



Supplementary Materials for  
**Resilience and Recovery of Overexploited Marine Populations**

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**This PDF file includes:**

Figs. S1 to S7  
Tables S1 and S2  
References

## Materials and Methods

### Definitions

We used the following operational definitions of depletion, recovery, and recovered. A stock was classified as depleted when its biomass (spawning stock or total biomass) fell below half of its MSY reference point,  $B_{MSY}$ . This definition aligns with the legal definition of overfished in the USA (30) and Australia (31), and is meant to allow for stock fluctuations below  $B_{MSY}$ . We considered a stock to be recovered once its biomass exceeded  $B_{MSY}$ .  $B_{MSY}$  is a legislated rebuilding target in at least the USA, and has been proposed as such in Europe. Maintaining stocks at or above  $B_{MSY}$  is also a legal obligation for signatories to the United Nations Convention on the Law of the Sea (UNCLOS). Recovery is then the demographic process of population growth between the time of depletion,  $B < 0.5B_{MSY}$ , and the time when the biomass first exceeds  $B_{MSY}$ . Although we do not use an explicit definition of overfishing for our analysis, we can define overfishing according to the above definitions as a fishing mortality that leads to a depleted stock (theoretically, according to our definitions,  $F > 2F_{MSY}$ ), and/or is too high to allow for recovery to  $B_{MSY}$  (in theory,  $F > F_{MSY}$ ). Note that according to these definitions a stock may be classified as overfished more than once throughout its exploitation history and we term each such event a depletion event (see Fig. S3 for an illustration).

### Data

Our analyses are based upon Version 1.0 of the Ram Legacy Stock Assessment Database (11), with European stock assessments conducted by International Council for the Exploration of the Seas (ICES) updated to 2011. For each stock, we obtained time series of estimated biomass  $B$  (spawning stock or total biomass, in order of preference) and fishing mortality  $F$ , as well as the corresponding reference points  $B_{MSY}$  and  $F_{MSY}$ , the biomass and fishing mortality estimated to lead to the maximum sustainable yield (MSY) (Fig. S1). Only time-series with at least 10 years of data were retained for analysis. We used MSY reference points directly from the assessments, where available, and estimated them using surplus production model fits to stocks' biomass and catch time series (as in refs 10, 11, 32) for the remaining stocks. Of the 253 stocks for which these data were available, 153 stocks, comprising 85 different species, were depleted at some point, and several were depleted multiple times, resulting in a total of 184 depletion events (Supporting Table S1).

### Modeling recovery

Our approach to modeling the recovery process is motivated by the underlying population dynamics of recovering stocks, which can be represented using a stochastic differential equation model for stock biomass dynamics:

$$dB_t = \varphi_t B_t dt + \sigma B_t dW_t \quad (1)$$

where  $B_t$  is the biomass at time  $t$ , the function  $\varphi_t$ , which represents the deterministic component of the biomass dynamics (e.g., survival and reproduction), models the rate of increase of the population, and could, for example take the form of an exponential or logistic growth model with variable fishing mortality (e.g., a Graham-Schaefer surplus production model).  $W_t$  is a Wiener process with mean 0 and variance coefficient  $\sigma$ . This continuous-time stochastic process is commonly used to model Brownian motion, and here represents the stochasticity of the biomass

dynamics. Thus, model (1) is a stochastic version of the biomass dynamics models commonly used in fisheries (33), in which the recovery target is approached at a recovery rate determined by  $\varphi_t$ . Use of this model directly, however, would necessitate specifying the form of  $\varphi_t$  and thus determining *a priori* which (and how) covariates influence the biomass dynamics. This is, however, exactly what we seek to determine empirically, and imposing a particular model for  $\varphi_t$  may therefore bias our inference. Rather than specifying a specific model for biomass dynamics, our aim is to estimate the importance of covariates that influence these dynamics and the associated stochasticity, and therefore determine the time to recovery. Thus, instead of modeling the time-series themselves, we can model the time to recovery directly by taking the time to recovery as the response variable.

Under the assumption that the a stochastic component of the time-series can be reasonably described by a Wiener process, the time from depletion to recovery follows an inverse-Gaussian (IG) distribution with density

$$f_{IG}(t) = \frac{c'}{\sigma\sqrt{2\pi}} t^{-3/2} \exp\left[-\frac{(c' - v't)^2}{2\sigma^2 t}\right] \quad (2)$$

where  $c' = -\log(B_d)$  is a function of the initial biomass at depletion,  $B_d$ ,  $v'$  is a function of  $\varphi_t$ , and coefficient  $\sigma$  is the Wiener process variance (34). Regardless of the precise model for the biomass, the parameters  $c'$  and  $v'$  can be interpreted as influencing the ‘distance’ to the recovery target and the ‘recovery rate’, respectively. Both parameters are relative to the stochasticity of the biomass dynamics, such that, for instance, the same biomass for highly stochastic dynamics will represent a lower distance from the recovery target since a recovery due to a stochastic event is more likely.  $f_{IG}$  thus depends on  $\sigma$  through  $c'/\sigma = c$  and  $v'/\sigma = v$  (i.e., there are only two free parameters, and we can set  $\sigma=1$  without loss of generality (34)), and we may then investigate the importance of covariates in determining the recovery rate and distance from recovery relative to the stochasticity in the time series by placing a regression formulation on each of  $c$  and  $v$  (34). This means that regression covariates can in theory influence the time to recovery either directly by influencing  $c'$  or  $v'$ , or by modifying the amount of stochasticity  $\sigma$ .

The final model for time to recovery for all  $i = 1 \dots N$  depletion events can be expressed hierarchically as:

$$\begin{aligned} t_i | v_{i,j}, c_i &\sim IG(v_{i,j}, c_i) \\ v_{i,j} &= \beta' X_i + \epsilon_j \\ c_i &= -\log(B_d) * \exp(\gamma' \Xi_i) \\ \epsilon_j &\sim N(0, \xi) \end{aligned}$$

where,  $X_i$  and  $\Xi_i$  are regression covariates influencing the relative recovery rate and the relative distance to recovery, respectively. For the latter, a multiplicative regression formulation assures that the distance remains positive, but is decreased by negative effects of covariates. To circumvent pseudo-replication in stocks with more than one depletion event, we introduce a random effect  $\epsilon_j$  for the recovery rate of stock  $j$ . The probability  $\varphi(t)$  that a stock will take at least a time  $T$  (e.g., 10 years) to recover is then  $F(t) = 1 - P_{IG}(T \leq t)$ , where  $P_{IG}$  is the inverse Gaussian cumulative distribution function at  $T$  integrated over the random effect (see below).

Importantly, this model form allows for the possibility that some stocks may not recover. Recovery will be increasingly unlikely with an increasingly negative recovery rate and

increasing distance from the recovery target (relative to the stochastic component in the time series). This probability can be directly quantified for our model, and can thus be investigated in terms of regression covariates (see below).

### Survival analysis for stock recoveries

Models of ‘time-to-recovery’ often involve censored (i.e., incomplete) data. Specifically, data are censored for each stock that was already depleted at the beginning of its time series (i.e., year of depletion unknown) or was not yet recovered in the final year of its time series (i.e., year of recovery unknown). For such populations, we know the minimum time  $t$  of the depletion event, but not the full time of recovery  $T$  (which is infinite for populations that never recover). Thus  $T > t$  for such depletion events, while  $T = t$  for recovered populations in which the full depletion duration is known. These data are most appropriately modeled in a statistical ‘time-to-event’ framework, which takes into account their incompleteness (35).

To estimate parameters in our model, we need to be able to write the likelihood for all non-censored and censored data. The inverse Gaussian density of time to recovery (2) can be decomposed into the probability of recovering in the time interval  $t + \Delta t$  with  $\Delta t \rightarrow 0$  given that recovery hasn’t taken place up to that point, times the probability that recovery hasn’t taken place up to that point. For censored observations, we know only that the depletion event lasted at least time  $t$ . We thus only have a partial likelihood for these data points. As above, the probability  $F_{IG}$  that a stock will take at least a time  $t$  to recover is

$$F_{IG}(t) = 1 - P_{IG}(T \leq t) = \Phi\left(\frac{c - vt}{\sqrt{t}}\right) - \exp(2cv)\Phi\left(\frac{-c - vt}{\sqrt{t}}\right).$$

The total likelihood is then

$$L(t) = \prod_{i \in n} F_{IG}(t)^{1-I} f_{IG}(t)^I,$$

where  $I$  is an indicator taking value 1 for complete and 0 for censored observations.

To make predictions about the statistical population of stocks, we integrate with respect to the random effect, which yields (34)

$$F_U(t) = 1 - P_U(T \leq t) = \Phi\left(\frac{c - vt}{\sqrt{t^2\xi^2 + t}}\right) - \exp(2cv + 2c^2\xi^2)\Phi\left(\frac{-c - 2ct\xi^2 - vt}{\sqrt{t^2\xi^2 + t}}\right),$$

where the  $U$  in the subscript indicates that this quantity is now unconditional, that is, not conditional on the random effect of a particular stock. To investigate if any of our covariates compromise long-term recovery, we take the limit of  $F_U$  as  $t \rightarrow \infty$  (34), which gives

$$\lim_{t \rightarrow \infty} F_U(t) = \Phi\left(\frac{v}{\xi}\right) - \exp(2cv + 2c^2\xi^2)\Phi\left(2c\xi - \frac{v}{\xi}\right).$$

### Drivers of recovery

We tested a suite of covariates hypothesized to influence recovery. Most obvious is the fishing mortality,  $F$ , relative to  $F_{MSY}$  during the recovery period; here we used the mean  $F/F_{MSY}$  during recovery as a potential predictor of the recovery rate. The minimum biomass reached during the depletion may also have an important effect on recovery times, both via density dependent effects on the recovery rate as well as by providing additional information about the distance from the recovery target. High sustained fishing mortality can lead to a number of (potentially hereditary) changes in the demography and physiology of exploited stocks (18, 22) that may be directly related to fishing pressure (24) and may limit or enhance the ability of a stock to recover. To account for potential adaptive and evolutionary effects of high and sustained fishing mortality we included the historic fishing intensity as well as the exploitation time as covariates for both the recovery rate and the relative distance. We defined exploitation time as the number of years from the development year, taken as the time from which catches first exceed 20% of the maximum catch, or the first record in the assessment database if the former was not available, until the year of depletion, and historic fishing intensity as the mean  $F/F_{MSY}$  over this period. We hypothesized stocks with long exploitation histories prior to depletion would be more strongly affected by historic fishing intensity, and thus included first order interaction terms of historic fishing intensity with exploitation time (termed ‘exploitation history’). All covariates were centered, such that the main effects describe influences at the mean covariate values, and the interaction term describes deviations from mean effects.

We also included the intrinsic rate of increase,  $r$ , as a covariate to control for ‘fast’ versus ‘slow’ life histories in determining the recovery rate (12, 14, 36). The intrinsic rate of increase was estimated for each of these stocks in a taxonomically hierarchical meta-analysis (see *Parameters and missing data models* below) of surplus production model  $r$  estimates (37). We included a binary habitat category for pelagic and demersal species as a predictor of both the recovery rate and relative distance, since the demersal species are often caught in multispecies fishery, where continued bycatch mortality may prolong recoveries (9, 38). Lastly, we included species’ trophic level (from Fishbase (39)) in both regressions to account for potentially differential recovery regimes at different levels of the food web. An illustration of covariate distributions is given in Fig. S1. To make effects sizes comparable among continuous and categorical variables, we divided all covariates by twice their standard deviation. We also checked for correlations among all covariates to eliminate the possibility of collinear variables.

#### Parameter and missing data models

To obtain reasonable estimates of intrinsic rates of increase ( $r$ ), we applied a taxonomic hierarchical meta-analysis method to intrinsic rates of increase ( $r$ ) estimates obtained from the Schaeffer model. The meta-analysis works by drawing stock level parameters from species level (normal) distributions, which are in turn drawn from family distributions, themselves drawn from an overarching general distribution. The parameter estimates are thus shrunk toward a taxonomically determined mean. This formulation was embedded into the main model in order to let uncertainty about  $r$  be directly reflected in parameter estimates (i.e., an ‘errors in variables’ approach).

A number of stock assessments included in our analysis did not include a time-series of fishing mortality, and it was therefore impossible to calculate  $F/F_{MSY}$  and the historic fishing intensity directly. Our Bayesian computation allowed us to nevertheless include these stocks which may be informative about other parameters, by giving a prior distribution to these parameters. In both cases we used a log-normal distribution as prior, with hyper-priors for its

mean being a normal distribution centered on the log sample mean and with variance of  $10^2$  and with a vague inverse-gamma hyper-prior (variance = 100) for the variance.

### Priors and implementation

All priors for regression parameters in the final model were vague normal distributions with mean 0 and variance  $10^5$ . For  $\xi$  we used a vague Gamma(0.01,0.01) prior. All covariates were centered and, to compare relative importance of predictors, we divided each covariate by twice its standard deviation. We ran three independent MCMC chains using the WinBUGS package for the computing environment R V.2.14.1 (39), using a burn-in of 50,000 iterations and 500,000 iterations post burn-in. Convergence was assessed visually after thinning the chains, keeping every 100<sup>th</sup> iteration.

### Model fit

We evaluated the fit of the inverse Gaussian model using standard procedures from survival analysis (41). We calculated Cox-Snell residuals (CSR) as a functional of the joint posterior distribution of model parameters to assess the fit of the Inverse Gaussian distribution to the data. There were slight deviations of the posterior mode from expected CSR values (along the  $y = x$  line) for high residuals (Figure S4). Such slight deviations are to be expected at the extremes of CSR values with a relatively limited size of full observations (41). The overall fit seemed reasonable, with the bulk of the posterior distribution of residuals centered along the expected  $y = x$  line.

### Robustness to alternative definitions, analyses and potential bias

To inspect whether our results are robust to changes in definitions used for our analysis, we tested a range of alternative models, which gave qualitatively similar results to those discussed above. For example, changing our definitions of depletion to all stocks at biomasses below  $B_{MSY}$  gave similar, but noisier results, with most of the noise resulting from stocks fluctuating about  $B/B_{MSY}$ .

We also explored the effects of generation time on the exploitation history effect by dividing the latter by the former. This analysis gave very similar results to that reported in the main text, as did a model with generation time included as covariate, and a model with recovery time expressed in terms of generation times. The absence of any notable effect from including generation time can be ascribed to its strong correlation with intrinsic rate of increase ( $r^2 = 0.40, p < 1.0 e^{-12}$ ). We thus omitted this effect from our overall analysis for reasons of model parsimony.

To ensure the robustness of our results pertaining to exploitation history, we checked for correlations among these variables (i.e., exploitation time and historic fishing intensity), and looked for geographical patterns in their distribution that may hint at these variables being a surrogate for regional differences. We did not find any notable patterns in these analyses (e.g., Fig. S5). We lastly considered an analysis that used the two covariates in question and the stock specific random effect from our analysis reported above to predict deviations from expected biomass increases under a Graham-Schaefer model, as in (12). This analysis confirms the patterns reported in the main text: deviations from expected biomass increases are symmetrically distributed around zero (Fig. S6), with deviations from expectations mainly predicted by exploitation history (Fig. S7); intrinsic rate of increase seems to contribute more than expected (since this parameter is already included in biomass dynamic model used to calculate the

expectation; Fig. S7). This is consistent with adaptations to exploitation happening faster in species with short generation times and high  $r$ . This analysis also confirms that faster recovery due to exploitation history patterns does not act solely via increased stochasticity in exploited populations (e.g., 42). Since parameters in our model (such as reference points and the intrinsic rate of increase) are estimated directly from such models it may not be too surprising to find that the models fit. Due to the circularity we only introduce this analysis as support for our findings about exploitation time and refrain from further interpretations.

Finally, the stock assessment outputs used as the basis for our analyses are themselves model estimates with potentially large uncertainties. Given the diversity of methods employed to estimate parameters and time-series in stock assessments, these estimation errors likely act to introduce additional uncertainty in our estimates rather than any consistent bias. For some stocks, however, we calculated parameters from the same time-series that were analyzed for recovery, thus leading to a potential upward bias in their relative importance (e.g., intrinsic rate of increase ( $r$ )). There are, however, few alternatives to the calculation of these parameters since stock assessments usually include most of the available information about a species' life-history. We aimed to reduce this potential bias by using a Bayesian meta-analysis technique for  $r$  that shrinks values towards a taxonomically determined mean (see *Parameter and missing data models* above). We further examined the potential bias for MSY reference points calculated from surplus production models, but found little evidence for consistent differences in the assessed depletion levels.

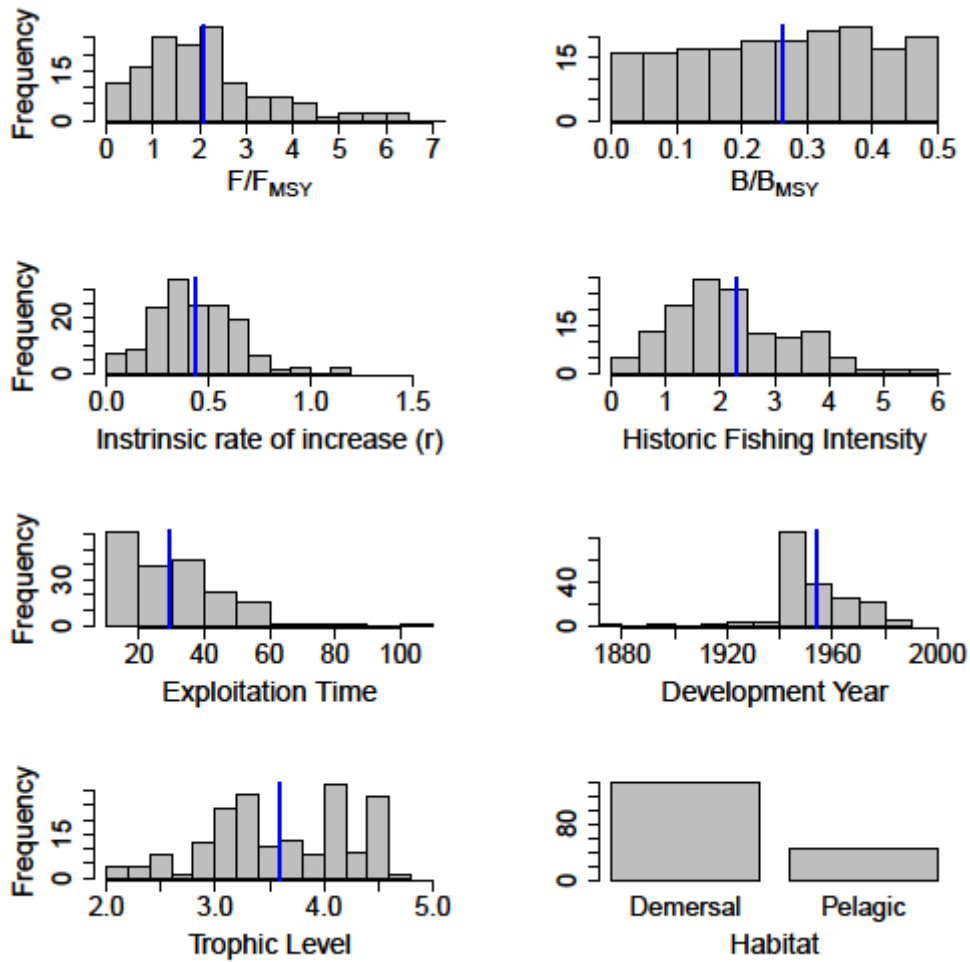
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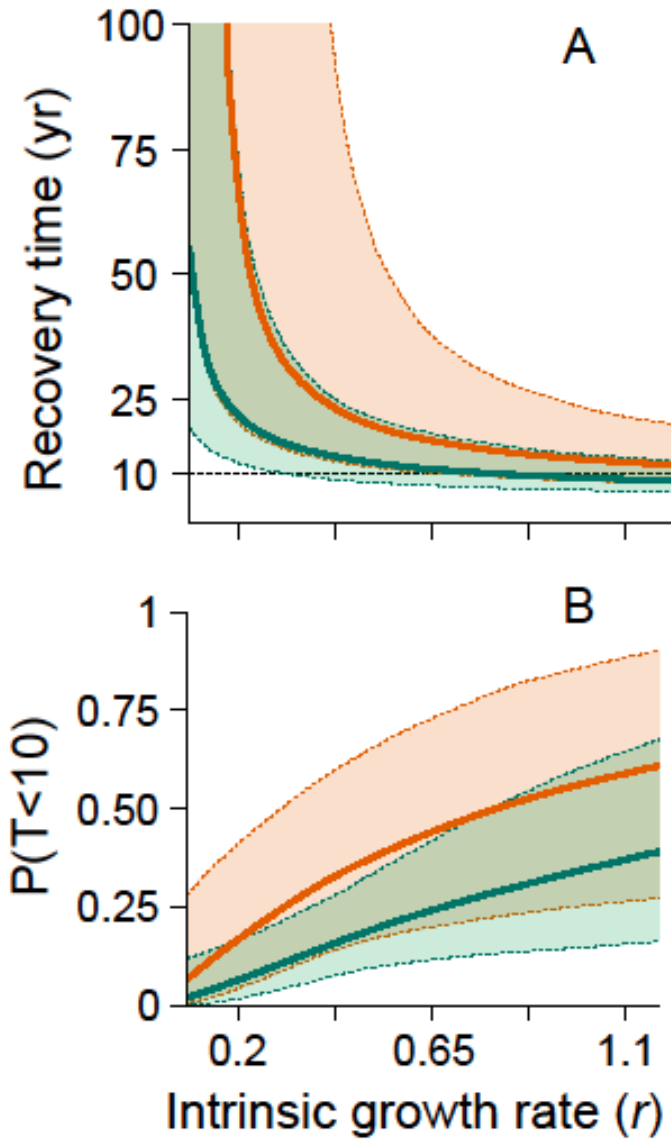
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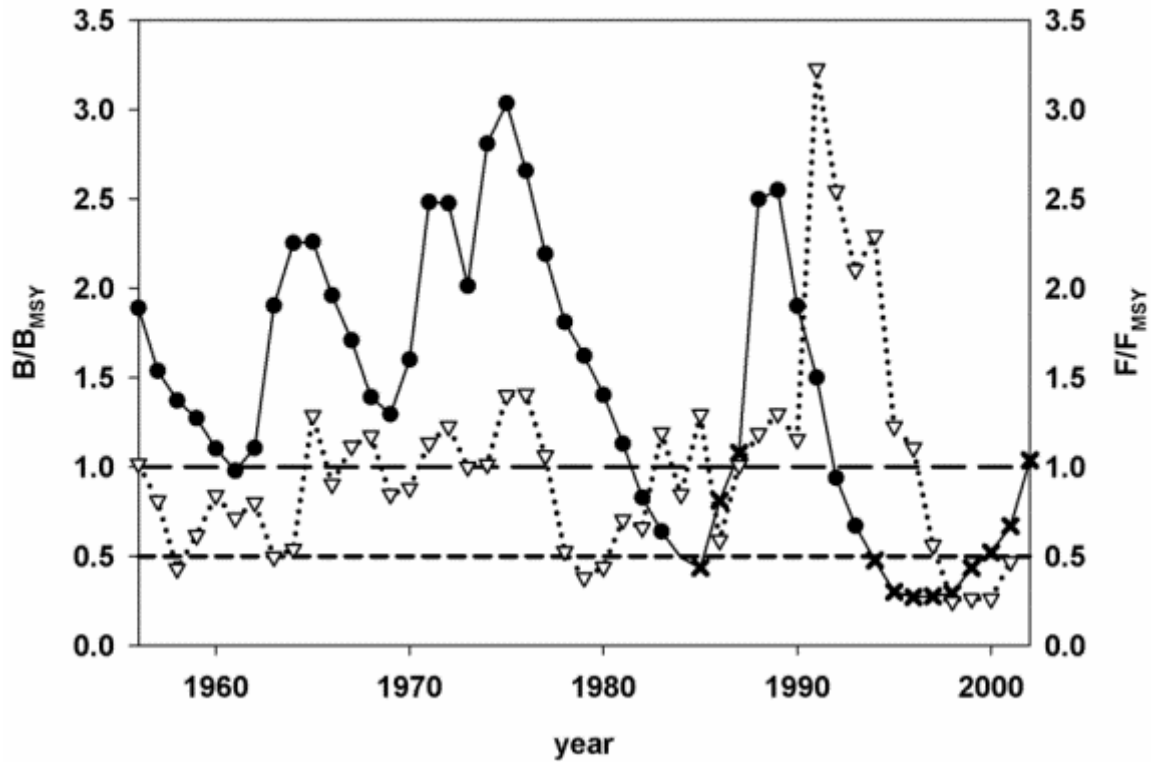
**Fig. S1**

Histograms of covariates used in the analysis. Blue vertical lines indicate mean of covariates over all depletion events.



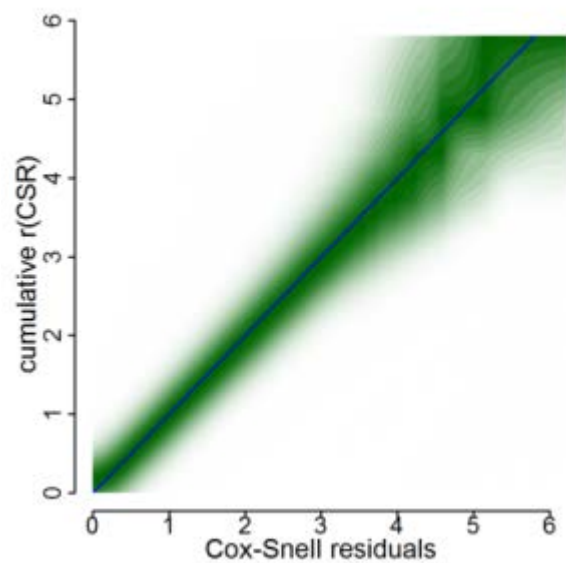
**Fig. S2**

Median predicted recovery times (A) and probability of recovering within 10 years (B) as a function of intrinsic rate of increase ( $r$ ) recovering from collapse at no fishing (light green) and fishing at  $F_{MSY}$  (orange). Areas of overlap between scenarios appear as olive green. For A, relative fishing mortality during the recovery phase is set to zero; all remaining covariates in each plot were fixed at their mean value. Lines are point estimates of median predicted recovery times, shaded regions delimit the 25<sup>th</sup> to the 75<sup>th</sup> percentile of predicted recovery times. For B, lines are median estimates; shaded regions are 95% credible intervals.



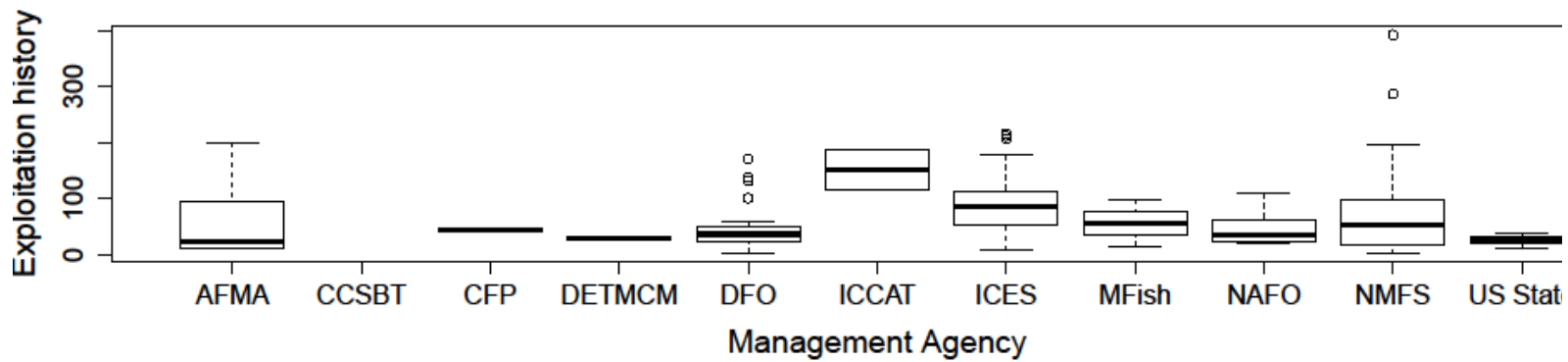
**Fig. S3**

Illustration of definitions used in the analysis. Time series indicate biomass ( $B$  – black circles and solid line) and fishing mortality ( $F$  – open triangles and dotted line) relative to the respective MSY reference points (long dashed line at  $B/B_{MSY}=1$ , short dashed line at  $B/B_{MSY}=0.5$ ) for Pacific cod (*Gadus macrocephalus*) off the west coast of Vancouver Island, Canada. The stock is initially depleted in 1984, and then again in 1994. Each recovery period is marked on the biomass time series by cross symbols as opposed to rounds for all other years.



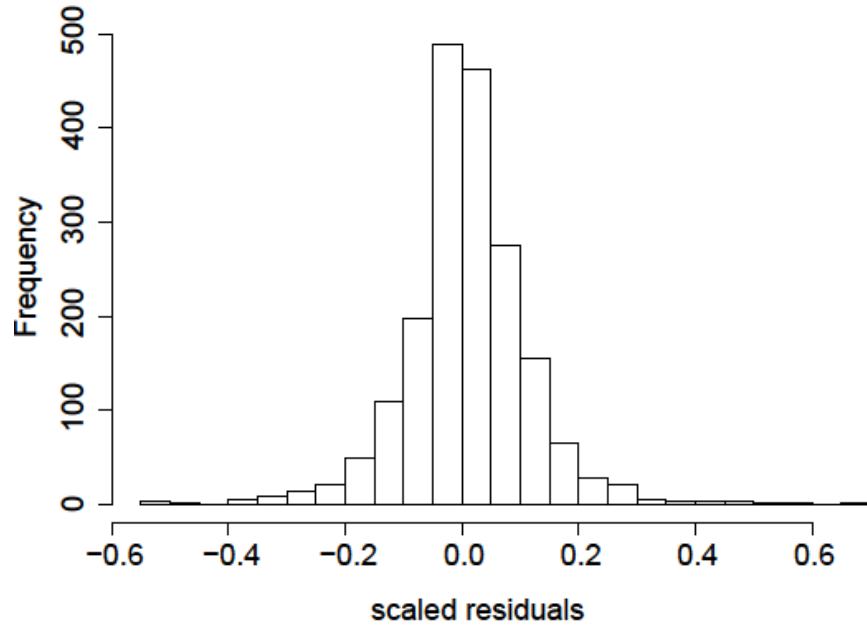
**Fig. S4**

Residual plot for posterior distribution of Cox-Snell residuals (CSR) from the fitted inverse Gaussian model. The posterior distribution of CSRs (green) was estimated using a normal kernel smoother with  $sd=0.2$ . These residuals should scale directly with the estimate of  $r(\text{CSR})$ , as indicated by the blue  $y=x$  line.



**Fig. S5**

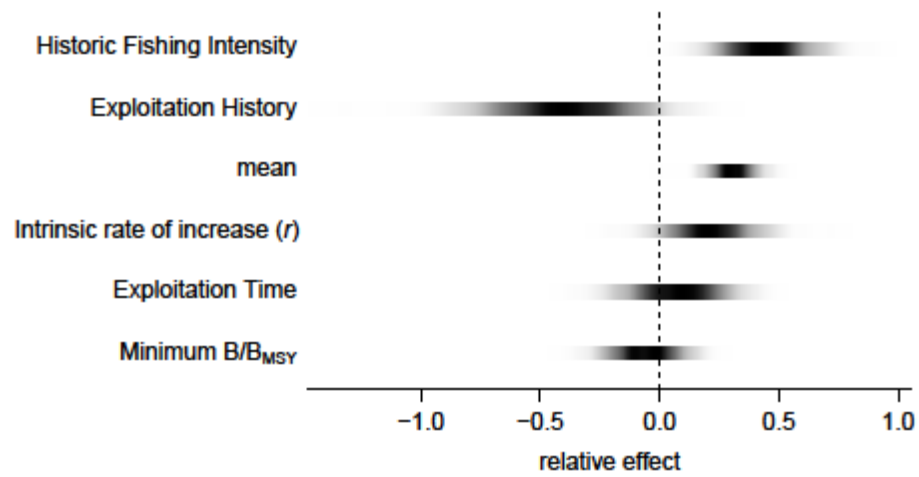
Exploitation history (exploitation time x average relative fishing intensity) prior to depletion among management agencies abbreviated as AFMA: Atlantic Fisheries Management Agency, CCSBT: Commission for the Conservation of Southern Bluefin Tuna, CFP: Consejo Federal Pesquero, Argentina, DETMCM: Department of Environment and Tourism, Marine and Coastal Management, South Africa, DFO: Department of Fisheries and Oceans, Canada, ICCAT: International Commission for the Conservation of Atlantic Tuna, ICES: International Council for the Exploration of the Seas, MFish: Ministry of Fisheries, New Zealand, NAFO: North Atlantic Fisheries Organization, NMFS: National Marine Fisheries Service, USA.



**Fig. S6**

Scaled residual plot for observed minus expected biomass increases from a Graham-Schaefer biomass dynamics model. Expected increases were calculated using reported fishing mortality rates.





**Fig. S7**

Relative importance of predictors of deviations from expected biomass increases from a Graham-Schaefer biomass dynamics model. Positive deviations indicate higher than expected increases in biomass. For a description of predictors, see Fig. 1 of the main text.

**Table S1.**

Stock description, country and last assessed year (Year) in the RAM Stock Assessment Database V.1.0 (with addition of ICES status assessments from 2011), as well as binomial species names, and variables used for the recovery analysis. Depletion events are ordered taxonomically (by genus and species).  $r$  is the intrinsic growth rate of the stock,  $\overline{F_H}$  and  $\overline{F_D}$  are the average relative fishing mortality from the development year to depletion, and during depletion and/or recovery, respectively. Min  $B/B_{MSY}$  is the maximum depletion level,  $t$  is the depletion time used for the analysis. Missing cases indicate that this information was not available from the assessments and was imputed (predicted) in the analysis using the posterior predictive distribution for the variable.

Description	Country	Year	Genus	Species	$r$	Development Year	Year $<0.5 B_{MSY}$	$\overline{F_H}$	$\overline{F_D}$	Min $B/B_{MSY}$	$t$
Sandeel North Sea	Multinational	2007	Ammodytes	marinus	0.89	1962	2003	1.26	1.11	0.29	5
Sablefish Pacific Coast of Canada	Canada	2004	Anoplopoma	fimbria	0.41	1962	1997	-	-	0.27	8
Gulf menhaden Gulf of Mexico	USA	2004	Brevoortia	patronus	0.66	1952	1965	7.27	5.71	0.33	4
Atlantic menhaden Atlantic	USA	2005	Brevoortia	tyrannus	0.53	1940	1963	-	-	0.30	43
Cusk -FO 4X	Canada	2007	Brosme	brosme	0.47	1981	2003	-	-	0.46	5
Black sea bass Mid-Atlantic Coast	USA	2007	Centropristis	striata	0.63	1950	1968	1.90	2.08	0.44	34

Tanner crab Bering Sea and Aleutian Islands	USA	2008	Chionoecetes	bairdi	0.59	1967	1978	0.64	0.36	0.10	31
Snow crab Bering Sea	USA	2008	Chionoecetes	opilio	0.17	1979	1985	-	-	0.20	3
Snow crab Bering Sea	USA	2008	Chionoecetes	opilio	0.17	1979	1999	-	-	0.36	10
New Zealand snapper New Zealand Area 8	New Zealand	2005	Chrysophrys	auratus	0.08	1950	1983	1.68	2.07	0.32	23
Herring ICES VIa- VIb-VIIc	Multinational	2000	Clupea	harengus	0.34	1950	2000	2.00	2.95	0.50	1
Herring ICES VIa	Multinational	2010	Clupea	harengus	0.33	1950	1976	2.37	2.25	0.21	34
Herring North Sea	Multinational	2011	Clupea	harengus	0.34	1950	1996	3.85	2.14	0.46	6
Herring ICES 30	Multinational	2010	Clupea	harengus	0.31	1950	1979	1.11	1.04	0.36	10
Herring ICES 31	Multinational	2006	Clupea	harengus	0.27	1950	1994	2.89	3.41	0.24	13
Herring Northern Irish Sea	Multinational	2010	Clupea	harengus	0.34	1950	1961	2.84	2.68	0.13	9

Herring Northern Irish Sea	Multinational	2010	Clupea	harengus	0.34	1950	1978	2.68	2.31	0.13	33
Atlantic herring Northwestern Atlantic Coast	USA	2005	Clupea	harengus	0.36	1950	1976	1.75	1.40	0.17	16
Herring North Sea	Multinational	2011	Clupea	harengus	0.34	1950	1972	5.07	3.74	0.06	15
Herring ICES 25-32	Multinational	2010	Clupea	harengus	0.27	1950	1996	2.43	2.97	0.33	15
Herring Iceland (Summer spawners)	Multinational	2010	Clupea	harengus	0.33	1950	1989	2.02	1.66	0.36	22
Pacific herring Central Coast	Canada	2007	Clupea	pallasii	0.57	1956	2006	1.15	0.34	0.30	2
Pacific herring West Coast of Vancouver Island	Canada	2007	Clupea	pallasii	0.50	1956	1995	1.00	0.41	0.03	13
Pacific herring Central Coast	Canada	2007	Clupea	pallasii	0.57	1956	1979	1.73	0.06	0.35	2
Pacific herring Strait of Georgia	Canada	2007	Clupea	pallasii	0.54	1956	1958	2.12	1.84	0.43	1

Pacific herring Queen Charlotte Islands	Canada	2007	Clupea	pallasii	0.46	1956	1986	1.63	0.42	0.08	22
Pacific herring Queen Charlotte Islands	Canada	2007	Clupea	pallasii	0.46	1956	1951	2.10	2.58	0.14	5
Pacific herring West Coast of Vancouver Island	Canada	2007	Clupea	pallasii	0.50	1956	1966	1.78	0.86	0.27	8
Pacific herring Central Coast	Canada	2007	Clupea	pallasii	0.57	1956	1968	2.23	0.67	0.13	7
Pacific herring Strait of Georgia	Canada	2007	Clupea	pallasii	0.54	1956	1966	2.32	0.82	0.15	11
Pacific herring Prince Rupert District	Canada	2007	Clupea	pallasii	0.39	1956	1953	3.95	2.31	0.31	10
Pacific herring Queen Charlotte Islands	Canada	2007	Clupea	pallasii	0.46	1956	1958	3.45	1.42	0.03	23
Pacific herring Prince Rupert District	Canada	2007	Clupea	pallasii	0.39	1956	1966	2.83	1.07	0.02	42

Weakfish Atlantic Coast	USA	2008	Cynoscion	regalis	0.60	1950	2002	-	-	0.13	7
Weakfish Atlantic Coast	USA	2008	Cynoscion	regalis	0.60	1950	1990	-	-	0.39	5
Anchovy South Africa	South Africa	2006	Engraulis	encrasicolus	0.43	1965	1989	1.16	0.78	0.29	11
Petrale sole Northern Pacific Coast	USA	2005	Eopsetta	jordani	0.24	1942	1989	-	-	0.45	12
Petrale sole Southern Pacific Coast	USA	2005	Eopsetta	jordani	0.19	1927	1979	-	-	0.25	26
Snowy grouper Southern Atlantic coast	USA	2002	Epinephelus	niveatus	0.45	1975	1987	2.44	3.39	0.19	16
Pacific cod West Coast of Vancouver Island	Canada	2002	Gadus	macrocephalus	0.43	1957	1984	0.89	0.93	0.44	3
Pacific cod Hecate Strait	Canada	2005	Gadus	macrocephalus	0.42	1957	2001	0.62	0.28	0.42	3
Pacific cod Gulf of Alaska	USA	2008	Gadus	macrocephalus	0.40	1965	1977	-	-	0.47	6

Pacific cod West Coast of Vancouver Island	Canada	2002	Gadus	macrocephalus	0.43	1957	1994	1.08	0.80	0.27	8
Atlantic cod Kattegat	Multinational	2010	Gadus	morhua	0.67	1950	1982	3.02	3.24	0.04	29
Atlantic cod Irish Sea	Multinational	2010	Gadus	morhua	0.65	1950	1978	3.31	4.00	0.07	33
Atlantic cod Georges Bank	USA	2007	Gadus	morhua	0.56	1950	1984	2.51	2.62	0.07	24
Atlantic cod Faroe Plateau	Multinational	2011	Gadus	morhua	0.56	1946	1990	1.83	1.47	0.29	5
Atlantic cod Faroe Plateau	Multinational	2011	Gadus	morhua	0.56	1946	2004	1.87	1.81	0.30	8
Atlantic cod coastal Norway	Multinational	2010	Gadus	morhua	0.32	1946	2005	2.67	2.31	0.50	6
Atlantic cod Baltic Areas 25-32	Multinational	2010	Gadus	morhua	0.52	1950	1987	3.65	3.50	0.11	24
Atlantic cod West of Scotland	Multinational	2011	Gadus	morhua	0.63	1950	1990	2.65	2.66	0.11	22
Atlantic cod North Sea	Multinational	2010	Gadus	morhua	0.63	1950	1989	2.36	2.41	0.14	22

Atlantic cod -FO 5Zjm	Canada	2003	Gadus	morhua	0.39	1950	1993	3.22	2.03	0.21	11
Atlantic cod Gulf of Maine	USA	2007	Gadus	morhua	0.52	1893	1983	4.37	3.61	0.19	25
Atlantic cod -FO 3Ps	Canada	2004	Gadus	morhua	0.41	1950	1991	3.20	2.20	0.16	14
Atlantic cod Baltic Areas 25-32	Multinational	2010	Gadus	morhua	0.52	1950	1966	4.04	3.39	0.30	16
Atlantic cod -FO 3NO	Multinational	2007	Gadus	morhua	0.51	1950	1960	2.12	1.47	0.02	48
Atlantic cod -FO 3Pn4RS	Canada	2007	Gadus	morhua	0.34	1950	1988	4.49	3.35	0.04	20
Atlantic cod Iceland	Multinational	2011	Gadus	morhua	0.50	1946	1991	2.40	2.43	0.37	21
Atlantic cod Baltic Areas 22 and 24	Multinational	2011	Gadus	morhua	0.75	1950	1986	2.92	2.85	0.17	26
Atlantic cod Northeast Arctic	Multinational	2010	Gadus	morhua	0.57	1946	1979	2.07	2.42	0.28	30
Witch Flounder - FO-5Y	USA	2007	Glyptocephalus	cynoglossus	0.40	1960	1994	2.89	3.49	0.30	14



New Zealand abalone species New Zealand Area PAU 5D	New Zealand	2006	Haliotis	iris	0.27	1950	2003	1.84	3.87	0.44	4
Flathead sole Bering Sea and Aleutian Islands	USA	2008	Hippoglossoides	elassodon	0.30	1954	1977	-	-	0.14	10
American Plaice -FO-3LNO	Multinational	2007	Hippoglossoides	platessoides	0.18	1957	1986	3.75	4.57	0.04	22
American Plaice -FO-5YZ	USA	2007	Hippoglossoides	platessoides	0.37	1957	1986	2.92	2.49	0.35	22
Atlantic Halibut -FO-5YZ	USA	2007	Hippoglossus	hippoglossus	0.40	1895	1890	1.80	2.19	0.01	118
American lobster Rhode Island	USA	2007	Homarus	americanus	0.67	1950	1959	1.19	1.60	0.06	49
Orange roughy Southeast Australia	Australia	2007	Hoplostethus	atlanticus	0.08	1980	1999	8.16	5.36	0.39	9
Red rock lobster New Zealand area CRA7	New Zealand	2005	Jasus	edwardsii	1.12	1951	1982	-	-	0.09	24
Red rock lobster New Zealand area CRA5	New Zealand	2002	Jasus	edwardsii	0.26	1947	1975	-	-	0.12	28

Red rock lobster New Zealand area CRA4	New Zealand	2005	Jasus	edwardsii	0.59	1945	1977	-	-	0.24	22
Red rock lobster New Zealand area CRA2	New Zealand	2001	Jasus	edwardsii	0.36	1945	1975	-	-	0.19	27
Red rock lobster New Zealand area CRA8	New Zealand	2005	Jasus	edwardsii	1.10	1951	1987	-	-	0.20	19
Red rock lobster New Zealand area CRA1	New Zealand	2001	Jasus	edwardsii	0.34	1948	1974	-	-	0.49	22
Rock sole Hecate Strait	Canada	2001	Lepidopsetta	bilineata	0.51	1947	1945	0.31	1.50	0.33	20
Northern rock sole Eastern Bering Sea and Aleutian Islands	USA	2007	Lepidopsetta	polyxystra	0.35	1971	1975	0.84	0.61	0.16	14
Fourspotted megrim ICES VIIIc-IXa	Multinational	2010	Lepidorhombus	boscii	0.37	1986	2000	1.92	1.66	0.47	11
Megrim ICES VIIIc-IXa	Multinational	2010	Lepidorhombus	whiffiagonis	0.32	1950	1994	1.85	1.52	0.24	17
Yellowfin sole Bering Sea and Aleutian Islands	USA	2008	Limanda	aspera	0.40	1977	1964	3.20	2.37	0.18	15

Yellowtail Flounder - FO 3LNO	Multinational	2009	Limanda	ferruginea	0.51	1961	1976	1.44	1.18	0.20	23
Yellowtail Flounder Southern New England- Mid Atlantic	USA	2007	Limanda	ferruginea	0.52	1939	1974	5.58	5.26	0.02	34
Yellowtail flounder Cape Cod / Gulf of Maine	USA	2007	Limanda	ferruginea	0.51	1941	1985	6.53	6.33	0.09	23
Yellowtail flounder Georges Bank	USA	2007	Limanda	ferruginea	0.57	1948	1974	4.36	4.08	0.05	34
Tilefish Mid-Atlantic Coast	USA	2005	Lopholatilus	chamaeleonticeps	0.43	1950	1988	1.50	1.35	0.27	18
Mutton snapper Southern Atlantic coast and Gulf of Mexico	USA	2006	Lutjanus	analis	0.44	1966	1994	-	-	0.48	11
Red snapper Western Gulf of Mexico	USA	2003	Lutjanus	campechanus	0.38	1950	1988	-	-	0.32	16
Red snapper Southern Atlantic coast	USA	2006	Lutjanus	campechanus	0.44	1950	1968	4.80	7.53	0.02	39

Red snapper Eastern Gulf of Mexico	USA	2003	Lutjanus	campechanus	0.39	1876	1984	-	-	0.08	20
Hoki Western New Zealand	New Zealand	2007	Macruronus	novaezelandiae	0.49	1977	2003	0.58	1.10	0.34	5
Capelin Iceland	Multinational	2006	Mallotus	villosus	0.66	1970	2005	-	-	0.40	2
Capelin Iceland	Multinational	2006	Mallotus	villosus	0.66	1970	1980	-	-	0.42	4
Capelin Barents Sea	Multinational	2006	Mallotus	villosus	0.59	1970	1985	-	-	0.02	6
Capelin Barents Sea	Multinational	2006	Mallotus	villosus	0.59	1970	1993	-	-	0.04	14
Haddock Faroe Plateau	Multinational	2010	Melanogrammus	aeglefinus	0.46	1950	2008	1.84	1.26	0.31	3
Haddock ICES IIIa and North Sea	Multinational	2010	Melanogrammus	aeglefinus	0.51	1950	2010	3.60	1.11	0.38	1
Haddock ICES IIIa and North Sea	Multinational	2010	Melanogrammus	aeglefinus	0.51	1950	2003	3.90	1.23	0.47	2
Haddock ICES IIIa and North Sea	Multinational	2010	Melanogrammus	aeglefinus	0.51	1950	2007	3.71	1.33	0.36	2

Haddock Faroe Plateau	Multinational	2010	Melanogrammus	aeglefinus	0.46	1950	1991	1.89	1.22	0.29	5
Haddock - FO-4X5Y	Canada	2003	Melanogrammus	aeglefinus	0.43	1941	1973	1.49	2.32	0.45	5
Haddock - FO-5Y	USA	2007	Melanogrammus	aeglefinus	0.39	1941	1986	3.34	3.97	0.09	12
Haddock Northeast Arctic	Multinational	2010	Melanogrammus	aeglefinus	0.59	1950	1977	1.66	1.22	0.16	16
Haddock West of Scotland	Multinational	2006	Melanogrammus	aeglefinus	0.54	1950	1990	1.95	2.37	0.44	10
Haddock ICES IIIa and North Sea	Multinational	2010	Melanogrammus	aeglefinus	0.51	1950	1988	4.31	4.00	0.37	11
Haddock Georges Bank	USA	2007	Melanogrammus	aeglefinus	0.49	1941	1933	-	-	0.44	28
Haddock Georges Bank	USA	2007	Melanogrammus	aeglefinus	0.49	1941	1968	-	-	0.09	38
Haddock - FO-4X5Y	Canada	2003	Melanogrammus	aeglefinus	0.43	1941	1987	2.19	1.05	0.33	17
Haddock Iceland	Multinational	2011	Melanogrammus	aeglefinus	0.55	1950	1983	2.11	2.02	0.29	29

Haddock - FO-5Zejm	Canada	2003	Melanogrammus	aeglefinus	0.41	1941	1970	1.74	1.50	0.21	32
Whiting ICES VIIe-k	Multinational	2010	Merlangius	merlangus	0.53	1951	2006	3.01	2.76	0.42	5
Whiting ICES VIIe-k	Multinational	2010	Merlangius	merlangus	0.53	1951	1982	3.79	3.80	0.37	11
Argentine hake Northern Argentina	Argentina	2007	Merluccius	hubbsi	0.86	1967	1988	1.97	2.03	0.12	20
Argentine hake Southern Argentina	Argentina	2008	Merluccius	hubbsi	0.93	1967	1999	1.46	1.77	0.31	10
Hake Northeast Atlantic North	Multinational	2010	Merluccius	merluccius	0.49	1950	1981	3.60	3.47	0.19	30
Deep-water cape hake South Africa	South Africa	2008	Merluccius	paradoxus	0.61	1952	1981	-	-	0.48	15
Whiting Northeast Atlantic	Multinational	2007	Micromesistius	poutassou	0.38	1979	2007	2.26	-	0.41	1
Whiting Northeast Atlantic	Multinational	2007	Micromesistius	poutassou	0.38	1979	1981	2.06	2.13	0.25	21
Atlantic croaker Mid- Atlantic Coast	USA	2002	Micropogonias	undulatus	0.51	1954	1973	0.74	0.54	0.21	14

Gag Gulf of Mexico	USA	2004	Mycteroperca	microlepis	0.31	1975	1979	1.22	1.76	0.44	26
Jackass morwong Southeast Australia	Australia	2007	Nemadactylus	macropterus	0.12	1946	1997	3.93	4.26	0.26	11
Tiger flathead Southeast Australia	Australia	2006	Neoplatycephalus	richardsoni	0.24	1919	1949	1.24	0.25	0.39	31
Red porgy Southern Atlantic coast	USA	2004	Pagrus	pagrus	0.16	1972	1990	1.93	2.17	0.26	15
Northern shrimp Gulf of Maine	USA	2009	Pandalus	borealis	0.61	1968	1998	0.50	0.38	0.26	8
Summer flounder Mid-Atlantic Coast	USA	2007	Paralichthys	dentatus	0.44	1950	1982	-	-	0.12	26
Red king crab Pribilof Islands	USA	2009	Paralithodes	camtschaticus	0.72	1950	1983	-	-	0.01	11
Red king crab Bristol Bay	USA	2008	Paralithodes	camtschaticus	0.22	1950	1985	3.98	2.51	0.39	17
Blue king crab Pribilof Islands	USA	2008	Paralithodes	platypus	0.60	1975	2000	-	-	0.03	9
Blue king crab Saint Matthews Island	USA	2008	Paralithodes	platypus	0.59	1975	1985	-	-	0.37	5

Blue king crab Pribilof Islands	USA	2008	Paralithodes	platypus	0.60	1975	1986	-	-	0.15	10
Blue king crab Saint Matthews Island	USA	2008	Paralithodes	platypus	0.59	1975	1999	-	-	0.37	8
English sole Hecate Strait	Canada	2001	Parophrys	vetulus	0.64	1948	1961	1.44	1.32	0.40	6
Sea scallop Georges Bank	USA	2006	Placopecten	magellanicus	0.55	1953	1982	3.46	2.58	0.12	19
Sea scallop Mid-Atlantic Coast	USA	2006	Placopecten	magellanicus	0.58	1953	1975	1.14	2.13	0.09	31
Starry flounder Southern Pacific Coast	USA	2005	Platichthys	stellatus	0.36	1970	1980	-	-	0.34	5
European Plaice ICES VIIe	Multinational	2010	Pleuronectes	platessa	0.54	1950	2009	2.37	1.74	0.48	1
European Plaice ICES VIIIf-g	Multinational	2006	Pleuronectes	platessa	0.65	1950	2002	1.84	1.89	0.42	5
European Plaice Irish Sea	Multinational	2006	Pleuronectes	platessa	0.59	1950	1995	1.37	0.64	0.45	11
European Plaice Irish Sea	Multinational	2006	Pleuronectes	platessa	0.59	1950	1976	-	-	0.39	12



Pollock -FO-4X5YZ	Canada	2006	Pollachius	virens	0.47	1980	1994	2.19	2.07	0.18	13
Pollock Northeast Arctic	Multinational	2010	Pollachius	virens	0.52	1950	1984	1.53	1.73	0.33	15
Pollock ICES IIIa, VI and North Sea	Multinational	2010	Pollachius	virens	0.44	1950	1967	2.28	2.03	0.26	44
Pollock Faroe Plateau	Multinational	2010	Pollachius	virens	0.40	1950	1961	0.61	1.56	0.44	26
Winter Flounder Southern New England-Mid Atlantic	USA	2007	Pseudo-pleuronectes	americanus	0.53	1950	1981	3.66	3.58	0.05	27
Winter Flounder - FO-5Z	USA	2006	Pseudo-pleuronectes	americanus	0.58	1950	1985	2.44	2.03	0.21	22
Winter flounder Rhode Island	USA	2007	Pseudo-pleuronectes	americanus	0.49	1950	1971	1.83	1.87	0.15	37
Greenland halibut -FO 23KLMNO	Multinational	2006	Reinhardtius	hippoglossoides	0.34	1964	1995	2.02	2.57	0.38	12
Greenland halibut Northeast Arctic	Multinational	2010	Reinhardtius	hippoglossoides	0.27	1964	1975	2.25	1.92	0.15	36
Arrowtooth flounder Gulf of Alaska	USA	2010	Reinhardtius	stomias	0.11	1955	1961	-	-	0.46	20

common gemfish Southeast Australia	Australia	2007	Rexea	solandri	0.14	1974	1991	0.62	0.35	0.13	17
Sardine South Africa	South Africa	2006	Sardinops	sagax	0.52	1977	1984	-	0.56	0.06	13
Pacific chub mackerel Pacific Coast	USA	2008	Scomber	japonicus	0.40	1929	2000	-	-	0.22	9
Pacific chub mackerel Pacific Coast	USA	2008	Scomber	japonicus	0.40	1929	1948	-	-	0.09	29
Atlantic mackerel Gulf of Maine / Cape Hatteras	USA	2004	Scomber	scombrus	0.39	1965	1962	0.27	0.45	0.46	6
Spanish mackerel Southern Atlantic Coast	USA	2007	Scomberomorus	maculatus	0.38	1951	1961	2.36	2.33	0.15	47
Cabazon Southern California	USA	2005	Scorpaenichthys	marmoratus	0.28	1972	1983	1.18	1.86	0.13	23
Pacific ocean perch Pacific Coast	USA	2007	Sebastes	alutus	0.07	1962	1994	1.76	0.64	0.46	14
Pacific Ocean perch Eastern Bering Sea and Aleutian Islands	USA	2009	Sebastes	alutus	0.24	1963	1977	-	-	0.22	19

Pacific ocean perch Gulf of Alaska	USA	2010	Sebastes	alutus	0.14	1963	1977	-	-	0.23	21
Darkblotched rockfish Pacific Coast	USA	2007	Sebastes	crameri	0.06	1951	1994	1.62	1.68	0.35	14
Acadian redfish Gulf of Maine / Georges Bank	USA	2007	Sebastes	fasciatus	0.20	1936	1957	-	-	0.03	51
Cowcod Southern California	USA	2007	Sebastes	levis	0.22	1916	1981	2.36	6.19	0.04	27
Blue rockfish California	USA	2007	Sebastes	mystinus	0.20	1951	1985	1.48	1.83	0.25	23
Bocaccio Southern Pacific Coast	USA	2006	Sebastes	paucispinis	0.23	1951	1960	2.16	1.67	0.47	5
Bocaccio Southern Pacific Coast	USA	2006	Sebastes	paucispinis	0.23	1951	1984	2.52	2.25	0.14	23
Canary rockfish Pacific Coast	USA	2009	Sebastes	pinniger	0.18	1944	1992	0.68	0.74	0.32	18
Yelloweye rockfish Pacific Coast	USA	2006	Sebastes	ruberrimus	0.07	1951	1994	3.55	4.16	0.31	13
Redfish species -FO 3LN	Multinational	2008	Sebastes	spp	0.35	1959	1992	1.06	0.67	0.35	8

Dusky rockfish Gulf of Alaska	USA	2007	Sebastes	variabilis	0.15	1951	1978	0.34	0.47	0.46	19
Blue Warehouse Eastern half of Southeast Australia	Australia	2006	Seriolella	brama	0.38	1987	2001	0.70	0.55	0.42	6
Blue Warehouse Western half of Southeast Australia	Australia	2006	Seriolella	brama	0.42	1987	1994	1.43	2.13	0.21	13
School whiting Southeast Australia	Australia	2007	Sillago	flindersi	0.48	1974	2000	0.90	0.93	0.49	8
common European sole Irish Sea	Multinational	2011	Solea	vulgaris	0.43	1950	2004	1.97	1.53	0.24	8
common European sole ICES Kattegat and Skagerrak	Multinational	2010	Solea	vulgaris	0.49	1950	1984	1.38	1.38	0.33	6
common European sole Western English Channel	Multinational	2010	Solea	vulgaris	0.32	1950	1969	0.85	1.74	0.48	42
Sprat ICES Baltic Areas 22-32	Multinational	2010	Sprattus	sprattus	0.44	1966	1979	2.04	1.36	0.33	4
Sprat ICES Baltic Areas 22-32	Multinational	2010	Sprattus	sprattus	0.44	1966	1986	1.67	1.41	0.35	6

Tautog Rhode Island	USA	2007	Tautoga	onitis	0.54	1976	1992	1.61	1.20	0.34	16
Walleye pollock Eastern Bering Sea	USA	2008	Theragra	chalcogramma	0.53	1967	1964	0.38	1.00	0.23	18
Southern bluefin tuna Southern Oceans	Multinational	2009	Thunnus	maccoyii	0.37	1978	1990	-	-	0.17	20
Bluefin tuna Eastern Atlantic	Multinational	2007	Thunnus	thynnus	0.40	1950	2004	3.47	5.91	0.34	4
Bluefin tuna Western Atlantic	Multinational	2007	Thunnus	thynnus	0.35	1950	1989	2.99	1.68	0.43	19
Norway pout North Sea	Multinational	2010	Trisopterus	esmarkii	0.50	1968	2003	3.27	1.80	0.32	5
White hake Georges Bank / Gulf of Maine	USA	2007	Urophycis	tenuis	0.29	1950	1994	1.51	1.86	0.24	14
White hake Georges Bank / Gulf of Maine	USA	2007	Urophycis	tenuis	0.29	1950	1963	1.30	0.81	0.36	12

**Table S2.**

Quantiles of regression parameter posterior distributions for standardized predictors of recovery schedules. The table is divided into predictors of the recovery rate, the relative distance from recovery target, and the lower level regression for Minimum B/B<sub>MSY</sub>. Median point estimates appear in bold.

Parameter	Predictor	Estimate			
		2.5%	<b>Median</b>	97.5%	$P(\beta > 0)$
recovery rate (v)	F/F <sub>MSY</sub>	-0.40	<b>-0.24</b>	-0.11	0.00
	Exploitation History	-0.35	<b>-0.21</b>	0.07	0.07
	Exploitation Time	-0.19	<b>0.15</b>	0.30	0.84
	Intrinsic Rate of Increase	0.04	<b>0.14</b>	0.28	1.00
	Historic Fishing Intensity	-0.08	<b>0.07</b>	0.23	0.83
	Trophic Level	-0.17	<b>-0.05</b>	0.06	0.21
	Habitat	-0.08	<b>0.02</b>	0.14	0.66
	Minimum B/B <sub>MSY</sub>	-0.08	<b>0.02</b>	0.12	0.65
relative distance from recovery target (c)	Minimum B/B <sub>MSY</sub>	-0.59	<b>-0.43</b>	-0.26	0.00
	Historic Fishing Intensity	-0.33	<b>-0.19</b>	-0.03	0.01
	Habitat	-0.23	<b>-0.08</b>	0.10	0.21
	Exploitation Time	-0.22	<b>-0.05</b>	0.15	0.34
	Trophic Level	-0.13	<b>0.04</b>	0.23	0.63
	Exploitation History	-0.24	<b>0.00</b>	0.28	0.50