5, 13, and 16; NEFMC, 1993, 2003, 2009). In 1995, amendments to the management plan were focused on reducing fishing pressure across stocks, and in 2004, further changes were made to reduce fishing pressure on groundfish stocks. In 2010, there was a shift to a quota-based fishery management system, which placed a cap on the total allowable catch and allocated quota to harvesting cooperatives (i.e. sector-based management).

The final driver we explored was changes in the catchability of the coastwide Northeast Fisheries Science Center bottom trawl survey, which is the basis for indices of abun-

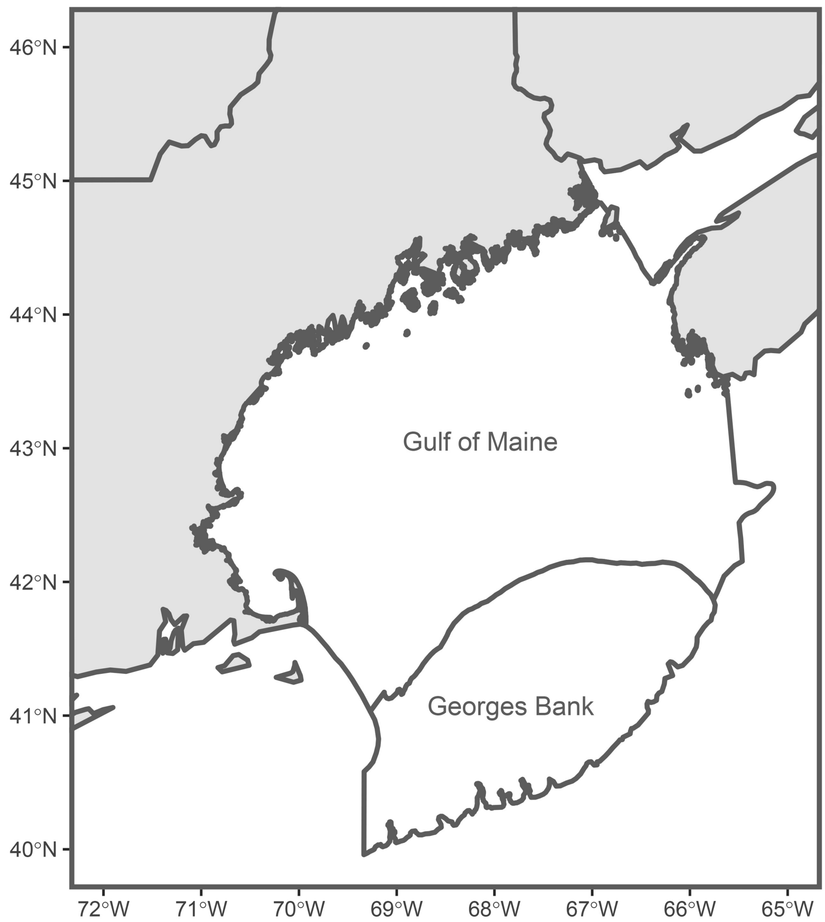

Figure 1. Map of waters off New England utilized by the groundfish stocks examined in this study. The outlined areas represent the scale at which temperature data was summarized to represent trends within the Gulf of Maine and Georges Bank stock areas.

dance for groundfish stocks, a key input to the stock assessment. In 2009, a change in survey vessels occurred (i.e. R/V Albatross to Bigelow). This change is currently accounted for in stock assessments using an adjustment factor from analysis of data collected in a paired trawl study (Miller *et al.*, 2010) or by having multiple selectivity blocks in the assessment model. Nevertheless, this change was significant and could be impacting retrospective patterns. To represent this change, we created a categorical variable composed of two survey blocks (1990–2008, 2009 to present) to include as a predictor variable.

We explored associations between the moving window Mohn's rho time series, and abiotic and biotic predictor variable values that coincided in time, as well as associations with lagged abiotic and biotic variables with lags ranging from 1 to 6 years. This time span was selected to encompass the lag time of groundfish reaching age at maturity with nearly 100% reaching maturity by 6 years across groundfish stocks and entering the groundfish fishery. Our focus on Mohn's rho values for SSB means we are indexing effects on mature biomass; thus we expect lagged variables to be important predictors.

Evaluating drivers of retrospective patterns

We used boosted regression trees to examine the associations between Mohn's rho time series for groundfish stocks and time series data for candidate drivers. We grouped stocks together based on geographic areas (i.e. Gulf of Maine and Georges Bank) as well as consideration of coherence in Mohn's rho time series. Mohn's rho values were z-score transformed for the purpose of the boosted regression tree analysis due to the varying scale of rho values across stock assessments and desire to combine these in the same analysis. This was helpful in enabling us to focus on the coherence of trends across stocks rather than the magnitude of individual stock impacts. This standardization would not be required in a single species analysis using this approach.

Boosted regression trees are an ensemble method for fitting statistical models that enables the identification of complex, nonlinear relationships and interactions between variables without formal distributional assumptions (Elith *et al.*, 2008). These machine learning models have the capacity to analyse large quantities of highly heterogeneous data to determine the effect of multiple predictors on a response variable and drive improvements in prediction. Boosted regression trees provide more efficient variable selection compared to generalized models developed with stepwise selection because boosted regression trees essentially ignore noninformative predictors when fitting (Elith *et al.*, 2008).

In developing models, we explored different combinations of tree complexity (i.e. level of interactions), bag fraction (i.e. the proportion of data used at each iteration), and learning rate (i.e. the contribution of each tree to growing the model). Final models had a tree complexity of 1, which specified no interactions between variables, bag fraction of 0.5, and a learning rate of 0.01. To evaluate models, we examined the mean

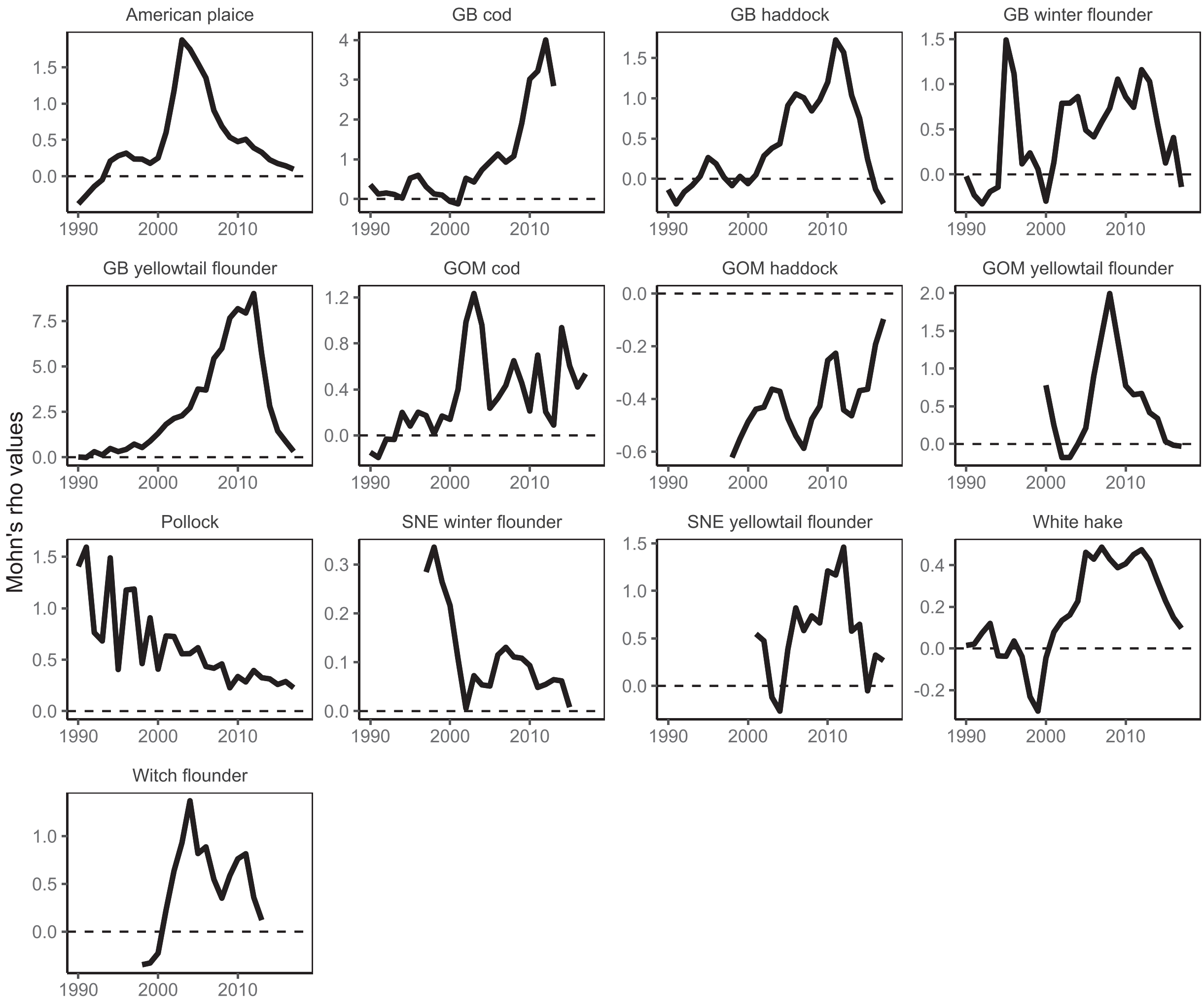

Figure 2. Annual Mohn's rho values for Northeast US groundfish stocks. Values were calculated using an extension of the moving window approach, as values depart from 0 (dashed horizontal line) in either direction the retrospective pattern is worsening, and when values approach 0 the pattern is improving.

total deviance, mean residual deviance, residual deviance, and % deviance explained using tenfold cross-validation. The influence of candidate drivers was quantified through measures of relative importance and the partial effects of influential drivers on Mohn's rho was visualized through partial dependence plots. Analyses were conducted in the R software platform version 4.1.0 using the *gbm* package (Greenwell, 2020). Reviewing the model estimates for each of the functional relationships between the explanatory variables and Mohn's rho allowed us to determine if any particular drivers are highly associated with the Mohn's rho time series and whether specific hypotheses might be ruled out based on lack of association.

Results

Coherence of groundfish retrospective patterns

Overall, we found all groundfish stocks examined exhibited retrospective patterns with varying Mohn's rho values over time (Figure 2). A total of 12 of the 13 stocks exhibited predominantly positive Mohn's rho values indicating a systematic trend whereby biomass is being overestimated in the reduced time series when compared with the estimate from the full time series. Gulf of Maine haddock was the only stock exhibiting consistently negative Mohn's rho values, indicating biomass is being underestimated in the reduced time series when compared with the estimate from the full time series (Figure 2). The magnitude of Mohn's rho indicates the severity of the retrospective pattern and eight stocks had maximum rho values between 0.9 and 2, representing inflation of estimated SSB values on the order of 90–200%. Two stocks, Georges Bank yellowtail and Georges Bank cod had considerably higher rho values, with maximum values of 9 and 4, respectively (Figure 2). Only three stocks exhibited maximum rho values $< \pm 0.6$ (i.e. Southern New England/Mid-Atlantic winter flounder, white hake, and Gulf of Maine haddock). For groundfish stocks with positive Mohn's rho values, values typically increased over time, indicating increasing severity, peaked, and then declined in magnitude. Pollock was an exception which exhibited decreasing values over the period of the Mohn's rho time series. In the case of Gulf of Maine haddock, which exhibited negative Mohn's rho values, values became more positive over the time series, indicating the retrospective pattern was becoming less severe.

We found high coherence in the temporal patterns of Mohn's rho SSB values for groundfish within the Gulf of Maine and Georges Bank stock areas based on pairwise

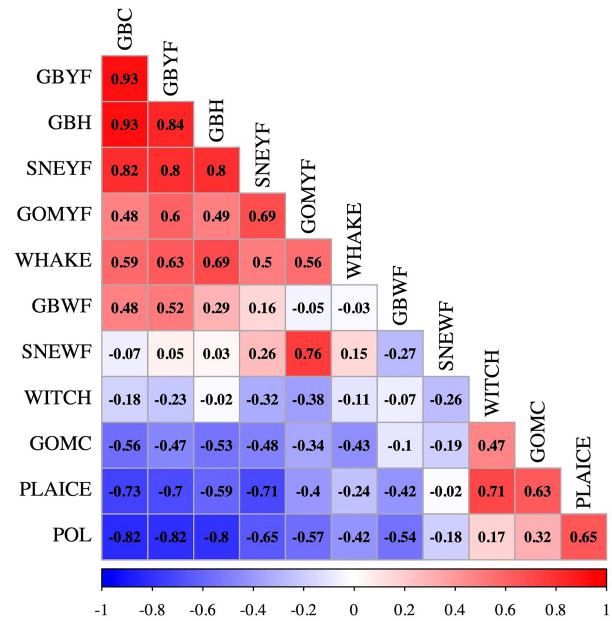

Figure 3. Spearman's rank correlation values of annual Mohn's rho estimates between groundfish stocks. Gulf of Maine haddock was not included in the correlation calculation (see text). Stock abbreviations are listed in Table 1.

comparisons of stocks using Spearman's rank correlation (Figure 3). Georges Bank stocks exhibited high positive correlations in annual Mohn's rho values with the highest positive correlations observed between Georges Bank cod, haddock, and yellowtail (correlation coefficients ($r \geq 0.84$; Figure 3). Mohn's rho values for Southern New England/Mid-Atlantic yellowtail flounder were also strongly correlated with these three Georges Bank stocks ($r \geq 0.8$) and all three of the yellowtail stocks were positively correlated ($r \geq 0.6$; Figure 3). We also found positive correlations in rho values between Gulf of Maine cod, witch flounder, and American plaice ($r \geq 0.47$). Gulf of Maine haddock was excluded from this analysis due to its fundamentally different retrospective pattern, having only negative rho values that decreased in magnitude over the time series.

Based on these correlation values and geographic location, (i.e. Gulf of Maine and Georges Bank) we explored potential drivers through boosted regression tree analysis. The Georges Bank stock area grouping included the Mohn's rho time series for Georges Bank cod, haddock, yellowtail flounder, and winter flounder, as well as Southern New England/Mid-Atlantic yellowtail flounder. Although Southern New England/Mid-Atlantic yellowtail flounder is not technically within the Georges Bank region, the high correlation with these stocks and geographic proximity to the area led us to include it within this group. The Gulf of Maine stock area group included Gulf of Maine cod, American plaice, and witch flounder. Although witch flounder and plaice are found throughout the region (i.e. unit stocks), the majority of their biomass is found within the Gulf of Maine.

Interestingly, the timing of increase in Mohn's rho time series differed in the Gulf of Maine and Georges Bank stock areas (Figure 4). Georges Bank stocks exhibited large increases in rho values in the early 2000s, with peak values around 2012, followed by a general decline, whereas Gulf of Maine stocks exhibited moderate increases in rho values over the 1990s with peak values in the early to mid-2000s (Figure 4).

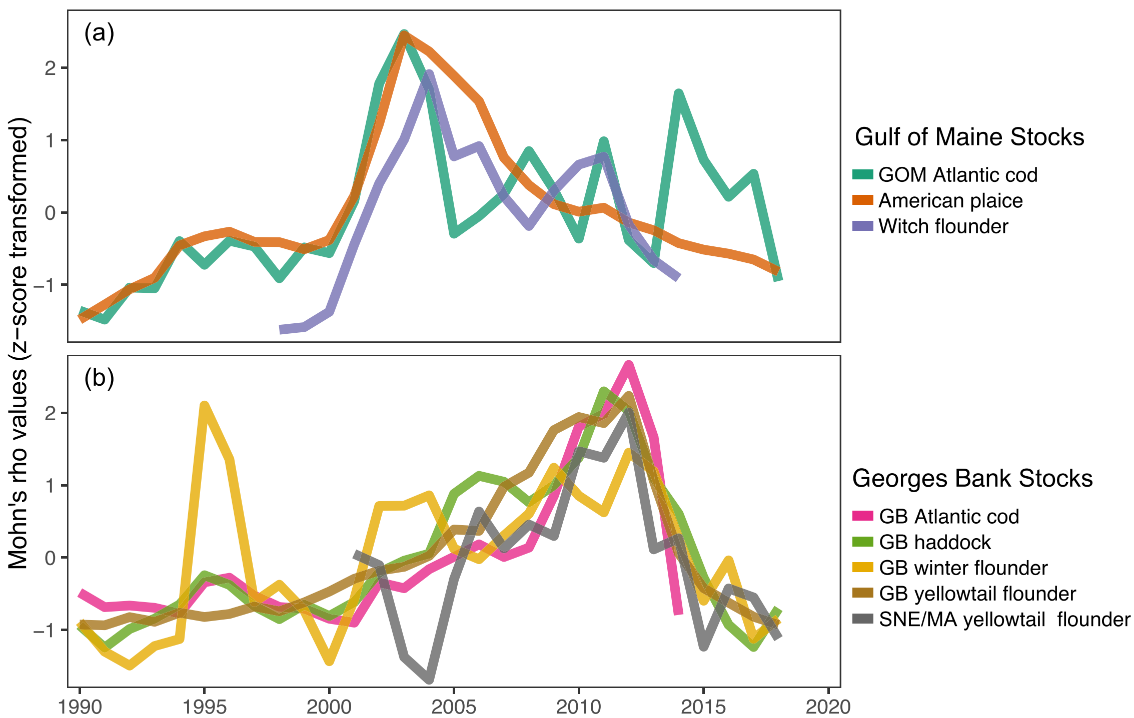

Figure 4. Annual Mohn's rho values (z-score transformed) across groundfish stocks grouped by geographic areas. The Gulf of Maine stock group (a) included Gulf of Maine cod, American plaice, and witch flounder and the Georges Bank cod stock group (b) included Georges Bank cod, Georges Bank haddock, Georges Bank winter flounder, Georges Bank yellowtail flounder, and, Southern New England/Mid-Atlantic yellowtail flounder.

Table 3. Performance of the Gulf of Maine and Georges Bank boosted regression tree models developed with tenfold cross-validation on retrospective patterns comprising 1000 and 700 trees, respectively (Gulf of Maine stocks: Gulf of Maine Atlantic cod, American plaice, and witch flounder; Georges Bank stocks: Georges Bank Atlantic cod, Georges Bank haddock, Georges Bank winter flounder, Georges Bank yellowtail flounder, and Southern New England/Mid-Atlantic yellowtail flounder).

	Gulf of Maine	Georges Bank
Mean total deviance	0.958	0.960
Mean residual deviance	0.378	0.225
Cross-validated residual deviance (SE)	0.527 (0.071)	0.325 (0.060)
Cross-validated percent deviance explained	44.9%	66.2%

Boosted regression tree models were fitted using tree complexity of 1, a bag fraction of 0.5, and a learning rate of 0.01.

Analysis of potential drivers of retrospective patterns

Boosted regression trees were applied to evaluate associations between groundfish Mohn's rho and environmental time series for Gulf of Maine and Georges Bank stocks. The percentage of cross-validated deviance explained was higher for the model of Georges Bank stocks at 66.2% compared to 44.9% deviance explained in the model of Gulf of Maine stocks (Table 3). Lagged variables were important within each of the models.

Fluctuations in Gulf of Maine groundfish Mohn's rho values were most strongly related to lagged time series of bottom temperature (i.e. lagged by 2 [6%], 3 [7%], and 4 [29%] years with a combined deviance explained of 42%) and spiny dogfish SSB (i.e. lagged by 2 [7%], 3 [20%], and 5 [10%] years with a combined deviance explained of 36%). In order of relative influence, the top two individual predictors were bottom temperature lagged by 4 years and dogfish SSB lagged by 3 years (Figure 5). Larger Mohn's rho values occurred at higher bottom temperatures (i.e. > ~7.5°C) and lower levels of spiny dogfish spawning biomass (i.e. < 300–400 million lbs.; Figure 6).

Fluctuations in Georges Bank groundfish Mohn's rho values were most strongly related to the time series of annual number of warm core rings (i.e. lagged by 4 [7%], 5 [25%], and 6 [15%] years with a combined deviance explained of ~48%), bottom temperature (i.e. lagged by 5 [11%] and 6 [9%] years with a combined deviance of ~20%), and spiny dogfish spawning biomass (lagged by 6 years with 10% deviance explained). In order of relative influence, the top two individual predictors were warm core rings lagged by 5 and 6 years (Figure 5). Larger Mohn's rho values were associated with increased warm core ring production (i.e. annual values >30), bottom temperature values between 8 and 9°C, but not the highest bottom temperature values (>9°C), and lower spiny dogfish spawning biomass levels (i.e. <350 million lbs.; Figure 7).

Both the Gulf of Maine and Georges Bank groundfish models included bottom temperature as an influential variable and exhibited high Mohn's rho values across a similar range of values, however, Georges Bank experienced an overall higher range of temperatures and thus exhibited different shaped responses in partial dependence plots (Figures 6 and 7). We also found differences in the magnitude of influence (42% of deviance explained in Gulf of Maine and 20% in Georges Bank) and time lags that were influential for this variable in each of the regional models. In the Gulf of Maine groundfish model, 2-, 3-, and 4-year lagged bottom temperature variables were influential, whereas 5- and 6-year lagged bottom temperatures were more important in the Georges Bank model (Figure 5). Both regional models included spiny dogfish SSB with similar responses in Mohn's rho, although there were regional differences in the relative importance (36% of deviance explained in Gulf of Maine and 10% in Georges Bank) and timing of lags in this variable. Another key difference between regional stock models was the influence of warm core ring production in the Georges Bank model, which were not found to be influential in the Gulf of Maine model. Candidate drivers not found to be influential in either model included the management blocks and survey categorical variables, as well as the GSI and the seal pup abundance time series.

Discussion

In this study, we characterized longitudinal trends in retrospective patterns of New England groundfish stock assessments and identified high levels of coherence in the retrospective patterns of several groundfish stocks within the Gulf of Maine and Georges Bank regions. Groundfish stock assessments generally exhibited positive Mohn's rho values that varied in severity over recent decades and reached peak magnitude at different times in the Gulf of Maine and Georges Bank. The identification of consistent retrospective patterns across groundfish stocks suggests common drivers, currently unaccounted for in stock assessments, may be impacting stocks within these geographic regions.

Overall, lagged trends in ocean thermal conditions (i.e. bottom temperature) and associated aspects of shelf warming (i.e. warm core ring formation) explained the most variance in groundfish Mohn's rho values across regions. Bottom temperature warming was identified as a driver of stock assessment inconsistency in the Gulf of Maine, whereas warm core ring formation was identified as a key driver in Georges Bank stocks. Warm core rings shed by the Gulf Stream have been linked to warming in the region with a recognized shift in warm core ring formation in the early 2000s in the Georges Bank region (Gawarkawicz *et al.*, 2012; Gangopadhyay *et al.*, 2019). Given the limited penetration of warm core rings in the western Gulf of Maine, it is not surprising that this factor was identified as influential for Georges Bank and not Gulf of Maine stocks. In the Gulf of Maine, increases in Mohn's rho time series were more influenced by increases in bottom temperature (Kavanaugh *et al.*, 2017), which has been identified as a driver of changes of productivity and distribution of groundfish stocks in the region, such as Atlantic cod (Pershing *et al.*, 2015; Kleisner *et al.*, 2017). While temperature-related indicators are identified as important, it is relevant to note that they may be indexing an intermediate effect of ecosystem change on groundfish. For example, ocean warming has been associated with a decline in *Calanus finmarchichus*, a subartic zooplankton and cornerstone of regional ecosystem productivity (Pershing *et al.,* 2021). *Calanus* is an important food

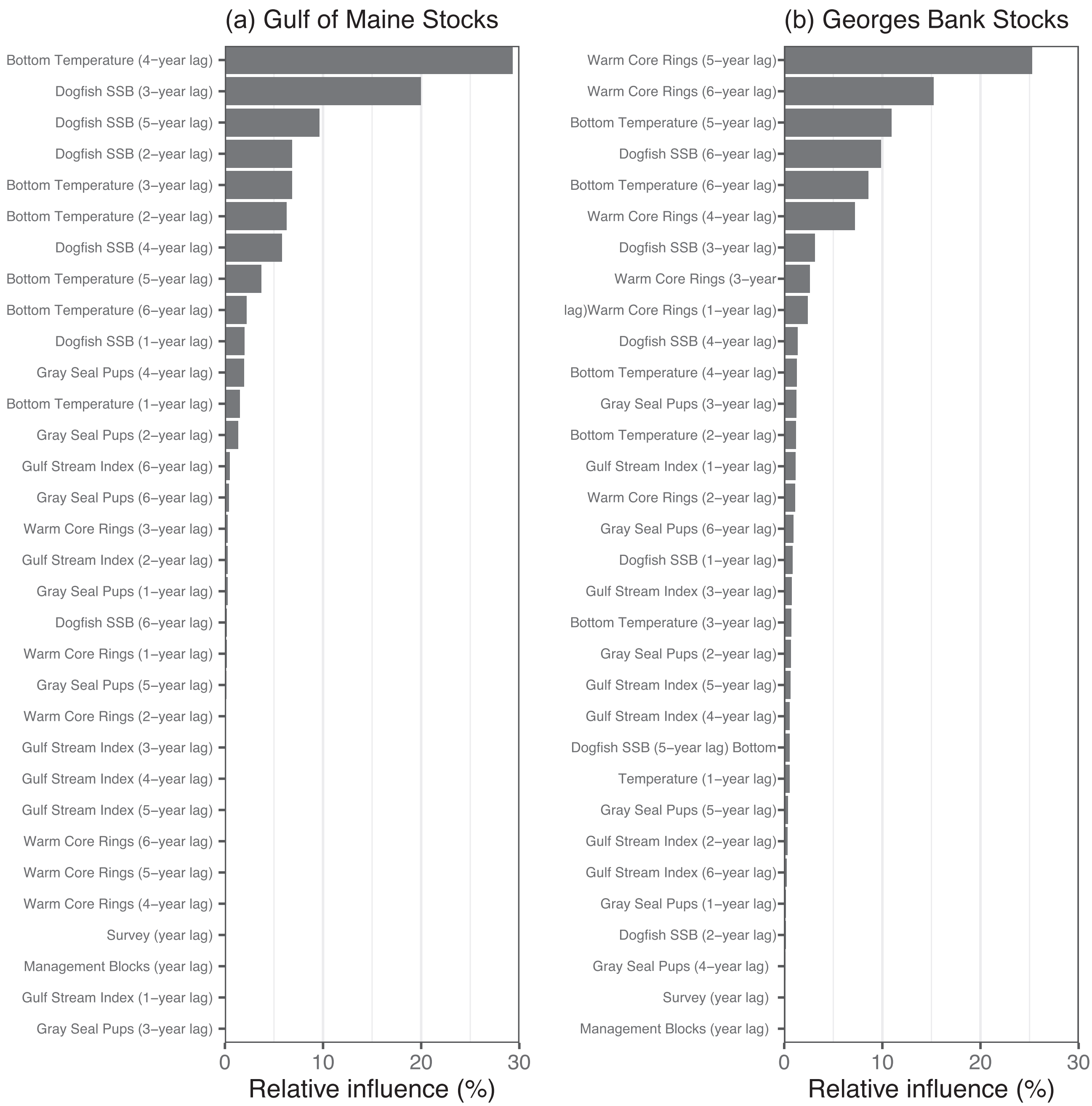

Figure 5. Relative influence of predictor variables for (a) Gulf of Maine and (b) Georges Bank stocks boosted regression tree models. Relative influence was calculated by averaging number of times a predictor was selected for splitting and the squared improvement resulting from splits.

source for forage fish (e.g. herring and sand lance) that are key prey items for groundfish (Suca *et al.*, 2021). Thus, ocean warming may have cascading effects through the food web influencing adult groundfish survival (Pershing *et al.*, 2021, Suca *et al.*, 2021).

For both stock areas, we found that spiny dogfish biomass was an important predictor, with higher Mohn's rho values associated with periods of low dogfish biomass. This finding was counter to our expectation that high rho values would be associated with high dogfish biomass due to increased unaccounted for mortality of groundfish from predation by or competition with dogfish. However, the support for spiny dogfish as a key predator is mixed across groundfish species. For example, a recent molecular analysis of spiny dogfish diet revealed relatively low representation of cod and high representation of haddock in dogfish stomachs which may reflect their relative abundance (Pitchford *et al.*, 2020). This unexpected association between Mohn's rho values and dogfish biomass could reflect a more complex interaction or proximate cause resulting in higher mortality of the groundfish stocks included in our analysis during periods of low dogfish abundance. For example, an increase in the predators of spiny dogfish during periods of low biomass could have resulted in increased predation pressure on groundfish stocks. Further research is needed to understand this unanticipated result.

We also found that our indicator of adult seal biomass (i.e. gray seal pup abundance) exhibited little predictive power in explaining trends in groundfish Mohn's rho values. The con-

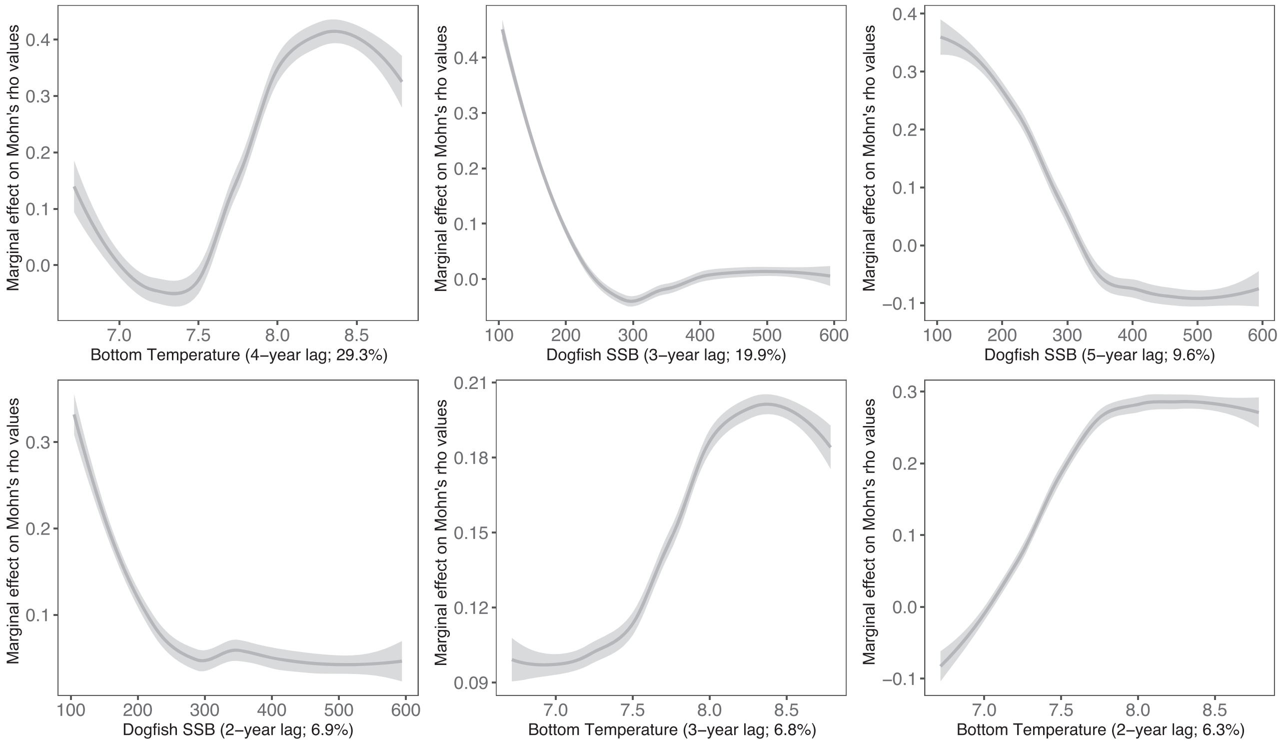

Figure 6. Smoothed partial dependence plots for the six most influential variables in the model for Gulf of Maine stocks retrospective patterns (units: Mohn's rho in z-score transformed values, bottom temperature in degrees C, dogfish SSB in million pounds).

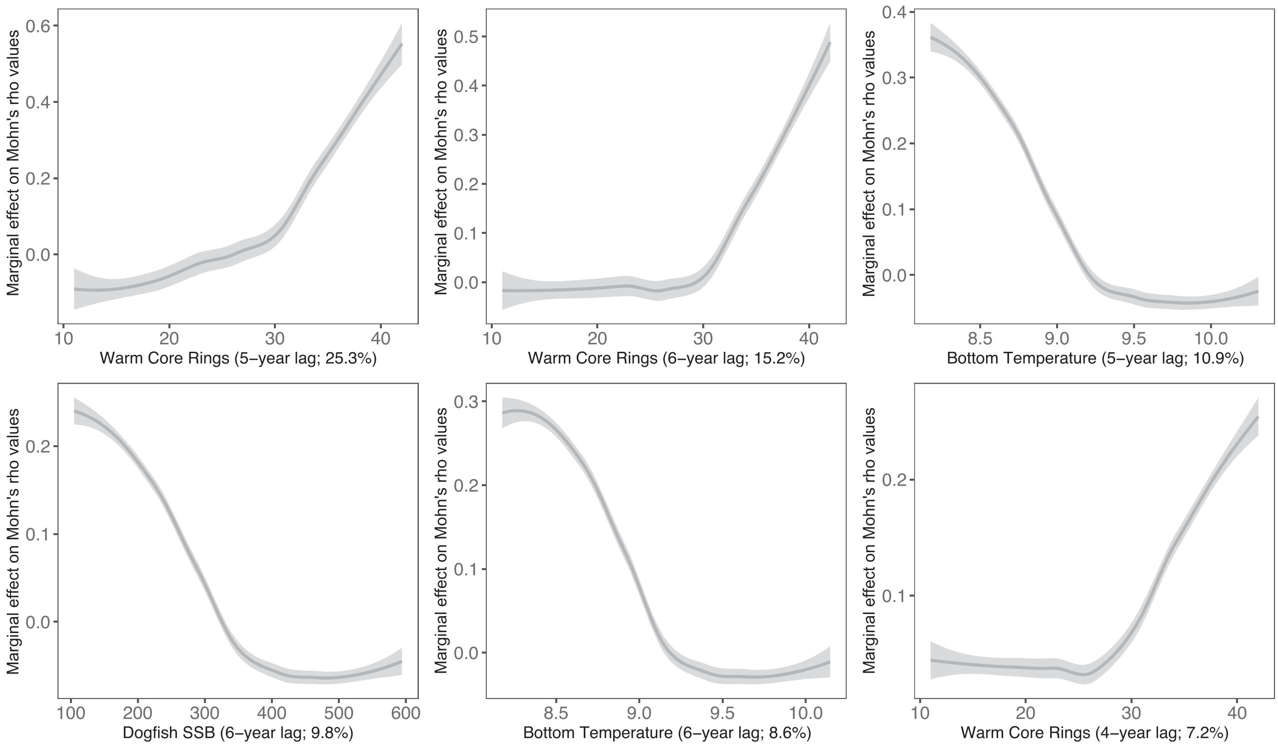

Figure 7. Smoothed partial dependence plots for the six most influential variables in the model for Georges Bank retrospective patterns (units: warm core rings in number of formations/year, bottom temperature in degrees C, dogfish SSB in million pounds).

siderable increase in grey seal populations has been suggested as having a potentially large impact on natural mortality of commercially important groundfish species, such as cod and haddock (Gruber, 2014). However, characterizing grey seal diet is challenging due to diet differences based on ontogeny, sex, location, and season as well as diet data collection limitations (e.g. samples are generally restricted to bycatch, young-of-year and pups, and scat; Beck *et al.*, 2007; Ono *et al.*, 2019). Recent modelling and dietary studies have suggested an increasing importance of dogfish in the diets of seals in the region (Morgan and Sulikowski, 2015; Byron and Morgan, 2016). Ono *et al.* (2019) noted that complex ecological interactions may occur between spiny dogfish, seals, and groundfish with seal predation on dogfish potentially freeing groundfish species from additional predation pressure, which could explain the absence of an influence of seals on Mohn's rho values. However, it is possible that seal predation is an important contributor to groundfish retrospective patterns, but the impact is dependent on the relative abundance between seals and groundfish stocks. Further exploration into the interactions between these predator and prey species (i.e. seals, groundfish, and spiny dogfish) is warranted to fully understand their impact on groundfish natural mortality.

Our analysis showed that neither the fishery management nor the survey time blocks had predictive power in explaining retrospective patterns of groundfish indicating that these large-scale changes in management and monitoring are not primary drivers of stock assessment inconsistency. For survey catchability, the periods included represent changes in the survey vessel and gear, which are known to have impacted the efficiency with which fish are caught in the survey area (Miller *et al.*, 2010). Currently, species-specific correction factors are applied to the newer survey vessel estimates based on the analysis of Miller *et al.* (2010), and thus these changes may be adequately accounted for through this adjustment. Beyond the shift in survey vessel, changes in the availability of fish within the survey area could impact the overall catchability of the survey. Range shifts (i.e. movement poleward and/or deeper) in response to climate change are well documented across fish species in the region, including groundfish (e.g. Nye *et al.*, 2009, 2011; Pinsky *et al.*, 2013). In addition, climate-associated changes in the timing of seasonal migrations relative to the timing of the survey could impact the availability of fish to spring or fall surveys (Langan *et al.*, 2021). Thus, climate change impacts on fish distribution could be impacting survey catchability and contributing to the model variance explained by ocean thermal conditions. We hypothesized that large-scale management changes aimed at reducing mortality on groundfish combined with a lack of rebuilding of several species in this mixed stock fishery changed fishing behaviour and incentivized noncompliance (i.e. underreported catch). For underreported catches, it is likely that incentives for noncompliance change annually across stocks and sectors within the groundfish fishery as catch limits may become more or less restrictive for target or bycatch species (i.e. "choke" species issues). The approach used to account for large-scale changes in fishery management and the survey (i.e. time blocks included as categorical variables in the model) is relatively simple and we do not discount that if finer-scale response variables that better capture these dynamics become available this could provide a revised view of predictive power and the impact of these changes on retrospective patterns.

The importance of lagged, rather than concurrent time series when examining associations between potential drivers and Mohn's rho values is not unexpected. Simulation studies have demonstrated that there can be initial lags in the impact of stock assessment misspecifications (Kerr *et al.*, 2020). In the case of catch misreporting, these lags were related to age structure and the time it took for all extant year-classes to transition from partially biased to entirely biased catch histories (Kerr *et al.*, 2020). The introduction of biased information caused an initial discontinuity in the progression of age classes with retrospective patterns progressively worsening with the addition of years of biased data. Furthermore, the impacts of ecosystem change on juvenile survival would not be immediately apparent in retrospective patterns focused on SSB but lagged by a few years. Finally, identifying when an intervention occurred that led to the retrospective pattern in the assessment is a challenge and noise in the dataset can make detection increasingly difficult (Legault, 2009). Several of the groundfish stocks analysed for retrospective patterns in the Gulf of Maine and Georges Bank exhibited a decrease in Mohn's rho after reaching peak values. This decline may indicate that the retrospective patterns diminished due to resolution of stock assessment misspecification, which is seen when a retrospective pattern is driven by a pulse event, whereby conditions change for a short period of time (e.g. 1–3 years) and then re-align with stock assessment assumptions compared to shift where a change happens and remains in the new state into the future (Legault, 2009). However, the decrease in Mohn's rho could also reflect a modelling artefact. Simulation studies have demonstrated this phenomenon whereby apparent improvements in model performance can occur as the period of misspecification increases despite core issues not having been resolved (Kerr *et al.*, 2020). Thus, in some instances consistent model misspecification may lead to consistent or improved retrospective patterns over time.

While both VPA and SCAA models are susceptible to retrospective patterns, Mohn's rho may be influenced by the additional model decisions possible within the context of a SCAA model. One of the Gulf of Maine stocks in this analysis used an SCAA model (i.e. Gulf of Maine cod) and three of the Georges Bank stocks used this model (i.e. Southern New England yellowtail, Georges Bank cod, and Georges Bank yellowtail flounder). Groundfish SCAA models typically implement selectivity blocks as a way of introducing time-varying selectivity. The groundfish stocks that apply SCAA models in this study included between two and three selectivity blocks over the time period of the retrospective peels. The choice of selectivity blocks is typically informed based on known periods of major change in the fishery (e.g. change in mesh size or minimum retention size) and changes in the regulatory reporting system. However, the time periods of these blocks do not coincide across all stocks in this study. Thus, the peeling of SCAA models including mixtures of selectivity patterns could cause model instability, but we do not see abrupt shifts in Mohn's rho values coinciding with selectivity blocks and we do see consistent patterns across VPA and SCAA models despite this difference.

Strong coherence in Mohn's rho time series was seen across several groundfish stocks by area; however, pollock and Gulf of Maine haddock exhibited fundamentally different patterns. The pollock time series exhibited a variable and declining trend since 1990, whereas the Gulf of Maine haddock time series was negative and became increasingly positive over the time series. The status of both of these stocks is not overfished with no overfishing occurring and biomass has exceeded the overfished threshold ($1/2SSB_{MSY}$) for these stocks since the 1990s and exceeded SSB_{MSY} in the most recent years (NOAA, 2019). One of the most important sources of uncertainty noted for the pollock stock assessment is the selectivity assumption; there are two models with alternative selectivity assumptions (i.e. flat-topped and dome-shaped survey selectivity, which suggests the existence of a large cryptic biomass; NOAA, 2019). Misspecified selectivity (i.e. domed was assumed in this model exercise) in the model could result in retrospective patterns. Gulf of Maine haddock was the only stock exhibiting consistently negative Mohn's rho values, suggesting that biomass is being underestimated when compared with the estimate from the full time series. SSB in 2018 was estimated to be 82763 mt, which is 1035% of the biomass target. The rapid increase in biomass of haddock in the most recent decade suggests a fundamentally different response to changing climate and ecosystem compared to most groundfish species. While retrospective issues exist for these stocks, the sources may be fundamentally different from the groundfish that exhibited coherency in pattern.

The high positive Mohn's rho values seen across many northeast US groundfish stocks indicate that with each successive year the overall stock SSB appeared to be lower than previously estimated, resulting in allowable catch levels that were based on overestimated SSB. If the recommended allowable catch of these stocks was fully harvested, the realized fishing mortality could have resulted in overfishing, and in some extreme cases, the allowable catch was comparable to the updated estimates of exploitable biomass for a stock (Wiedenmann and Jensen, 2018). In many cases, retrospective adjustments were made to estimated parameters before conducting projections or applying a harvest control rule to provide management advice with the aim of avoiding this outcome (Legault, 2009; Deroba, 2014). For these groundfish stocks, assessments are typically rho-adjusted (i.e. dividing the terminal year estimate of abundance by 1 + Mohn's rho) when the adjusted value is outside the 90% *CI* of the terminal year estimate of spawning stock biomass. However, it is important to note that these adjustments do not necessarily result in more accurate assessment estimates (Deroba, 2014; Hurtado-Ferro *et al*., 2015).

The identification of coherence in retrospective patterns across multiple groundfish stocks in the Gulf of Maine and Georges Bank regions suggests systematic issues across stocks that are likely driven by common factors. This is the first attempt we are aware of to look at the coherence of retrospective patterns across stocks in a region and to explore the potential sources of retrospective patterns across groundfish stocks in a holistic manner. While this study provides insight regarding potential mechanism driving these patterns, it is important to note that the deviance explained in models suggests that there are likely unaccounted for drivers of these patterns. Other sources of mortality not accounted for could include unreported catch (e.g. bycatch in the lobster fishery; Boenish and Chen, 2020) and the influence of other predators or change in the availability of prey. Identification of coherent patterns in retrospective trends and identification of potential common drivers can help inform the appropriate approaches for treatment of these issues in the context of stock assessment (e.g. specifying time-varying catchability or natural mortality in the assessment model or inclusion of an environmental covariate; Miller and Legault, 2017) or through management measures (e.g. enhanced monitoring of catch).

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript. Supplementary material contains details of the moving window approach to calculate the Mohn's rho retrospective time series, as described in the text.

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