Received: 4 March 2021 | Revised: 5 June 2021 | Accepted: 15 June 2021

DOI: 10.1111/faf.12591

ORIGINAL ARTICLE

FISH and FISHERIES WILEY

Moving reference point goalposts and implications for fisheries sustainability

Paula Silvar-Viladomiu[1] | **Cóilín Minto**[1] | **Ghassen Halouani**[1,2] | **Luke Batts**[1] | **Deirdre Brophy**[1] | **Colm Lordan**[3] | **David G. Reid**[3]

[1]Marine and Freshwater Research Centre, Galway-Mayo Institute of Technology, Galway, Ireland

[2]IFREMER, Unité halieutique Manche Mer du Nord Ifremer, HMMN, Boulogne sur mer, France

[3]Marine Institute, Oranmore, Galway, Ireland

Correspondence
Paula Silvar-Viladomiu, Galway-Mayo Institute of Technology GMIT, Dublin road, Galway, Ireland.
Email: paula.silvarviladomiu@research.gmit.ie

Funding information
Department of Agriculture, Food and the Marine, Ireland, Grant/Award Number: Ref 15/S/744

Abstract

For many environmental indicators, the sustainable status can change because of changes in either the monitored state or the policy goal. Fisheries provide an intensively monitored setting to investigate the relative impacts of such change. Key fisheries sustainability indicators comprise the ratio between fishing pressure or biomass and their respective reference levels. We developed a retrospective database of population status, reference point changes and reported reasons for changes for all data-rich stocks in the ICES region. We derived methods to distinguish the impacts of either source of change (monitored state or policy goal) on sustainable status. We found that reference points changed frequently (64% of populations had reference point changes) with varying magnitudes. Contrary to expectation, reference point changes were often not compensated by changes in the state thus significantly impacting inferred sustainability status and dependent scientific advice. Across a range of life histories and assessments, changes in reference points dominate retrospective revisions in status over the full time series. Overall, status before and after the change of reference point had no significant directional differences that would suggest reference point change effecting movement towards or away from sustainability. Although multiple factors have contributed to reference point changes, our results show that the reference point definition and the technical basis for estimation were the most important reasons for change. Recognizing that reference points are not constant in time but rather form reference series is paramount to quantifying present and historical sustainability. Properly documenting, justifying and quantifying the impacts of such change is an ongoing challenge.

KEYWORDS

Fisheries management, North Atlantic Ocean, population monitoring and assessment, sustainable targets and limits, UN sustainable development

1 | INTRODUCTION

Within the United Nations 2030 Agenda, goal 14 for sustainable development relates to life below water and targets improved understanding of the status of commercial fish stocks (FAO, 2020). Historically, overfishing has been widespread concern and the most decisive factor driving the collapse of marine ecosystems and losses of ecosystem biodiversity (Jackson, 2001; Worm et al., 2006). The ability of fishery management systems to maintain fishing pressure at levels that can sustain productive fisheries depends on the availability of stock information and the capacity to adjust harvest in response to changes in stock abundance. Recent analyses demonstrate that on average assessed fisheries are improving with respect to management goals in regions where there are research, assessment, and management plans (Fernandes & Cook, 2013; Hilborn et al., 2020; Ricard et al., 2012; Worm et al., 2009).

Fisheries science has made substantial progress in developing tools to assist in achieving policy goals. Management goals, commonly referred to as goalposts by fisheries managers, are expressed as reference points for a sustainable harvest. Quantitative measures of stock status relative to reference points are used to provide advice on sustainable catches, often in conjunction with harvest control rules (Kvamsdal et al., 2016). The status of a stock can be estimated in terms of both the fishing pressure level (typically fishing mortality rate, *F*) and abundance state level (typically biomass or spawning stock biomass, *SSB*) relative to their reference point, often at Maximum Sustainable Yield (MSY). The ratio of *F* to F_{MSY} (termed relative fishing mortality) indicates how far a stock is being fished from an optimally sustainable rate. Similarly, the ratio of *SSB* to the biomass reference point (termed relative biomass) shows if a stock is at a size that will provide MSY in the long term.

The concept of MSY is a common management goal underpinning reference points (Mace, 2001). MSY can be defined as "the highest theoretical equilibrium yield that can be continuously taken on average from a stock under existing average environmental conditions without significantly affecting the reproduction process" (EC, 2013). The precautionary approach (PA) plays an important role in fisheries management and is necessary, but a not exclusive condition for MSY. The International Council of the Exploration of the Sea (ICES) provides advice in accordance with MSY when data are available, that is consistent with the PA (ICES, 2019a); populations need to be maintained within safe biological limits to make MSY possible. ICES advice is based on the fishing mortality reference point F_{MSY}, and the biomass trigger point $MSYB_{trigger}$ (see Table 1 with definitions of those and related reference points). For data-rich stocks, advice on sustainable catch focuses on attaining a fishing mortality rate of no more than F_{MSY} (fishing mortality status lower than 1) while maintaining the stock above full reproductive capacity. When *SSB* declines below $MSYB_{trigger}$ (biomass status lower than 1), management must take action to reduce fishing mortality (ICES, 2019a).

The production of scientific fisheries management advice involves feedback loops of data and analysis, review, and decision-making (Privitera-Johnson & Punt, 2020). The assessment type performed for each stock and the type of advice given depends mainly on available knowledge. In ICES, stocks are classified into six main data categories; for categories 1 to 4, there are guidelines to estimate reference points (ICES, 2017a, 2018). ICES provides advice according to their MSY approach for category 1 and 2 stocks and PA advice for category 3–6 stocks. Through the ICES framework, most stocks undergo benchmarks every 3–5 years, where the methods and data used in given assessments are externally reviewed to determine assessment quality. Reference points used in ICES stock assessments are thought to be valid only in the short and medium term due to changes in marine ecosystems (ICES, 2021). As part of the benchmark process, reference points are reviewed to ensure that they reflect the current understanding of stock dynamics and are updated if necessary (ICES, 2019a). Since reference points are estimated from assessment outcomes, they are impacted by revisions (to the underlying assumptions, data input and methods) made not only to the assessment but also to the process specific to their derivation.

Previous studies have investigated how fishing mortality and/or biomass estimates vary among assessments over time using several approaches to measure variation (Evans, 1996; Ralston et al., 2011; Wiedenmann & Jensen, 2018). While investigating changes in the numerator of a sustainability indicator (e.g. F/F_{MSY}) is important, we highlight the importance of changes in both the numerator and denominator (i.e. the defined sustainable target or limit). To our knowledge, no study has analysed the sources and the relative impact of changes in reference points on the inferred stock status, which is of critical concern to management. Changes to reference points may be seen as "moving the goalposts" in one direction or another. To

TABLE 1 The main reference points used in the ICES advice rule

Reference point	Definition
$MSYB_{trigger}$	Maximum sustainable yield biomass trigger is defined as the 5th percentile of the distribution of *SSB* when fishing at F_{MSY}, but for most stocks that lack data on fishing at F_{MSY}, $MSYB_{trigger}$ is set at B_{PA}
B_{PA}	Precautionary approach biomass reference point is a stock status reference point above which the stock is considered to have full reproductive capacity. Typically defined such that there is a 5% probability that the actual biomass is below B_{lim} taking account of assessment error.
B_{lim}	Biomass limit reference point is the key reference point, from which all other PA reference points are estimated. B_{lim} is the deterministic biomass limit below which a stock is considered to have reduced reproductive capacity
F_{MSY}	Fishing mortality that provides maximum yield given the current assessment/advice error and biology and fisheries parameters.

improve understanding of changes in fisheries status it is necessary to discern how components that comprise status (i.e. numerator and denominator) change. Using an extended ICES assessments database, we disentangle changes in key stock status indicators such as relative fishing mortality (F/F_{MSY}) and relative biomass ($SSB/MSYB_{trigger}$). In addition, we present an analysis of reasons for changes among assessments to identify important sources of variation and uncertainty in reference points. Our key research questions thus comprise (i) how have reference points changed in the region?; (ii) how do changes in reference points impact sustainable stock status?; and (iii) what drives changes in reference points?

2 | METHODS

2.1 | Time series and reference points datasets

International Council of the Exploration of the Sea (ICES) stock assessments provide detailed analyses of the dynamics and status of almost 200 stocks representing important commercial fisheries for the European Union and neighbouring countries. We obtained assessment output and reference points from ICES stock assessments accessed by XML query portal System (http://standardgraphs.ices.dk/StandardGraphsWebServices.asmx/) or from the relevant ICES reports (http://stockdatabase.ices.dk/Default.aspx).

A total of 124 Stocks were subsetted to those that have reference point estimates. These were mainly category 1 stocks although six of the selected stocks were re-categorized during the timeframe of the study (either downgraded or upgraded in data/advice categories). In 2017, ICES changed the codes that are used to identify each stock (stock label key). These changes were incorporated into our analysis. For the stock label keys in our list, we acquired and integrated time series data on fishing mortality rate (*F*), spawning stock biomass (*SSB*) and MSY reference points (F_{MSY} and $MSYB_{trigger}$). These data were downloaded on 17 April 2020. We excluded *Nephrops* stocks due to the comparatively short length of the time series and the predominant use of proxy yield-per-recruit reference points. Changes in reference points between sequential assessments were identified for analysis. Change in reference point (*RP*) was calculated as the proportional change relative to the preceding assessment $(RP^{y}-RP^{y-1})/RP^{y-1}$, where *y* is the assessment year. The cleaning of the database was supported by reference to the relevant published reports. We filtered changes due to rounding and to being relative reference points to the time series mean of fishing mortality or spawning stock biomass. Adjustments were made to stocks that had non-comparable reference point values (different measurement definitions used between assessments), see Table S1. Status analysis was not performed for reference points with substituted values because, for example, the fishing mortality definition relative *F* in these assessments could not be compared to absolute values in the other assessments.

2.2 | Status change decomposition

For a given assessment and year, status is calculated by dividing time series of estimated fishing mortality rate (*F*) or biomass state (*SSB*) by the relevant reference point. Sustainability status can change depending on changes to the numerator (*F* or *SSB*) or denominator (F_{MSY} or $MSYB_{trigger}$). We derived expectations for the effect of changes in both numerator and denominator on sustainability status. To analyse changes in status between assessments, we first introduced the notation *y* to denote the assessment year and *t* the actual year of the time series, for example $F_{t=2000}^{y=2020}$, denotes the fishing mortality in year 2000 as estimated in the assessment of 2020. For each stock, year, and pair of consecutive assessments, we defined the inter-assessment change in status D_t as the proportional difference in status for a given time series year *t*:

$$D_t = \frac{\frac{X_t^y}{X_{MSY}^y} - \frac{X_t^{y-1}}{X_{MSY}^{y-1}}}{\frac{X_t^{y-1}}{X_{MSY}^{y-1}}} \quad (1)$$

where *X* is either fishing mortality rate or spawning stock biomass and X_{MSY} is the relevant reference point. Pairs of consecutive assessments were categorized according to whether or not a change in a reference point occurred. We visualized time series of inter-assessment differences (Equation 1) to understand how much status changes between consecutive assessments with reference point changes.

We estimated mean status before and after the change in reference point and an unequal variances *t* test was used to compare the values and evaluated if there were significant directional changes. We also compared the magnitude of the variability of the changes in *F* and *SSB* for the complete data set (containing all pairs of sequential assessments) to the variability of the subsetted data set containing only pairs when a change in reference point occurred. For that purpose, we measured the median absolute deviation (MAD) of the difference in mean rate *F* and state *SSB*.

For the status decomposition analysis, we used the subsetted data when a change in the reference point occurred. Change in status among sequential assessments was quantified by the change in average status between consecutive assessments over either the entire overlapping time series or the last 5 years of overlap (to infer recent status changes). The difference in average status can be decomposed into mean effects of the influence of changes in rate or state between consecutive assessments (i.e. the numerator) and changes in the reference point (i.e. the denominator). This decomposition comprises two parameters: δ, which encapsulates the proportional change in the reference point $X^y_{MSY} = \delta X^{y-1}_{MSY}$; and γ, which encapsulates the proportional change in average rate (*F*) or state (*SSB*) over time ($\sum_{t=1}^{n} X_t^{\,y}/n = \gamma \sum_{t=1}^{n} X_t^{\,y-1}/n$). We derive the expected difference in status using γ and δ:

$$E\left(\frac{X^y}{X^y_{MSY}} - \frac{X^{y-1}}{X^{y-1}_{MSY}}\right) = \frac{\gamma E(X^{y-1})}{\delta X^{y-1}_{MSY}} - \frac{E(X^{y-1})}{X^{y-1}_{MSY}} \quad (2)$$

The mean proportional status change (*w*) is obtained by dividing the expected difference in status by the expected previous status:

$$w = \frac{E\left(\frac{X^y}{X^y_{MSY}} - \frac{X^{y-1}}{X^{y-1}_{MSY}}\right)}{E\left(\frac{X^{y-1}}{X^{y-1}_{MSY}}\right)} = \frac{\gamma}{\delta} - 1$$

The impact of either change cannot be isolated (as the derivatives with respect to each naturally depend on the other). Nevertheless, we can empirically evaluate given changes to determine how much the relative status changes with respect to changes in either component. The mean change in status with respect to the proportional change in the reference point (δ) and with respect to the proportional change in estimate time series (γ) can be estimated with the following differential equations:

$$\frac{dw}{d\gamma} = \frac{1}{\delta}; \frac{dw}{d\delta} = \frac{-\gamma}{\delta^2}$$

We used a Pearson correlation test to evaluate the relationship between the two estimated parameters of proportional change.

2.3 | Covariates of change dataset

We review relevant advice reports for assessment years *y* and *y-1* to collect information on modifications that may have impacted the value of the reference points. Information on specific important revisions in assessment or benchmark meetings was typically presented in the advisory reports. Information regarding the technical basis for a reference point is presented at the reference point summary table. However, detailed information on settings for the estimation of the reference point was extracted from extensive reading of the referenced document, for example assessment reports or reference point estimation working group WKMSYREF (ICES, 2013; 2017b) . These reports are available at the ICES library website (http://www.ices.dk/publications/library/Pages/default.aspx).

Every event of reference point change might have been associated with multiple modifications, typically within a benchmark assessment process. For example, the North Sea, eastern English Channel, Skagerrak cod (*Gadus morhua*, Gadidae) assessment was benchmarked in 2015, resulting in changes to the input data structure, maturity, natural mortality and model settings causing reference points to be re-estimated. Besides, the MSY fishing mortality reference point was updated from F_{max} to F_{MSY} from *Eqsim* (stochastic equilibrium reference point software) analysis, and the rationale for B_{lim} was changed from B_{loss} to the *SSB* associated with the last above-average recruitment.

For every event of change in a reference point, the relevant information was collated into a new database and summarized as reference point covariates. We defined covariates based on the most frequent changes and modifications made. We aim to summarize revision generalized across all stock assessments. Covariates comprise categorical variables of occurrence and factor variables of a varying number of levels (Table S2). "Assessment" covariates were used for the analysis of both fishing mortality and biomass reference points. These comprised modifications such as (1) modification of stock definition; (2) revisions of input data both fisheries-dependent; and (3) independent (e.g. inclusion or exclusion of fisheries-dependent and fisheries-independent data, e.g. discards, commercial index, survey index); (4) re-assessed maturity; (5) re-assessed natural mortality; and (6) a heterogeneous group encompassing other revisions and updates of assessment methodology, additionally (7) revision of the assessment type, which includes information of changes in the model selected to assess the stock, with categories representing levels by the combination of the previous and subsequent model.

For most ICES assessments, derivation of F_{MSY} is typically a separate process that uses assessment outputs for age-based models, and so we evaluated changes in F_{MSY} with "Assessment" covariates and covariates specific to its derivation ("RP" covariates). These comprise (8) modifications to the definition of F_{MSY}, (9) change in the functional form of the stock–recruitment relationship, (10) revisions to the time frame of recruitment data input and (11) the time window of productivity parameters (growth, maturity, natural mortality, selectivity). The two former were included because ICES guidelines (ICES, 2017a) recommend the use full time series of recruitment unless strong evidence exists of a regime shift; and the use of the last 10 years of biological parameters (weights, maturity, natural mortality) and fishery parameters (selectivity) unless there is evidence of persistent trends. Revision to the definition of F_{MSY} was categorized according to the information provided regarding the initial and subsequent choice of advised F_{MSY}, for example changes from the use of certain F_{MSY} proxies to the use of F_{MSY}.

Following the ICES MSY approach (Table 1, ICES, 2017a), for $MSYB_{trigger}$ we included in the covariates the re-evaluation of the technical basis of $MSYB_{trigger}$ and related reference points (B_{PA} and B_{lim}). This framework includes transition rules, for example when a stock is fished at or below F_{MSY} for 5 or more years then the basis is $MSYB_{trigger}$ changes from B_{PA} to the 5th percentile of B_{MSY}. For ICES stock assessments, the biomass reference point B_{lim} is the main precautionary reference point, and B_{PA} is usually derived from it accounting for assessment uncertainty. Thus, to analyse changes in $MSYB_{trigger}$ we included covariates that are involved in setting $MSYB_{trigger}$ as (12) the revaluation of the technical basis of $MSYB_{trigger}$ and its related reference points (13) B_{lim} and (14) B_{PA}.

2.4 | Reference point change analysis

We conducted an a posteriori regression analysis of sources of those historical changes collated from the published reports. The influence of covariates on reference points was analysed by a multiple linear regression taking the proportional change in the reference point (δ) as the response. All covariates relevant to the reference point were first included as main effects to explain proportional changes in reference points; all possible combinations of sub-models were then fit and ranked by the Akaike information criterion (AIC), we used the R function glmulti() for the model selection (Calcagno & Mazancourt, 2010). Finally, we conducted a two-sided *F*-test ANOVA to the best-supported multiple linear model and investigated the percentage of the variance explained by the selected covariates.

3 | RESULTS

3.1 | Reference point changes

We identified that 50 stocks (21 species) have had changes in MSY-based reference points between 2011 and 2019 (Figure 1). This represents 64% of the stocks with estimates of absolute reference points. There were a total of 79 events of change in F_{MSY} and 51 in $MSYB_{trigger,}$ of which 42 were simultaneous changes in both reference points. Of all stocks, North Sea, eastern English Channel and Skagerrak cod 2015 and West of Scotland cod 2019 had the highest increase in F_{MSY} (74%). Cantabrian Seas and Atlantic Iberian waters sardine (*Sardina pilchardus*, Clupeidae) 2019 had the greatest decrease (73%), which is considerably larger than the magnitude of any other decreases. The biomass reference point, $MSYB_{trigger}$, increased by 145% for North Sea, Skagerrak plaice (*Pleuronectes platessa*, Pleuronectidae) 2017, when $MSYB_{trigger}$ changed from B_{PA} to the 5th percentile of B_{MSY}. The largest decrease in $MSYB_{trigger}$ occurred in Rockall haddock (*Melanogrammus aeglefinus*, Gadidae) in 2019 (64%).

For some stocks, reference points continually declined or increased, for example Baltic Sea sprat (*Sprattus sprattus*, Clupeidae) F_{MSY} and seabass (*Dicentrarchus labrax*, Moronidae) $MSYB_{trigger}$, but importantly for many stocks with multiple reference point changes, these included a mixture of decreases and increases (Figure 1). This raises the question of whether those changes reflect short-term productivity fluctuations or difficulties estimating suitable reference points. We found that simultaneous changes in both reference points showed no relationship between increases or decreases in F_{MSY} and $MSYB_{trigger}$ (Figure S1).

3.2 | Sustainability status changes

Examining timelines of changes in status (F/F_{MSY} and $SSB/MSYB_{trigger}$) between assessments in which reference points changed (Figures S2 and S3), we observed a variety of temporal patterns in the nature and magnitude of the changes (Figures S4 and S5). In some cases, the changes of reference point caused almost indiscernible changes in status (e.g. relative fishing mortality of Western Baltic Sea sole (*Solea solea*, Soleidae) 2014 in Figure 2), while elsewhere important status changes occurred when reference points changed (e.g. relative fishing mortality Cantabrian Seas and Atlantic Iberian waters sardine 2019). Occasionally, the sign of the change in status cross-over, meaning that the status trajectories between the assessments intersect, for example Skagerrak and Kattegat, western Baltic Sea sole 2015 in Figure 2. Status often varied markedly in the most recent years due to variability in fishing mortality rate (*F*) or biomass state (*SSB*) estimates, which are typically more variable in terminal years owing to a lack of convergence of the estimates (e.g. as caused by cohorts just entering the fishery and assessment). For example, in Cantabrian Seas and Atlantic Iberian waters sardine, a change to the 2019 assessment caused a relative increase in the F/F_{MSY} estimates that decreased in magnitude from 2010 to 2019 while a change to the 2015 assessment for Rockhall haddock caused a positive trend in the relative decrease of $SSB/MSYB_{trigger}$ from 2012 to 2015 (Figure 2). Several cases showed significant fluctuations in the magnitude of the relative change in status; some with a clear pattern (e.g. Rockhall haddock 2019) and others with a steady directional trend (e.g. Celtic Sea, Irish Sea herring (*Clupea harengus*, Clupeidae) deviation in 2013, Figure 2). To reflect these differences, we analysed status changes using both the complete time series and only the last 5 years to capture trends in changes in recent years.

Overall, while there are many examples of large changes in status for individual stock, there is no clear movement away from or towards sustainability (Figure 3 top panel). For the most recent five years, the

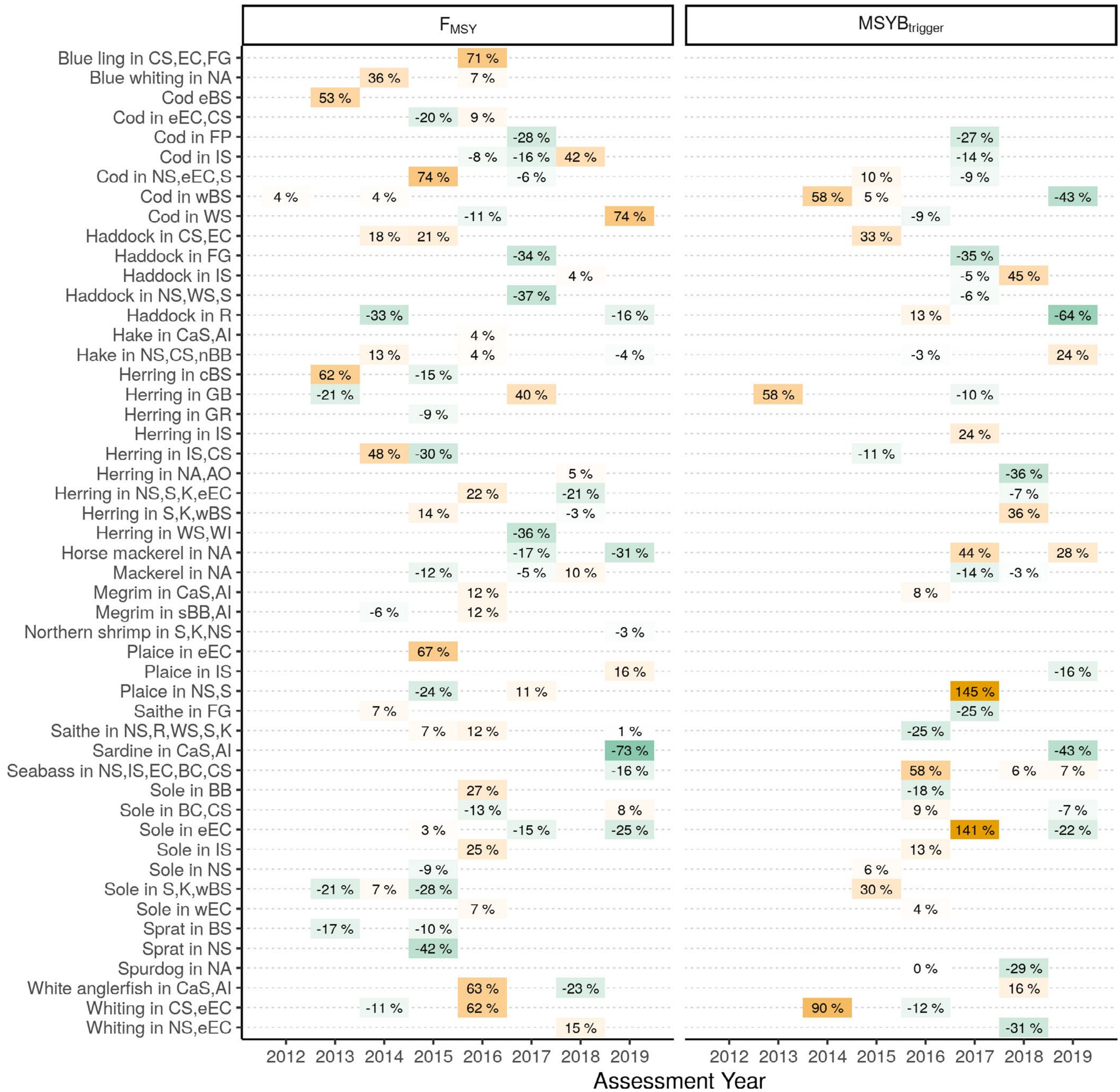

FIGURE 1 Changes in reference points for stocks assessments for the period 2011–2019, measured in percentage change relative to the preceding assessment. Stocks are ordered by species. Acronyms used in stock description are: BB, Bay of Biscay; BC, Bristol Channel; CS, Celtic Sea; BS, Baltic sea; CaS, Cantabrian Sea; AI, Atlantic Iberian waters; EC, English Channel; FG, Faroes grounds; GR, Gulf of Riga; GB Gulf of Bothnia; FP, Faroes Plateau; IS, Irish Sea; NA North Atlantic; AO, Arctic Ocean; NS North Sea; S, Skagerrak; K, Kattegat; R, Rockall; WS West of Scotland; c, central; n, northern; e, eastern; w, western

changes in relative fishing mortality and relative biomass state showed greater spread than when all years were included. Changes in status were not directional based on unequal variances *t* test of the status before and after the assessment update (change in average relative fishing mortality recent: $t_{(159,46)} = -0.04$, $p = .965$; complete time series: $t_{(164,81)} = -0.06$, $p = .95$; change in average relative biomass recent: $t_{(101,23)} = -0.19$, $p = .849$; complete time series: $t_{(99,41)} = 0.05$, $p = .957$). The changes in average F or SSB, when a change in reference point occurred, had similar or greater variability than when all pairs of sequential assessments are considered (change in average relative fishing mortality recent: $MAD_{change} = 1.49$, $MAD_{all\ pairs} = 0.03$; complete time series: $MAD_{change} = 1.48$, $MAD_{all\ pairs} = 0.009$; change in average relative biomass recent: $MAD_{change} = 4{,}807.33$, $MAD_{all\ pairs} = 5{,}187.62$; complete time series: $MAD_{change} = 2{,}494.93$, $MAD_{all\ pairs} = 1{,}490.71$). Therefore, the changes in sequential estimates of *F* and *SSB* were more marked when a change in reference point occurred.

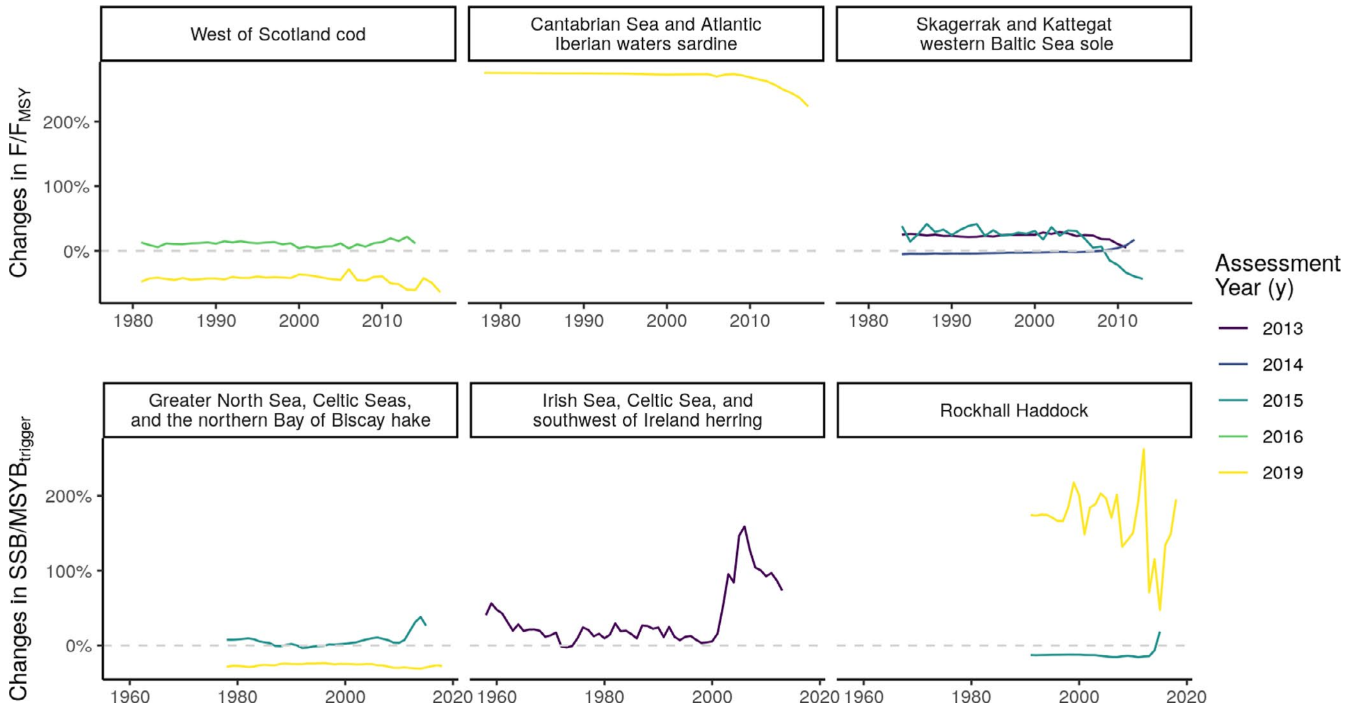

FIGURE 2 Example of changes in status timelines. Top-panel shows relative fishing mortality rate (F/F_{MSY}); and bottom panel shows relative biomass state ($SSB/MSYB_{trigger}$) proportional changes of assessment year (y) relative to the previous (y-1), for assessments in which changes in reference points were implemented

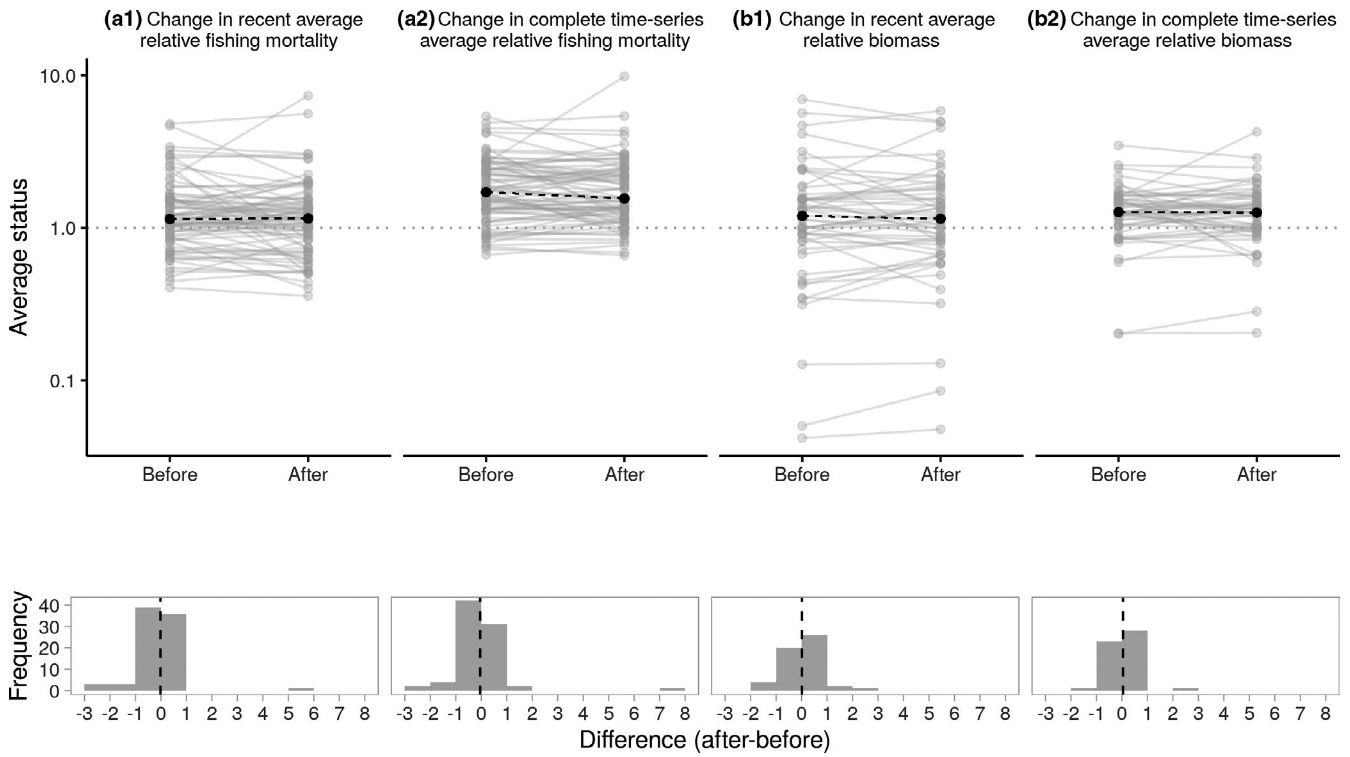

FIGURE 3 Mean status before and after at changes in reference points. Top-panel shows mean status on logarithmic scale in terms of relative fishing mortality (a) and relative biomass (b), over last five recent years (a1, b1) and complete time series (a2, b2). Bottom panel shows the distribution of the difference of status between before and after the reference point change. Black point and dashed line represents median values

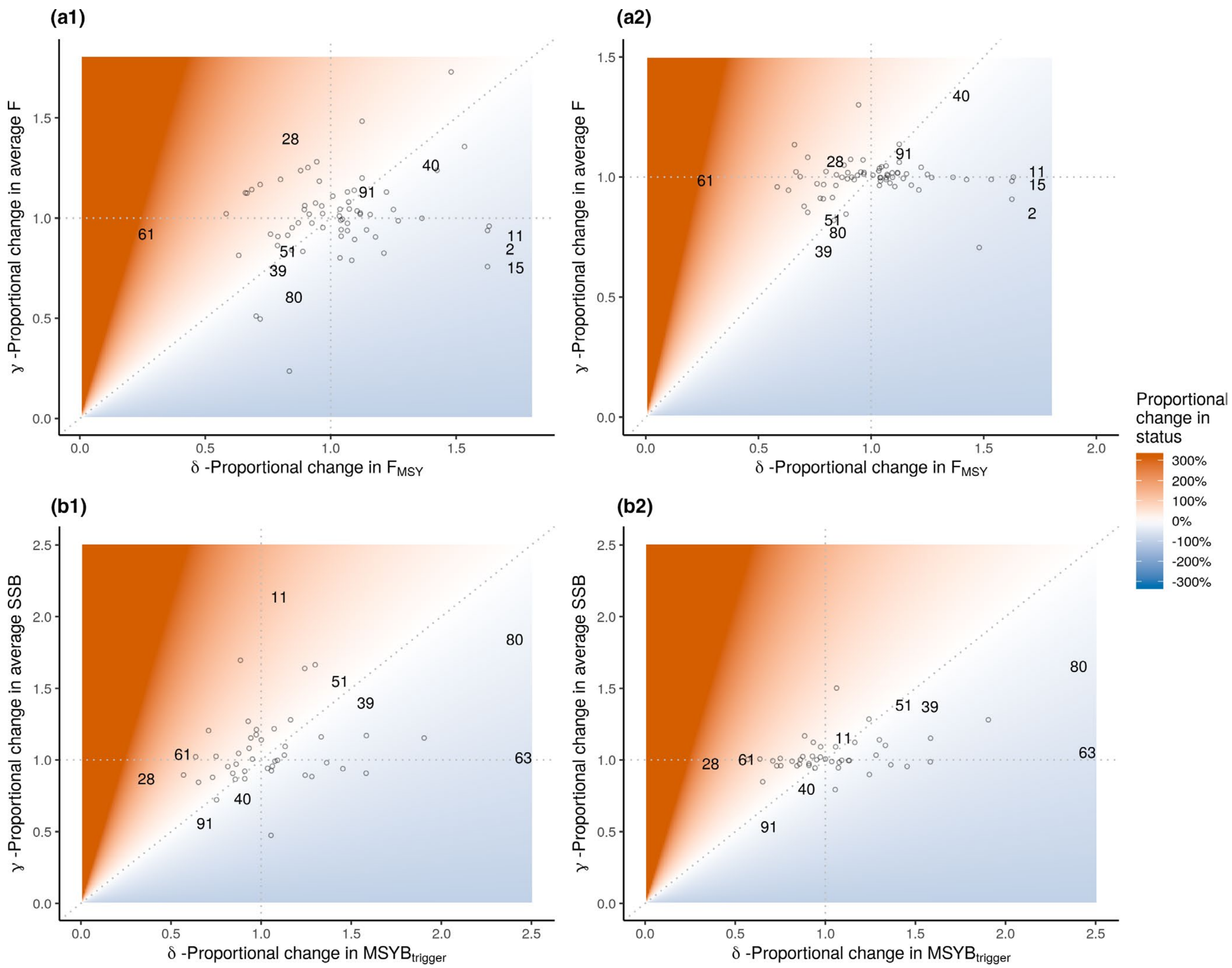

FIGURE 4 Change in sustainability status decomposition. Relationship between proportional change in average rate or state (γ) and proportional change in reference point ($\delta_a = F_{MSY}{}^{y}/F_{MSY}{}^{y-1}$; $\delta_b = MSYB_{trigger}{}^{y}/MSYB_{trigger}{}^{y-1}$), background colour represents impact in status change for relative fishing mortality rate, F/F_{MSY} (a) and relative biomass state, $SSB/MSYB_{trigger}$ (b), over recent years (a1, b1) and the complete time series (a2, b2). The plot numbers correspond to the event numbers in Table S1: (2) 2016 blue ling in Celtic Seas, English Channel and Faroes grounds; (11) 2015 cod in North sea, eastern English Channel, Skagerrak; (15) 2019 cod in West of Scotland; (28) 2019 haddock in Rockall; (39) 2013 herring in gulf of Bothnia; (40) 2017 herring in gulf of Bothnia; (51) 2017 horse mackerel in North Atlantic; (61) 2018 white anglerfish in Cantabrian Sea and Atlantic Iberian waters; (80) 2017 sole in eastern English Channel; (91) 2018 whiting in North Sea and eastern English Channel

3.3 | Effect of reference point changes on sustainability status

We define δ as the proportional change in the reference point and γ as the proportional change in average rate (*F*) or state (*SSB*) over time. There was some evidence of a weak positive relationship between changes in rate or state and reference point (Figure 4), which was significant only for biomass over the recent part of the time series (rho = 0.33, $p = .018$) and over the complete time series (rho = 0.53, $p < .001$). Where the proportional changes in the numerator and denominator were equal, no change in status occurs (1:1 line in Figure 4). However, particularly looking at the data for the complete time series, average status changes were mainly due to changes in reference points (horizontal spread of points in Figure 4a2, 4b2). Some of the greatest changes in relative fishing mortality were associated with changes in F_{MSY}, for example increase in relative fishing mortality for sardine in 2019 (Figure 4a point 61); and decrease in North Sea, eastern English Channel, Skagerrak cod in 2015 (Figure 4a point 11). Similarly for relative biomass, large changes were related mainly with changes in $MSYB_{trigger}$, for example Rockhall haddock in 2019 (Figure 4b point 28) and North Sea and Skagerrak plaice in 2017 (Figure 4b point 63). Yet, eastern English Channel sole 2017 had important changes in both the biomass estimate and $MSYB_{trigger}$ (Figure 4b point 80). Only occasionally were the changes in rate or state compensated by changes in reference point over the most recent period such that no change in status occurred. This counters a common belief that changes in the estimated state will be compensated for by changes in the reference points, which

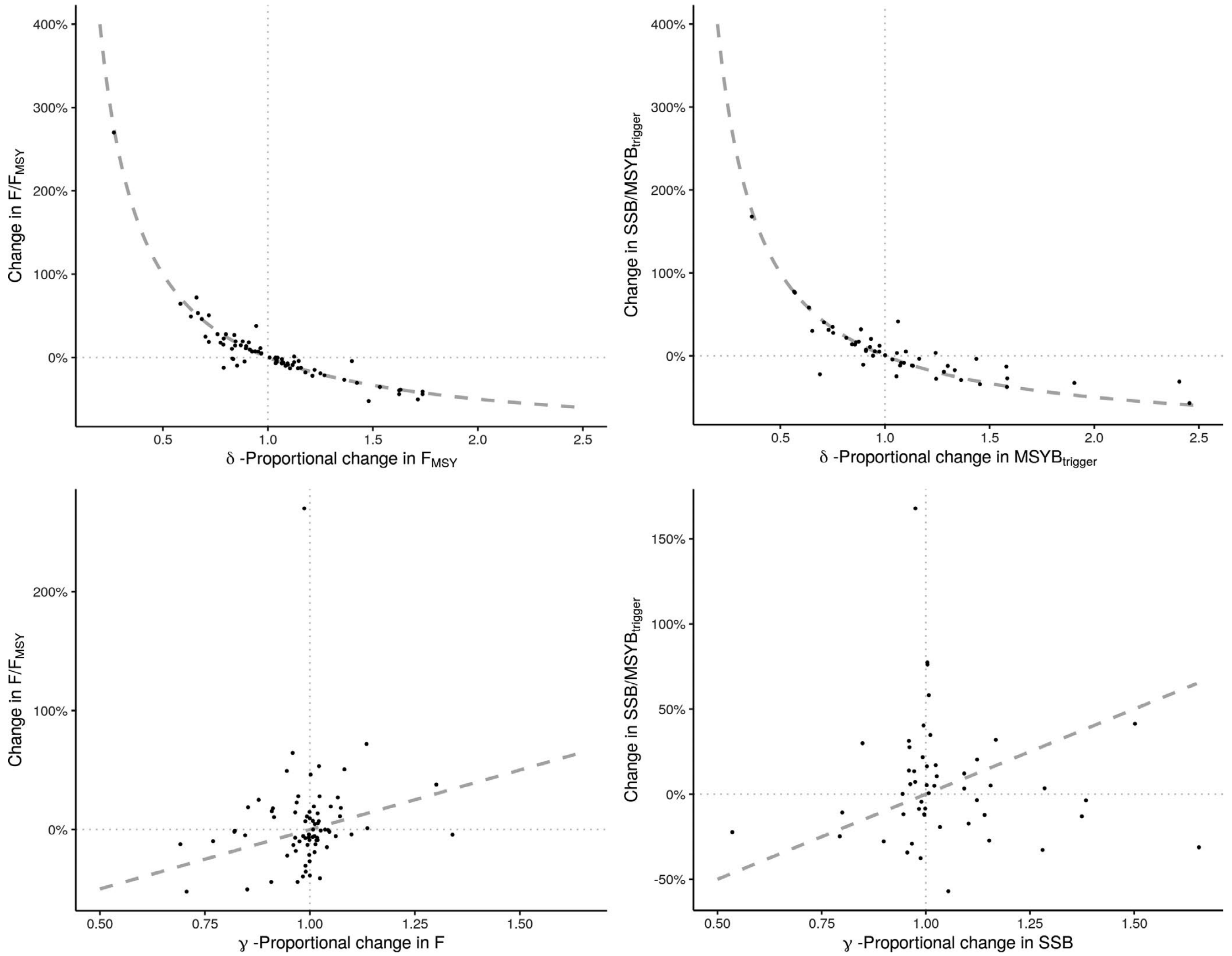

FIGURE 5 Marginal relationship between average change in status and δ, proportional change in reference point, at the top panel; and γ, proportional change in rate (left) or state (right), at the bottom panel considering the complete time series. Grey line shows the expected theoretical change with a change in δ (top) or γ (bottom)

are caused by new information on processes. There were examples of where this compensation occurred: relative fishing mortality of Gulf of Bothnia herring (Figure 4a point 39); and relative biomass of Northeast Atlantic horse mackerel (*Scomber scombrus*, Scombridae; in Figure 4b point 51), and North Sea and eastern English Channel whiting (*Merlangius merlangus*, Gadidae; in Figure 4b point 91).

The marginal relationship between mean status change (over the complete time series) and proportional change in reference point displayed a curvilinear inverse response adhering to the expected relationship (Figure 5 top panel). As the reference point is the denominator of status (F/F_{MSY} and $SSB/MSYB_{trigger}$), if the numerator compensated for the change in the denominator one would expect a flat relationship in Figure 5. We found that reductions in reference points ($\delta < 1$) resulted in steeper increases in status, whereas increases in reference points ($\delta > 1$) resulted in more moderate reductions in status (e.g. from the theoretical proportional change in mean status $\frac{\gamma}{\delta} - 1$, a 10% reduction in the reference point would result in an approximate 11% increase in status whereas a 10% increase in the reference point would result in an approximate 9% increase in the status where $\gamma = 1$). This negative relationship between changes in status and the change in the reference point appears stronger (less variable) for relative fishing mortality than for the relative biomass (Figure 5 top panel). Occasionally, there were assessments where the reference point decreased but status also decreased, or where both increase. The observed marginal relationship with the proportional change in rate or state (γ) was diffuse compared to the theoretical relationship (Figure 5 bottom panel). Over recent years of overlap, the marginal relationship of changes showed in general more variability for the proportional change in reference point and less variability in the marginal relationship with the proportional change in rate or state estimates (Figure S6).

3.4 | Possible reasons for reference points change

Across all the covariates, the distribution of the magnitude of change in both reference points displayed heterogeneous patterns with wide ranges; no covariate showed a clear directional effect (Figures S7 and S8). Most changes in reference point occurred due to a combination of effects rather than a single cause; we found that covariates occurred simultaneously, they might be correlated and also interact (Figures S9 and S10).

Events of change in both F_{MSY} and $MSYB_{trigger}$ presented similar frequency of occurrence for "Assessment" covariates. Input fisheries-dependent and fisheries-independent data were revised for roughly 20% of the cases. The assessment model was modified in approximately 15% of the cases, the most frequent change being from XSA to SAM (*n* = 5). Re-assessment of natural mortality was found in 11% of the cases for F_{MSY} and 6% of the cases for $MSYB_{trigger}$. Changes in natural mortality estimates comprise revision of assumptions (e.g. using a new single species method, introducing multispecies estimates), or updates (e.g. time-varying mortality updated, multispecies estimates using a new multispecies model run). Less frequently encountered covariates (>10% of the cases) were the revision of maturity estimates and the revision of the definition of the stock.

Although multiple factors have contributed to changes in reference points, our results showed that the evolution in the definition for fishing mortality reference point (F_{MSY}) and re-evaluation of the technical basis for limit biomass reference point (B_{lim}) were the most important (Table 2). Revision of fishing mortality reference point definition was the most frequent covariate identified (*n* = 30, 40% of the cases). This key covariate explained the largest part of the variance (39.8%) of the model ($F\text{-statistic}_{(13)} = 3.6$, $p = .0004$, Table 2). It presented the change of many previous definitions (e.g. proxy values) and diversity of stochasticity implementation methods, to a unified F_{MSY} estimation framework *Eqsim* (Figure 6a). We found that advised F_{MSY} based on analogies from other stocks (*n* = 2) or provisional from simulation frameworks (*n* = 8) were on average higher than subsequent F_{MSY}; however, per-recruit proxies were lower based on small sample sizes (F_{max} *n* = 8; $F_{0.1}$ *n* = 4). Only one observed change was related to a revision of the fishing mortality reference point from the calculated value (F_{MSY}) to $F_{p0.5}$ established by stochastic simulations when the precautionary criterion is not met (Figure 6a). For the biomass reference point, revision of B_{lim} technical basis explained 29.94% of the variance of the model ($F\text{-statistic}_{(13)} = 2.23$, $p = .04$, Table 2). B_{lim} technical basis was revised for 19% of the cases and $MSYB_{trigger}$ for 16%. From the re-evaluations of $MSYB_{trigger}$ (*n* = 13), for 23% of the cases the technical basis was changed from B_{PA} to the 5th percentile of B_{MSY} (Figure 6b). The most frequent revision found was re-evaluation of the technical basis of B_{PA} (23% of the cases), which involves modification of how the assessment uncertainty is accounted for. Both selected models to explain changes in reference points had large residual variability at 44.62% and 21.02% for F_{MSY} and $MSYB_{trigger}$, respectively (Table 2) likely reflecting the binary nature of the covariates without the magnitude of change.

The different nature of ICES fishing mortality target and biomass threshold reference point was reflected in the analysis. As F_{MSY} is a model estimate output, it is impacted by modifications to input data (e.g. selection pattern and biological parameter) and underlying assumptions (i.e. stock–recruitment relationship functional form). We found that to derive F_{MSY}, the assumption of the stock–recruitment relationship functional form was revised for 24% of the cases (*n* = 19). Modelling of the stock–recruitment relationship (a key density-dependent process) remains a challenge and this is known as the main source of variation (ICES, 2015; Simmonds et al., 2011). During workshops to consider the basis for F_{MSY} ranges for all stocks, WKMSYREF (ICES, 2015; 2017b) several stock–recruitment models were investigated from functional form combinations to the use of segmented regression. In terms of data input to derive reference points, we found that the time series to estimate F_{MSY} was revised in 11% of the cases for recruitment and 7.5% for productivity parameters. Time series of recruitment and *SSB* to model the stock–recruitment relationship are re-evaluated to ensure the selection of the relevant period when there is a change in the perception of the productivity regime (i.e. shifts or trend). Both, revision of stock–recruitment functional form and selected time series of recruitment, were important variables in the model, which explained around 5% of the variance each ($p < .05$, Table 2). In contrast, $MSYB_{trigger}$ (when set to B_{PA}) is based on biomass assessment estimates, because is often derived from B_{lim} (typically set by stock–recruitment typology rules). Therefore, it is more sensitive to changes affecting the estimates of biomass, for example revision of assessment model type, fishery-dependent and fishery-independent data, methodological revisions and re-assessment of maturity (Table 2).

4 | DISCUSSION

4.1 | Evolution of sustainable targets and thresholds

Reference points play a key role in fisheries management by providing targets and thresholds to guide management actions (Mace, 2001). Reference points may change, not only reflecting the non-stationary nature of the ecosystem but also our ability to capture those changes. The frequency at which reference points are updated varies globally, for example, tuna Regional Fisheries Management Organizations and North Pacific Fisheries Management council update reference points with each assessment (Kell et al., 2016). ICES stocks provide a unique opportunity in terms of breadth and frequency of change (Figure 1) to investigate the impact of changes in reference points. By using ICES stocks for this analysis, we gained a data-rich and detailed overview of the evolution of reference points and their key management use in measuring sustainability status. Stock status before and after a change in a reference point had no significant directional differences (Figure 3) that would suggest a retrospective movement towards or away from sustainability. But there have been important effects of reference point changes for specific stocks with implications for sustainable harvest advice and perceived conservation status. We showed that, across a range of life histories and assessments, changes in reference point dominate changes in status over the full time series (Figure 4). Analysis of recent years shows more variability due to terminal estimate variability and bias (known as retrospective pattern in assessment updates (ICES, 2020)) but

TABLE 2 Table displaying the results of selected model explained by the covariates

Covariate	Model for changes in F_{MSY} ($R^2 = 0.55$, $R^2_{adj} = 0.37$, *F*-Statistic = 3.16 with $p = 2.69e{-}4$)	Percentage of the variance explained	Model for changes in $MSYB_{trigger}$ ($R^2 = 0.79$, $R^2_{adj} = 0.54$, *F*-Statistic = 3.2 with $p = .003$)	Percentage of the variance explained
(1) Revision_Assessment_Stock_definition	—	—	—	—
(2) Revision_Assessment_input_data_ FisheriesDependent	—	—	$F\text{-statistic}_{(1)} = 6.74$; $p = .0161^{*}$	9.68%
(3) Revision_Assessment_input_data_ FisheriesIndependent	—	—	$F\text{-statistic}_{(1)} = 1.77$; $p = .1958$	7.37%
(4) Revision_Assessment_maturity	$F\text{-statistic}_{(1)} = 3.93$; $p = .0522\cdot$	3.14%	$F\text{-statistic}_{(1)} = 1.85$; $p = .187$	1.69%
(5) Revision_Assessment_M	—	—	—	—
(6) Revision_Assessment_methodology	—	—	$F\text{-statistic}_{(1)} = 8.17$; $p = .00889^{**}$	6.51%
(7) Revision_Assessment_type	$F\text{-statistic}_{(6)} = 1.57$; $p = .174$	15.34%	$F\text{-statistic}_{(4)} = 5.94$; $p = .00196^{**}$	14.42%
(8) Revision_RP_FMSY_definition	$F\text{-statistic}_{(13)} = 3.62$; $p = .0004^{***}$	39.75%	—	—
(9) Revision_RP_SR_functional_form	$F\text{-statistic}_{(1)} = 4.25$; $p = .0439^{*}$	5.64%	—	—
(10) Revision_RP_input_timeseriesRecruitment	$F\text{-statistic}_{(1)} = 3.94$; $p = .0320^{*}$	5.64%	—	—
(11) Revision_RP_input_parameterstimeseries	—	—		—
(12) Revision_RP_MSYBtrigger_tb	—	—	$F\text{-statistic}_{(5)} = 2.59$; $p = .0531\cdot$	5.05%
(13) Revision_RP_Blim_tb	—	—	$F\text{-statistic}_{(13)} = 2.23$; $p = .0439^{*}$	29.94%
(14) Revision_RP_Bpa_tb	—	—	—	—
Residuals	—	44.62%	—	21.02%

Note: Signif. Codes: 0 "***" 0.001 "**" 0.01 "*" 0.05 "·" 0.1 " " 1.

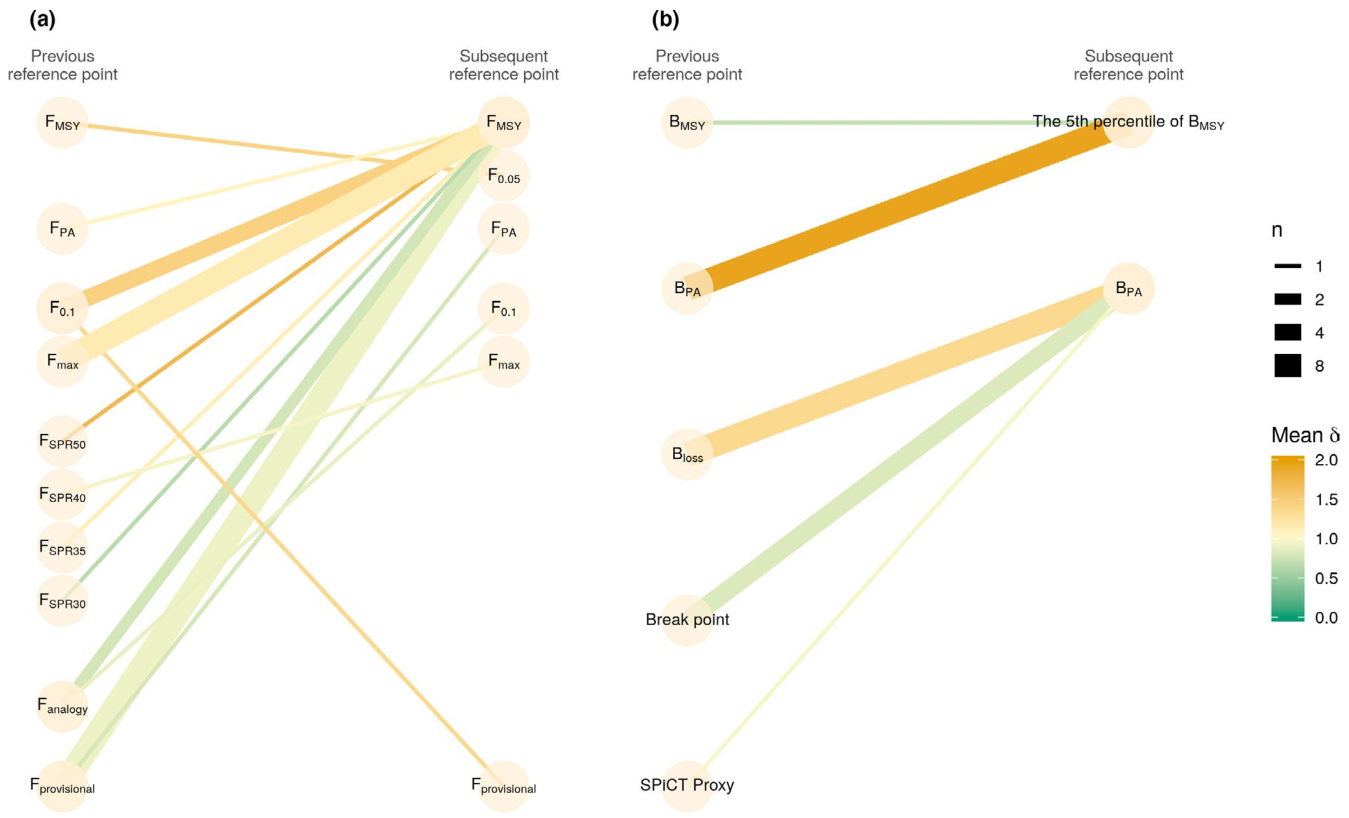

FIGURE 6 (a) Average change in adviced reference point F_{MSY} with levels of revision in definition of fishing mortality reference point: F_{MSY}, yield-per-recruit proxies ($F_{0.1}$, F_{max}), spawner biomass per-recruit proxies (F_{SPR30}, F_{SPR35}, F_{SPR40}, F_{SPR50}), F_{PA}, reference point from analogy of other stocks and provisional reference point; and (b) average change in adviced reference point $MSYB_{trigger}$ with levels of revision of the technical basis: B_{MSY}, B_{PA}, Break point, B_{loss}, proxy from Spict model. The width of the line shows the number of occurrence of that specific revision. Warm colours are mean increase and cool colours mean decrease of reference point advised value

also highlights the importance of changes in reference points on status. For simultaneous changes in F_{MSY} and $MSYB_{trigger}$, we would expect an inverse relationship (i.e. a decrease in F_{MSY} would be associated with an increase in $MSYB_{trigger}$ and vice versa), assuming that the same method was used and only new information in processes was included. However, a substantial number of events deviated from the expected direction (Figure S1), which might be indicative of changes in perceived productivity.

Reference point changes reflect simultaneously the evolution of management policy and scientific understanding and methodology. In 2009 ICES adopted the MSY framework on top of their precautionary framework and began adapting the advice provided (Lassen et al., 2014). The framework includes transition rules; for example, when a stock is fished at or below F_{MSY} for 5 or more years then the basis if $MSYB_{trigger}$ changes from B_{PA} to the 5th percentile of B_{MSY} (ICES, 2017a). This is because productivity and B_{MSY} estimates may change as stocks increase when fishing mortality is reduced to more sustainable levels (i.e. F_{MSY}). Another occurrence was the re-estimation of F_{MSY} and precautionary reference points during the workshops WKMSYREF (2013–2015). This was stimulated by the request of the European Commission for advice on potential intervals above and below F_{MSY} for selected stocks. Evaluations of MSY were made using *Eqsim* or similar methods to implement stochasticity (ICES, 2013; 2017b). Changes in software used to derive F_{MSY} are important because the underlying uncertainty assumptions and the way stochasticity is implemented may vary, which affects the estimates (ICES, 2017b; 2019b).

Across different regions, past studies of the variability among historical assessment and projection simulations have shown that there are numerous potential causes for changes in assessment estimates over time (Privitera-Johnson & Punt, 2020; Punt et al., 2018; Ralston et al., 2011; Wiedenmann & Jensen, 2018). Previous studies have shown sensitivity of MSY-based reference points to the functional form and parameters of the stock–recruitment relationship (Simmonds et al., 2011; Zhu et al., 2012). A recent study initiates the research on the uncertainty associated with biomass limit reference points (Deurs et al., 2021). They were found to be sensitive to the estimation method, time series length, and stock development trends. However, to our knowledge, no study has systematically quantified the impact and reasons for changes in reference points over time. We explored the effect of modifications to reference points that were stated in assessment reports. Were we to also re-run the assessment models and reference point estimation procedure it would be possible to investigate the deterministic impact of any given changes singularly or in combination. This mechanistic approach would be greatly facilitated through transparent frameworks for data and modelling and advice such as the recently developed ICES Transparent

Assessment Framework (https://taf.ices.dk/app/about last accessed August 15th, 2020). Such an analysis is beyond the scope of this work but would be extremely useful and could be operationalized where changes are proposed. Our analysis sets the groundwork for future mechanistic investigation of the causes underlying changes in reference points and status on a stock-by-stock basis.

4.2 | Implications for fisheries management

Time-varying reference points will become increasingly important for management given: (i) continual improvements in stock assessments (in terms of new and improved data and estimation) and continually improved knowledge of stock biology; (ii) the development of operational ecosystem approach and the increasing inclusion of ecosystem concerns in assessments (Marshall et al., 2019; Skern-Mauritzen et al., 2016); and (iii) growing evidence of dynamics, shifts in productivity, and the influence of climate change, which emphasizes the need to adapt reference points (Britten et al., 2017; Collie et al., 2012; Minto et al., 2014; Szuwalski & Hollowed, 2016; Table au et al., 2019; Vert-pre et al., 2013). These changes in reference points will require inclusion in future interpretations of stock status (Hilborn, 2020).

We underscore the importance of keeping track of changes and modifications to understand their impact and allow comparisons across stock assessments that underpin fisheries management. Our results also highlight the continual importance of accounting for scientific uncertainty to distinguish it from real changes in the ecosystem or the fishery, which are fundamentally different. We emphasize the many examples in Figure 1 of where reference points decrease and then increase or vice versa and posit that these cases will offer useful insights into the general process lending towards further investigation of the stability and performance of management advice under true and perceived change. Given the challenges faced by estimation and the use of reliable reference points for management (Hilborn, 2002), reference points are better seen as reference series. The relevant reference point in the reference series should also be time-dependent (possibly with lags) when inferring historical sustainability rather than assessing historical status relative to the most recent reference point. We recommend careful documentation of changes to assessment assumptions and data inputs (Punt et al., 2018), as well as the revision in estimation or selection of reference points and detection of shifts in productivity (Clausen et al., 2018). Communicating, explaining and justifying the changes is remarkably important to understand them and their relevance. Nowadays, this can be readily achieved using changelogs that are common in other continual development processes such as software development.

Although this work is tailored for ICES reference points, the approach to decompose changes in status into components can be applied to other regions and globally (e.g. using the RAM Legacy Database). Methods developed here are applicable in settings where the ratio of a state to a changing goal is used to indicate status (e.g. Sustainable Development Goals: 6 Clean Water and Sanitation; 13 Climate Action; 15: Life On Land).

ACKNOWLEDGEMENTS

We are grateful to Kenneth Patterson for his valuable contributions and feedback in early stages of this manuscript. We thank European stock assessment scientists, data collectors, and ICES upon whose assessments our work is based. This analysis was funded by the Irish Department of Agriculture, Food and the Marine's Competitive Research Funding Programmes (DAFM) as part of the FishKOSM project (Ref 15/S/744).

CONFLICT OF INTEREST

Authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All data and code we used for analyses are available on our GitHub repository: https://github.com/paulasv/IMGP_2020. All raw assessment data is available for download at ICES webpage.

ORCID

Paula Silvar-Viladomiu https://orcid.org/0000-0002-9983-3744

REFERENCES

Britten, G. L., Dowd, M., Kanary, L., & Worm, B. (2017). Extended fisheries recovery timelines in a changing environment. *Nature Communications*, *8*(1), 15325. https://doi.org/10.1038/ncomms15325

Calcagno, V., & de Mazancourt, C. (2010). glmulti: An R package for easy automated model selection with (Generalized) linear models. *Journal of Statistical Software*, *34*(12), 29. https://doi.org/10.18637/jss.v034.i12

Clausen, L. W., Rindorf, A., van Deurs, M., Dickey-Collas, M., & Hintzen, N. T. (2018). Shifts in North Sea forage fish productivity and potential fisheries yield. *Journal of Applied Ecology*, *55*(3), 1092–1101. https://doi.org/10.1111/1365-2664.13038

Collie, J. S., Peterman, R. M., & Zuehlke, B. M. (2012). A fisheries risk-assessment framework to evaluate trade-offs among management options in the presence of time-varying productivity. *Canadian Journal of Fisheries and Aquatic Sciences*, *69*(2), 209–223. https://doi.org/10.1139/f2011-148

Deurs, M., Brooks, M. E., Lindegren, M., Henriksen, O., & Rindorf, A. (2021). Biomass limit reference points are sensitive to estimation method, time-series length and stock development. *Fish and Fisheries*, *22*(1), 18–30. https://doi.org/10.1111/faf.12503

EC. (2013). Common fisheries policy (CFP) Regulation No. 1380/2013 of the European Paliament and of the Council. *Official Journal of the European Communities*, *001*, 354. http://data.europa.eu/eli/reg/2013/1380/oj

Evans, G. T. (1996). Using the elementary operations of sequential population analysis to display problems in catch or survey data. *Canadian Journal of Fisheries and Aquatic Sciences*, *53*(2), 239–243. https://doi.org/10.1139/f95-191

FAO. (2020). *Proceedings of the international symposium on fisheries sustainability: Strengthening the science-policy nexus. FAO fisheries and aquaculture proceedings* No. 65 (Vol. FAO Headqu). FAO. https://doi.org/10.4060/ca9165en

Fernandes, P. G., & Cook, R. M. (2013). Reversal of fish stock decline in the Northeast Atlantic. *Current Biology*, *23*(15), 1432–1437. https://doi.org/10.1016/j.cub.2013.06.016

Hilborn, R. (2002). The dark side of reference points. *Bulletin of Marine Science*, *70*(2), 403–408.

Hilborn, R. (2020). Measuring fisheries management performance. *ICES Journal of Marine Science*, *77*(7–8), 2432–2438. https://doi.org/10.1093/icesjms/fsaa119

Hilborn, R., Amoroso, R. O., Anderson, C. M., Baum, J. K., Branch, T. A., Costello, C., de Moor, C. L., Faraj, A., Hively, D., Jensen, O. P., Kurota, H., Little, L. R., Mace, P., McClanahan, T., Melnychuk, M. C., Minto, C., Osio, G. C., Parma, A. M., Pons, M., … Ye, Y. (2020). Effective fisheries management instrumental in improving fish stock status. *Proceedings of the National Academy of Sciences*, *117*(4), 2218–2224. https://doi.org/10.1073/pnas.1909726116

ICES. (2013). Report of the Workshop to consider reference points for all stocks (WKMSYREF2), *8–10 Janua*(ICES CM 2014/ACOM:47), 91 pp.

ICES. (2015). Report of the Joint ICES-MYFISH Workshop to consider the basis for FMSY ranges for all stocks (WKMSYREF3). *ICES*, *17–21 Nove*(ICES CM 2014/ACOM:64), 156 pp. https://doi.org/ICES CM 2014/ACOM:64. https://doi.org/10.17895/ices.pub.5661

ICES (2017a). ICES advice technical guidelines. ICES fisheries management reference points for category 1 and 2 stocks. *ICES Advice*, Book 12(20 January), 19. https://doi.org/10.17895/ices.pub.3036

ICES. (2017b). Report of the Workshop to consider FMSY ranges for stocks in ICES categories 1 and 2 in Western Waters (WKMSYREF4). *13–16 October 2015*, *Brest*, *France*, (ICES CM 2015/ACOM:58), 187 pp.

ICES (2018). ICES Technical Guidelines. ICES reference points for stocks in categories 3 and 4. *ICES Advice*, (13 February), 50. https://doi.org/10.17895/ices.pub.3977

ICES. (2019a). Advice basis. *In Report of the ICES Advisory Committee*, *2019*. https://doi.org/10.17895/ices.advice.5757

ICES (2019b). Workshop on North Sea Stocks Management Strategy Evaluation (WKNSMSE). *ICES Scientific Reports*, *1*(12), 378. https://doi.org/10.17895/ices.pub.5090

ICES. (2020). Workshop on Catch Forecast from Biased Assessments (WKFORBIAS; outputs from 2019 meeting). *ICES Scientific Reports*, (2:28), 38. https://doi.org/10.17895/ices.pub.5997

ICES (2021). Workshop of Fisheries Management Reference Points in a Changing Environment (WKRPChange, outputs from 2020 meeting). *ICES Scientific Reports*, *3*(6), 39. https://doi.org/10.17895/ices.pub.7660

Jackson, J. B. C. (2001). Historical overfishing and the recent collapse of coastal ecosystems. *Science*, *293*(5530), 629–637. https://doi.org/10.1126/science.1059199

Kell, L. T., Nash, R. D. M., Dickey-Collas, M., Mosqueira, I., & Szuwalski, C. (2016). Is spawning stock biomass a robust proxy for reproductive potential? *Fish and Fisheries*, *17*(3), 596–616. https://doi.org/10.1111/faf.12131

Kvamsdal, S. F., Eide, A., Ekerhovd, N.-A., Enberg, K., Gudmundsdottir, A., Hoel, A. H., & Vestergaard, N. (2016). Harvest control rules in modern fisheries management. *Elementa: Science of the Anthropocene*, *4*(000114), 1–22. https://doi.org/10.12952/journal.elementa.000114

Lassen, H., Kelly, C., & Sissenwine, M. (2014). ICES advisory framework 1977–2012: From Fmax to precautionary approach and beyond. *ICES Journal of Marine Science*, *71*(2), 166–172. https://doi.org/10.1093/icesjms/fst146

Mace. (2001). A new role for MSY in single-species and ecosystem approaches to fisheries stock assessment and management. *Fish and Fisheries*, *2*(1), 2–32. https://doi.org/10.1046/j.1467-2979.2001.00033.x

Marshall, K. N., Koehn, L. E., Levin, P. S., Essington, T. E., & Jensen, O. P. (2019). Inclusion of ecosystem information in US fish stock assessments suggests progress toward ecosystem-based fisheries management. *ICES Journal of Marine Science*, *76*(1), 1–9. https://doi.org/10.1093/icesjms/fsy152

Minto, C., Mills Flemming, J., Britten, G. L., & Worm, B. (2014). Productivity dynamics of Atlantic cod. *Canadian Journal of Fisheries and Aquatic Sciences*, *71*(2), 203–216. https://doi.org/10.1139/cjfas-2013-0161

Privitera-Johnson, K. M., & Punt, A. E. (2020). Leveraging scientific uncertainty in fisheries management for estimating among-assessment variation in overfishing limits. *ICES Journal of Marine Science*, *77*(2), 515–526. https://doi.org/10.1093/icesjms/fsz237

Punt, A. E., Day, J., Fay, G., Haddon, M., Klaer, N., Little, L. R., & Wayte, S. (2018). Retrospective investigation of assessment uncertainty for fish stocks off southeast Australia. *Fisheries Research*, *198*, 117–128. https://doi.org/10.1016/j.fishres.2017.10.007

Ralston, S., Punt, A. E., Hamel, O. S., Devore, J. D., & Conser, R. J. (2011). A meta-analytic approach to quantifying scientific uncertainty in stock assessments. *Fishery Bulletin*, *109*(2), 217–231.

Ricard, D., Minto, C., Jensen, O. P., & Baum, J. K. (2012). Examining the knowledge base and status of commercially exploited marine species with the RAM legacy stock assessment database. *Fish and Fisheries*, *13*(4), 380–398. https://doi.org/10.1111/j.1467-2979.2011.00435.x

Simmonds, E. J., Campbell, A., Skagen, D., Roel, B. A., & Kelly, C. (2011). Development of a stock–recruit model for simulating stock dynamics for uncertain situations: The example of Northeast Atlantic mackerel (Scomber scombrus). *ICES Journal of Marine Science*, *68*(5), 848–859. https://doi.org/10.1093/icesjms/fsr014

Skern-Mauritzen, M., Ottersen, G., Handegard, N. O., Huse, G., Dingsør, G. E., Stenseth, N. C., & Kjesbu, O. S. (2016). Ecosystem processes are rarely included in tactical fisheries management. *Fish and Fisheries*, *17*(1), 165–175. https://doi.org/10.1111/faf.12111

Szuwalski, C. S., & Hollowed, A. B. (2016). Climate change and non-stationary population processes in fisheries management. *ICES Journal of Marine Science*, *73*(5), 1297–1305. https://doi.org/10.1093/icesjms/fsv229

Tableau, A., Collie, J. S., Bell, R. J., & Minto, C. (2019). Decadal changes in the productivity of New England fish populations. *Canadian Journal of Fisheries and Aquatic Sciences*, *76*(9), 1528–1540. https://doi.org/10.1139/cjfas-2018-0255

Vert-pre, K. A., Amoroso, R. O., Jensen, O. P., & Hilborn, R. (2013). Frequency and intensity of productivity regime shifts in marine fish stocks. *Proceedings of the National Academy of Sciences*, *110*(5), 1779–1784. https://doi.org/10.1073/pnas.1214879110

Wiedenmann, J., & Jensen, O. P. (2018). Uncertainty in stock assessment estimates for New England groundfish and its impact on achieving target harvest rates. *Canadian Journal of Fisheries and Aquatic Sciences*, *75*(3), 342–356. https://doi.org/10.1139/cjfas-2016-0484

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., & Watson, R. (2006). Impacts of biodiversity loss on ocean ecosystem services. *Science*, *314*(5800), 787–790. https://doi.org/10.1126/science.1132294

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., & Zeller, D. (2009). Rebuilding global fisheries. *Science*, *325*(5940), 578–585. https://doi.org/10.1126/science.1173146

Zhu, J., Chen, Y., Dai, X., Harley, S. J., Hoyle, S. D., Maunder, M. N., & Aires-da-Silva, A. M. (2012). Implications of uncertainty in the spawner–recruitment relationship for fisheries management: An illustration using bigeye tuna (Thunnus obesus) in the eastern Pacific Ocean. *Fisheries Research*, *119–120*, 89–93. https://doi.org/10.1016/j.fishres.2011.12.008

SUPPORTING INFORMATION

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

How to cite this article: Silvar-Viladomiu, P., Minto, C., Halouani, G., Batts, L., Brophy, D., Lordan, C., & Reid, D. G. (2021). Moving reference point goalposts and implications for fisheries sustainability. *Fish and Fisheries*, 22, 1345–1358. https://doi.org/10.1111/faf.12591