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The effect of reduced data on the ability to monitor rebuilding of overfished fish stocks

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Abstract—Several rockfish stocks off the U.S. west coast are below target biomass and are managed under rebuilding plans that severely limit the allowable harvest. Limited harvest, however, reduces the opportunity to collect fishery-dependent data, which are the primary source of information on changes in abundance for species poorly sampled by fishery-independent methods. A simulation study was conducted by using an operating model to evaluate the effect of reduced data on estimation of spawning biomass and biological parameters during rebuilding of a stock. Decreased availability of data during rebuilding resulted in increased among-simulation variation in estimates of spawning biomass. Additionally, decreased data resulted in reduced average catches and increased interannual variation in catches during rebuilding compared with averages of and variation in catches when data collection was maintained at higher levels. The presence of time-varying parameters in the operating model that were not accounted for within the estimation method resulted in increased among-simulation variability in spawning biomass than with the time-invariant case, and the largest increase in variability occurred during stock rebuilding when data were reduced or eliminated. Retaining data collections at historical levels allowed improved parameter estimation during rebuilding, resulting in reduced variability in estimated stock size, increased average catches during rebuilding, and in reduced frequency of stocks being prematurely estimated as rebuilt.

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In the United States, federally managed stocks that fall below a minimum stock size threshold (MSST) are declared overfished and are mandated to be rebuilt to target biomass levels in the shortest amount of time, accounting for present biological and environmental conditions (Sustainable…1996; National…2016). In the absence of an unexpected run of good recruitment, rebuilding overfished stocks requires a reduction in fishing mortality to a level that allows stock biomass to increase and therefore leads to substantial reductions in fishing effort in relation to historical levels. The severity of management restrictions during rebuilding can, for some stocks, lead to a situation where the ability to collect data becomes limited when the stock is under a rebuilding plan, a period when managers are likely most concerned about stock size and trends in biomass.

Overfished rockfish species off the U.S. west coast have experienced large reductions in harvest during rebuilding. One example, yelloweye rockfish (*Sebastes ruberrimus*), was declared overfished in 2002 (Methot and Piner[1]). Similar to other rockfish species off the U.S. west coast, catches of yelloweye rockfish were unsustainable during the 1980s and early 1990s. Catches of yelloweye rockfish decreased dramatically in relation to historical catches after the overfished declaration, and the allowable catch during the first year of rebuilding fell to approximately 10% of the catch from 4 years earlier (Stewart et al.[2]). Yelloweye rockfish is one notable example of an overfished west coast rockfish species that has experienced similar large reductions in harvest during rebuilding. Other examples include the cowcod (*Sebastes levis*; Dick and MacCall[3]), canary

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[1] Methot, R., and K. Piner. 2002. Rebuilding analysis for yelloweye rockfish: update to incorporate results of coastwide assessment in 2002, 11 p. Pacific Fishery Management Council, Portland, OR. [Available from website.]

[2] Stewart, I. J., J. R. Wallace, and C. McGilliard. 2009. Status of the U.S. yelloweye rockfish resource in 2009, 235 p. Pacific Fishery Management Council, Portland, OR. [Available from website.]

[3] Dick, E. J., and A. MacCall. 2014. Sta-

Table 1

Life-history and observation parameters used in the operating model and their treatment within the estimation method to simulate a rockfish life-history type common to the west coast of the United States.

Parameter	Time-invariant	Time-varying	Treatment in estimation method
Natural mortality (M) per year	0.08	0.08	Fixed
Natural mortality standard error (σ_m)	0	0.10	
Natural mortality autocorrelation (ρ)	0	0.707	
Steepness (h)	0.65	0.65	Estimated
Maximum length (L_∞) (cm)	64	64	Estimated
Growth coefficient (K)	0.05	0.05	Estimated
Weight at length $w_l = \alpha L^\beta$ (kg)	α=0.50×10^{-5}, β=3	α=1.50×10^{-5}, β=3	Fixed
Length at 50% maturity (cm)	37	37	Fixed
Recruitment variation (σ_R)	0.50	0.50	Fixed
Fishery CPUE standard error (σ_f)	0.30	0.30	Fixed
Fishery CPUE catchability coefficient (Q_f)	0.01	0.01	Analytically estimated
Width at maximum selectivity (cm)	−3	−3	Estimated
Width at maximum selectivity standard error (σ_w)	0	0.20	
Size at maximum selectivity (cm)	45	45	Estimated
Size at maximum selectivity standard error (σ_s)	0	0.05	

rockfish (*Sebastes pinniger*; Thorson and Wetzel[4]), and Pacific ocean perch (*Sebastes alutus*; Hamel and Ono[5]).

The reduction of fishery catch, and of the resulting fishery data during rebuilding, presents a challenge for assessment and management of rebuilding stocks. Many species of rockfish off the U.S. west coast (e.g., cowcod, yelloweye rockfish) are not reliably sampled by the main fishery-independent survey, the NOAA Northwest Fisheries Science Center's West Coast groundfish bottom trawl survey, either because of the inability of the survey to sample rocky habitat with trawl gear or because of other restrictions on sampling locations. Because these species are not well sampled, the majority of historical information (e.g., length and age data) available for assessment comes primarily from recreational and commercial fishery samples. Yet, because of restrictions on retention of fish triggered by rebuilding plans, often, recreational and commercial fishery behavior has been profoundly altered (Stewart et al.[2]). In the most recent assessment of yelloweye rockfish, limited fishery data during rebuilding were cited as a challenge to "produce conclusive information about the stock for the foreseeable future" (Stewart et al.[2]). Another overfished rockfish species, cowcod, was assessed most recently by using a data-moderate approach that did not include length or age data instead of the historical data-rich integrated assessment because of lack of data during the rebuilding period. Often fishermen avoid targeting stocks during rebuilding efforts for rockfish species even as harvest limits increase with rebuilding populations and this precaution results in harvests that are well below the rebuilding harvest limits and in continued low levels of biological samples from the fishery catch. Additionally, harvest restrictions can affect the harvest of more abundant fish stocks that co-occur with rebuilding stocks and can result in reduced data availability that extends beyond a single species.

Despite a limited harvest of a stock, continued data collection is necessary to determine the extent to which that stock has rebuilt. The ability to measure the rate of recovery is crucial for management, and increased uncertainty due to limited data can impede the determination of whether a stock is on track to rebuild in a specified time frame. Additionally, biological data are critical for improvement of estimates of key parameters within stock assessments (e.g., natural mortality; growth; recruitment compensation, which is termed *steepness*) and can indicate incoming poor or strong recruitment year classes that will affect estimates of relative stock biomass (the ratio of current biomass to unfished biomass) and rebuilding rates. Potential improvements in parameter estimates and the ability to detect incoming fluctuations in recruitment during rebuilding are restricted when collection

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tus and productivity of Cowcod, *Sebastes levis*, in the Southern California Bight, 2013, 166 p. Fish Ecol. Div., Southwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Santa Cruz, CA. [Available from website.]

[4] Thorson, J. T., and C. Wetzel. 2016. The status of canary rockfish (*Sebastes pinniger*) in the California Current in 2015, 241 p. Northwest Fish. Sci. Cent., Natl. Mar. Fish. Serv., NOAA, Seattle, WA. [Available from website.]

[5] Hamel, O. S., and K. Ono. 2011. Stock assessment of Pacific ocean perch in waters off of the U.S. West Coast in 2011, 135 p. Pacific Fishery Management Council, Portland, OR. [Available from website.]

of new biological data is severely limited because of harvest restrictions.

An understanding of the long-term effect of reduced data on the ability to monitor a stock during rebuilding would provide insight and guidance for management. Numerous simulation studies have evaluated the impact of data quality and quantity on the performance of stock assessment methods (e.g., Hilborn, 1979; Chen et al., 2003; Yin and Sampson, 2004; Magnusson and Hilborn, 2007; Wetzel and Punt, 2011; Lee et al., 2012); however, studies often focus on the ability to estimate either management quantities or biological parameters. The simulation performed in our study evaluated the ability to accurately monitor rebuilding of an overfished, long-lived rockfish stock for which harvest and the collection of fishery data are restricted during rebuilding. This simulation study addressed 3 main questions: 1) Do limited data result in increased uncertainty that affects the ability to detect when an overfished stock has rebuilt, 2) Can limited data from the fishery be used to detect a shift in fishery selectivity that results from changing fishing behavior during rebuilding, and 3) How are model estimates of stock size and biological parameters affected during periods of limited data?

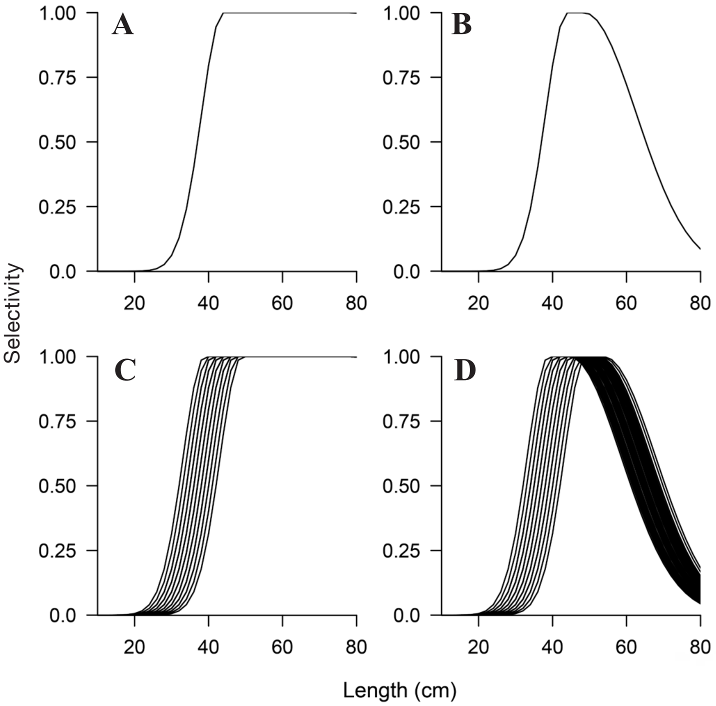

Figure 1

Fishery selectivity for the time-invariant case during (**A**) the historical and rebuilt periods and (**B**) the overfished period and for the time-varying case during the (**C**) historical and rebuilt periods and the (**D**) overfished period. These 2 alternative cases were used in the operating model to account for the potential effects of time-varying natural mortality and fishery selectivity on simulated rockfish stocks. A standard error of 0.05 was applied annually for size at maximum selectivity, which defined the variability of the ascending limb of the selectivity curve (in panels C and D, and a standard error of 0.20 was applied for the width at maximum selectivity that defined the length at which the dome in selectivity began while the stock was estimated to be overfished (in panel D) (for additional details on double normal selectivity, see Methot and Wetzel, 2013).

Materials and methods

General approach

A rockfish life-history type common to the U.S. west coast was simulated (Table 1). West coast rockfish species are assumed to have a range of natural mortality and productivity levels, from long-lived and slow growing (e.g., yelloweye rockfish) to medium-lived and intermediate-growing life histories (e.g., black rockfish [*Sebastes melanops*]). The operating model was parameterized by using intermediate natural mortality and steepness values to represent the general life-history dynamics of a U.S. west coast rockfish species.

Two alternative cases were simulated by using the operating model to account for the potential impacts of time-varying natural mortality and fishery selectivity. The first case, referred to as *time-invariant*, involved a single fixed rate of natural mortality over the entire time period. The fishery selectivity was assumed (and fixed) to be asymptotic during the historical period, dome-shaped during the overfished period, and then again asymptotic after the simulated stock was rebuilt (Fig. 1, A and B). The simulated stocks were reduced to an overfished state (below MSST) at the time of the first assessment in year 50. The shift in selectivity during the period in which the simulated stock was estimated to be overfished was designed to represent potential changes in fishing behavior that result from harvest restrictions that could affect the estimation performance, if not detected because of lack of data to inform the model about the shape of fishery selectivity.

The second case, referred to as *time-varying*, involved annual deviations in natural mortality and in the parameters on which the fishery selectivity pattern was based during the historical, overfished, and rebuilt periods (Fig. 1, C and D). All time-varying parameters were designed to produce data that would be less informative about either the biology or the fishery behavior and to better emulate the complexity of real fishery data. Annual deviations in fishery selectivity were applied to 2 selectivity parameters: 1) the length bin (in centimeters) at which the as-

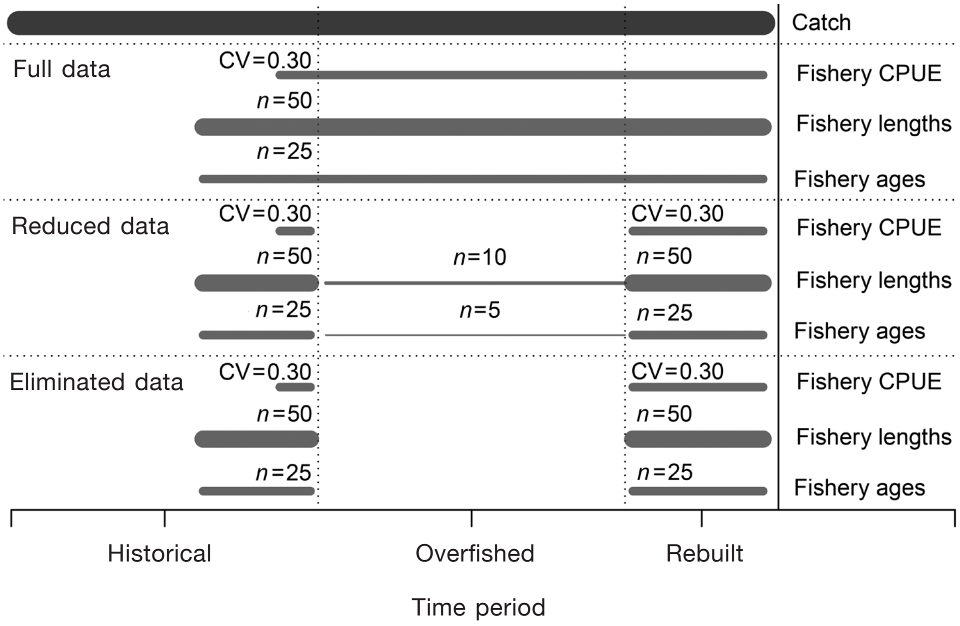

Figure 2

Summary of the data available for each of the 3 data scenarios (full data, reduced data, and eliminated data) created to explore the impact of data availability on the ability to monitor rebuilding of an overfished stock of rockfish species: coefficient of variation (CV) and number of samples (n) for catch per unit of effort (CPUE), lengths, and ages from the fishery. Historical length and age data from the fishery begin in year 35, 15 years before the first assessment, and the fishery CPUE data start in year 45. The management period begins in year 50 when data quantity and quality change by data scenario. Data quantity and quality return to historical levels when the simulated stock has been estimated to be rebuilt to the target biomass. Thickness of the horizontal lines reflects the different sample sizes; all fishery data are shown in dark gray and catches are shown in black. Catches were known without error and were available for all data scenarios.

cending limb of selectivity curve reached maximum selectivity (termed *size at maximum selectivity*, Fig. 1C, Fig. 2) the width of the plateau for the maximum selectivity (defined as a logistic function between the peak and the maximum length bin) that results in a dome-shaped selectivity curve (termed *width at maximum selectivity*, Fig. 1D) during the years the simulated stock was overfished. A standard error of 0.05 was applied annually for the size at maximum selectivity parameter for all years, and a standard error of 0.20 was applied for the width at maximum selectivity parameter during the years the simulated stock was estimated to be overfished. The level of variation for each parameter was selected to ensure that the ascending limb of the selectivity curve was greater than the length at 50% maturity (37 cm) within the operating model and that the width of maximum selectivity (the parameter that creates the dome-shaped curve) was small enough to allow potential detection by the estimation method (a portion of the population with reduced selectivity that is detected because of a dome-shaped curve). Additionally, autocorrelated annual deviations in natural mortality were applied to the population within the operating model.

The operating model was a single-sex, age-structured model in which an annual index of fishery catch per unit of effort (CPUE) was observed with error and in which length- and age-composition data were collected for select years. These data were used by the estimation method to estimate population size and a catch level. The catches were removed without error from the simulated stock. Data generation, catch estimation, and simulated stock updating were conducted in an iterative fashion for 100 years (termed the *management period*), a length of time that would allow the simulated stock to recover to at least the target biomass.

The operating model

The numbers-at-age at the start of the year are computed with the following equation:

$$N_{t+1,a}=\begin{cases} R_t & \text{if } a=0 \\ N_{t,a-1}e^{-(M_t+S_{t,a-1}F_t)} & \text{if } 1\le a<A-1, \\ N_{t,A-1}e^{-(M_t+S_{t,A-1}F_t)}+N_{t,A-1}e^{-(M_t+S_{t,A}F_t)} & \text{if } a=A \end{cases} \quad (1)$$

where $N_{t,a}$ = the number of fish of age at the start of the year t;
R_t = the number of age-0 fish at the start of year t;
$S_{t,a}$ = the selectivity during year t for fish of age a;
A = the plus group (i.e., the oldest age group modeled, set equal to age 70);
F_t = the instantaneous fishing mortality rate during year t; and
M_t = the instantaneous rate of natural mortality during year t.

Natural mortality for year is defined as

$$M_t = Me^{-0.5\sigma_M^2+\varepsilon_t^M}, \quad (2)$$

where M = the mean value of natural mortality;
σ_M = the standard error of the annual deviations in natural mortality; and
ε_t^M = the autocorrelated lognormal deviation in natural mortality for year t:

$$\varepsilon_t^M = \rho\varepsilon_{t-1}^M + \sqrt{1-\rho^2\phi_t}\ \phi_t \sim N(0;\sigma_M^2), \quad (3)$$

where ρ = the level of autocorrelation associated with natural mortality; and
ϕ_t = the deviation in natural mortality for year t. The time-invariant natural mortality case assumed σ_M=0 and hence ε_t^M=0.

The number of age-0 fish is related to spawning biomass according to the Beverton–Holt stock recruitment relationship (Beverton and Holt, 1957):

$$R_t = \frac{4hR_0SB_t}{SB_0(1-h)+SB_t(5h-1)}e^{-0.5\sigma_R^2+\varepsilon_t^R}\ \varepsilon_t^R \sim N(0;\sigma_R^2), \quad (4)$$

where R_0 = the number of age-0 fish when the population is in an unfished state;
SB_0 = the unfished spawning biomass;
SB_t = the spawning biomass at the start of the spawning season in year t;
σ_R = the standard deviation of recruitment in log space; and
h = steepness.

A nonequilibrium starting condition was created by applying the numbers-at-age (combined with the natural mortality calculations for the number of years equal to the maximum age before the start of fishing) with variation in recruitment from the Beverton–Holt stock recruitment relationship. Historical catches for years 1–50 were generated so that the populations were at $0.15SB_0$ in year 50, a state that would allow correct detection by the estimation method that the simulated stocks were in an overfished state. Additionally, the simulated populations would require an extended number of years for the simulated stock to rebuild to the target biomass when a period of reduced data could affect the performance of the estimation method to correctly estimate the stock size and status. The catch of fish of age a during year t in numbers was given by

$$C_{t,a} = \frac{S_{t,a}F_t}{M_t+S_{t,a}F_t}N_{t,a}(1-e^{-M_t-S_{t,a}F_t}). \quad (5)$$

The observation model was used to generate a fishery CPUE index for each year t:

$$I_t = QB_te^{-0.5\sigma_f^2+\varepsilon_t^f}\ \varepsilon_t^f \sim N(0;\sigma_f^2), \quad (6)$$

where Q = the catchability coefficient;
σ_f = the standard deviation of catchability in log space; and
B_t = the vulnerable biomass available to the fishery in the middle of year t:

$$B_t = \Sigma_{a=1}^{A}w_aS_{t,a}N_{t,a}e^{-0.5(M_t+S_{t,a}F_t)}, \quad (7)$$

where w_a = the weight of a fish of age a.

The length- and age-composition data for the fishery were assumed to be multinomially distributed (for details, see the "Data scenarios" section). Age-determination error was assumed to be normally distributed with ages subject to a 5% standard deviation by age.

The fishery selectivity was modeled by using the double normal parameterization (for details, see Methot and Wetzel, 2013), which is a flexible form that allows selectivity to range in shape from asymptotic to dome-shaped. Fishery selectivity during the historical period (years 1–50) was assumed to be asymptotic (Fig. 1, A and C). Fishery selectivity shifted to a dome-shaped (in contrast with the historical asymptotic) form (Fig. 1, B and D) within the operating model during the period that the simulated stock was estimated to be below the target biomass (0.40 SB_0). Once the population was estimated to have recovered to above the target biomass, fishery selectivity reverted to the asymptotic form. The shift in selectivity was designed as a way to mimic a change in the behavior of fishermen that results from an overfished designation (e.g., 1) the creation of rockfish conservation areas that protect portions of the stock, or 2) areas of known specific habitat that are avoided by fishermen, or 3) areas associated with high abundance of the overfished stock). The change in shape of the selectivity curve depended on the estimated stock status rather than on the true status from the operating model (i.e., changes in behavior of fishermen modeled by a change in selectivity were assumed to be driven by management restrictions based on the perception of the simulated stock by the estimation method rather than on the true unobservable state of the simulated stock).

The estimation method

Stock synthesis, an integrated statistical catch-at-age model (Methot and Wetzel, 2013), was the estimation method used to assess the simulated stocks. Stock synthesis was applied for the first time in year 50 and then every 6th year thereafter. Assessment frequency for U.S. west coast groundfish species varies as a consequence of commercial importance (an indicator of exploitation), the time since last assessment, and life history dynamics of the stock (Methot, 2015). Long-lived rockfish species generally have slow dynamics, resulting in minimal fluctuations in biomass from year to year (assuming non-extreme harvesting). To mimic the likely cycle of assessments for this type of stock in real life, we conducted the assessment every 6th year.

Parameters determining unfished recruitment (R_0), steepness, growth, annual recruitment deviations, initial age-structure deviations, and the size and width at maximum selectivity for the fishery selectivity that assumed a double normal parameterization (same as assumed in the operating model). Steepness was estimated by using a diffuse beta prior within the estimation method. All other parameters were estimated without priors. Natural mortality, the variation of length-at-age, weight-at-length, the fecundity relationship, and the variation of recruitment (σ_R) were assumed known. The ratio of spawning biomass to unfished spawning biomass (termed *relative spawning biomass*) in the assessment year was estimated and the forecasted catches were determined by using the harvest control rule adopted by the Pacific Fishery Management Council (PFMC) for rockfish species. The catches were removed from the operating population without error, and then the fishery CPUE index and length- and age-composition data were generated for the subsequent 6 years.

The harvest control rule adopted by the PMFC for rockfish species involves a linear reduction in catch when a stock falls below $0.40SB_0$, and no fishing when the stock falls below $0.10SB_0$. The maximum catch, termed the *overfishing level catch* was defined as the catch corresponding to the proxy for the fishing mortality rate at which maximum sustainable yield is achieved and if surpassed would constitute overfishing, was set equal to the target harvest rate measured as spawning biomass per recruit ($F_{0.50}$) multiplied by SB_t. Spawning biomass per recruit is a measure of fishing mortality on the projected average contribution of each recruit to the spawning biomass. Applying an $F_{0.50}$ harvest rate reduces the spawning biomass per recruit to 50% of the unfished condition. The catch predicted by the overfishing level was reduced by a management buffer to determine the acceptable biological catch level (i.e., the default reduction for the PMFC for an age-structured assessment sets the acceptable biological catch equal to 95.6% of the overfishing level catch, Ralston et al., 2011). The annual catch limit was set equal to the acceptable biological catch when the simulated stock was above the target biomass, $0.40SB_0$, or reduced from the acceptable biological catch according to the harvest control rule when the simulated stock fell below $0.40SB_0$.

One major simplification in this simulation design was the omission of the rebuilding plans that are implemented when a stock is assessed to have fallen below the MSST (defined as $0.25SB_0$ for U.S. west coast rockfish species). In reality, harvest for stocks that fall below the MSST is not based on the standard harvest control rule but rather on a rebuilding plan in which catches are determined until the stock is rebuilt to the target biomass (for additional details on PFMC rebuilding plans, see Wetzel and Punt, 2016).

Data scenarios

Three data scenarios were created to explore the impact of data availability on the ability to monitor rebuilding of an overfished stock (Fig. 2). The data scenarios were designed to emulate a stock, similar to many rockfish species off the U.S. west coast, that is infrequently encountered by a fishery-independent survey (e.g., because of depth or habitat) and for which only fishery data were available. The sample sizes of the historical length and age data generally were based on the effective sample sizes observed for yelloweye rockfish. Historical length and age data from the fishery begins in year 35, 15 years before the first assessment, and the fishery CPUE data starts in year 45. Following the first assessment in year 50, the 3 scenarios have different data availability based on estimated stock status (e.g., overfished versus rebuilt) in the assessment year.

The *full data* scenario maintained the fishery CPUE index and length- and age-composition data at the historical levels (before the stock being declared overfished in year 50) during rebuilding (Fig. 2). The *reduced data* scenario decreased the amount of data available from the fishery during rebuilding (Fig. 2). The length- and age-composition data were reduced to 20% of the historical sample sizes during rebuilding and the fishery CPUE index was eliminated during the rebuilding period. When the simulated stock was estimated to have rebuilt to the target biomass, the CPUE index resumed and the sample sizes of composition data reverted to historical levels. The *eliminated data* scenario had no fishery data during rebuilding (Fig. 2). The fishery CPUE index and composition data resumed at historical sample sizes when the simulated stock was projected to be rebuilt.

The estimation method in the full and reduced data scenarios was allowed to estimate a change in selectivity from asymptotic to dome-shaped during the rebuilding period through the application of a time block on selectivity. However, the eliminated data scenario assumed constant asymptotic selectivity in the assessment for all years because no fishery composition data were available to detect a potential shift in selectivity. In reality, input from fishermen may be used to justify an updating of the selectivity form. Methods that have been used for stocks off the U.S. west coast have applied a default assumption for asymptotic selectivity in assessments that do not incorporate composition data. Incorrectly assuming dome-shaped selectivity when the true form is asymptotic could result in overly optimistic estimates of the population status because dome-shaped selectivity means that there are older individuals in the population that are not subject to fishing pressure. The eliminated data scenario assumes what might be considered a more precautionary assumption for selectivity in the absence of composition data.

Sensitivity to adding survey data

Additional simulations were conducted to evaluate the impact of having only fishery information versus indices of abundance and length- and age-composition data available from both a fishery-independent survey and a fishery. The operating model generated a highly uncertain survey (coefficient of variation: 0.40) that was conducted on a biennial basis with low sample sizes (n=10 per year) for length- and age-composition data starting in year 40, 10 years before the first assessment in year 50. The survey selectivity was assumed to be fixed at an asymptotic shape, selecting fish at smaller sizes in relation to the fishery selectivity. All other specifications for the fishery within the operating model and the assumptions applied by the estimation method were the same as those detailed previously.

Performance measures

The outcomes of the simulations for each case and data scenario were summarized by using 5 metrics that were selected to evaluate the effect of data on estimation of indicators of stock status (e.g., relative spawning biomass) and management quantities (e.g., rebuilding catch).

1 The relative errors (REs) for estimated parameters, calculated as

$$RE = \frac{E - T}{T}, \tag{8}$$

where E = the estimated quantity of interest; and

T = the true value from the operating model.

The REs for spawning biomass and relative spawning biomass were calculated for each simulation for the ending year estimate each time the simulated stock was assessed.

2 The percent root mean square error (RMSE), a measure of precision and bias, was calculated to assess the overall level of error given the amount of data available:

$$RMSE = \sqrt{\tfrac{1}{n}\Sigma_{i=1}^{n}\frac{(E_i - T_i)^2}{T_i^2}}, \tag{9}$$

where n is the number of simulations (n=100).

3 The average (over simulations) of the total catch while the simulated stock was recovering to the target biomass.

4 The annual average variability of the catches (AAV), defined as

$$AAV = 100\frac{\Sigma_t |C_t - C_{t+1}|}{\Sigma_t C_t}, \tag{10}$$

where C_t = the catch during year t.

5 The percentage of simulations with stocks that rebuilt to the target biomass and percentage of simulations with stocks that remained overfished at the end of the management period.

Results

Assessment performance with time-invariant parameters

The full and reduced data scenarios performed similarly while simulated stocks were rebuilding and after stocks had rebuilt, and the trends of the relative error for spawning biomass and relative spawning biomass were generally consistent between the full and reduced data scenarios (Fig. 3, A, B, D, and E). The median estimates of spawning biomass and relative spawning biomass were less than the true values during rebuilding for both scenarios (Fig. 3, A, B, D, and E). As expected, the full data scenario had less among-simulation variability in the differences in spawning biomass and relative spawning biomass between the operating model and estimation method during the rebuilding period than the variability in the reduced and eliminated data scenarios (Fig. 3, A–F). However, the among-simulation variability of errors in biomass metrics was similar between the full and reduced data scenarios by the end of the management period, when a majority of the simulated stocks were estimated to be rebuilt and data collections had returned to historical, higher sample sizes for the reduced data scenario.

The eliminated data scenario in which no data were available during the rebuilding period resulted in median (across simulations) estimates of spawning biomass and relative spawning biomass errors that were similar to the true values but were highly imprecise at the start of the management period (years 50–74) (Fig. 3, C and F). The eliminated data scenario, in the absence of new data during rebuilding, projected the simulated stocks on the basis of the historical data and new catches until the simulated stock was rebuilt, at which time data collection resumed and allowed the estimation method to estimate population status. The median estimates of spawning biomass and relative spawning biomass for the eliminated data scenario were less than the true values, and had high among-simulation variability in error as simulated stocks began to be projected to be rebuilt and data collection resumed. In contrast to the full and reduced data scenarios, the estimates of spawning biomass and the relative spawning biomass for the eliminated data scenario had little improvement in the among-simulation variability in error estimates by the end of the management period (Fig. 3, C and F).

Even when data collection continued at reduced levels in the reduced data scenario, the estimates of steepness varied in relation to the steepness estimates from the full data scenario. The full data scenario resulted in generally median unbiased estimates during the rebuilding period and small positive median bias by

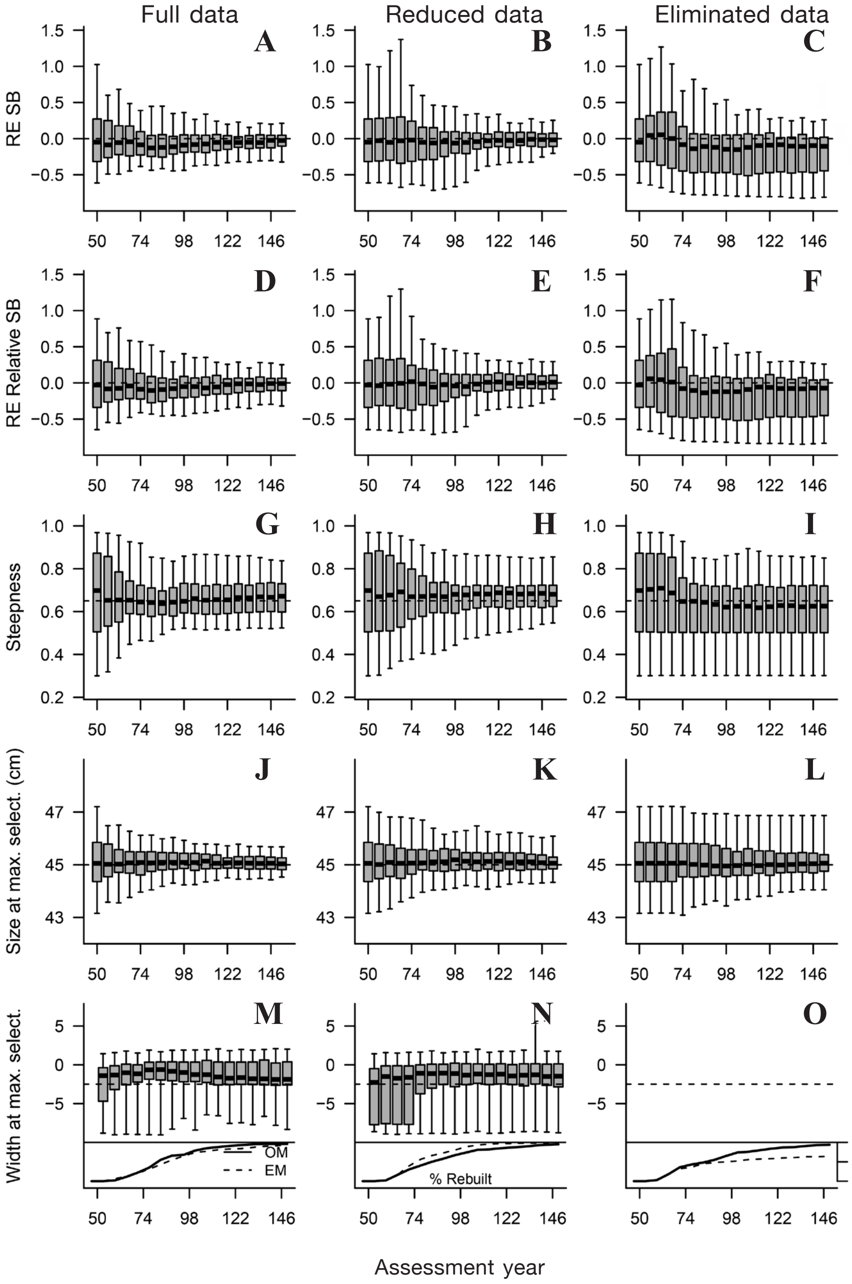

Figure 3

Relative error (RE) of estimated spawning biomass (SB) and relative SB, estimates of steepness, size at maximum selectivity, and the width at maximum selectivity in each assessment year for the time-invariant case and all 3 data scenarios (full data, reduced data, and eliminated data) for all simulations used to examine the effect of data availability on the ability to monitor rebuilding of an overfished stock of a rockfish species. The eliminated data scenario in the absence of composition data had selectivity fixed at the asymptotic assumption and hence did not estimate the width at maximum selectivity parameter. The percentage of stocks that had rebuilt to the target biomass during the management period (shown in bottom panels) within the operating model (OM, solid black line) and the estimation method (EM, dashed black line); data collection consequently returned to historical levels when the EM determined that the stock was rebuilt. The black lines in the gray boxes denote the median of the estimates, the gray boxes cover the 25–75% simulation interval, and the boxplot whiskers indicate the 95% simulation interval for each assessment year.

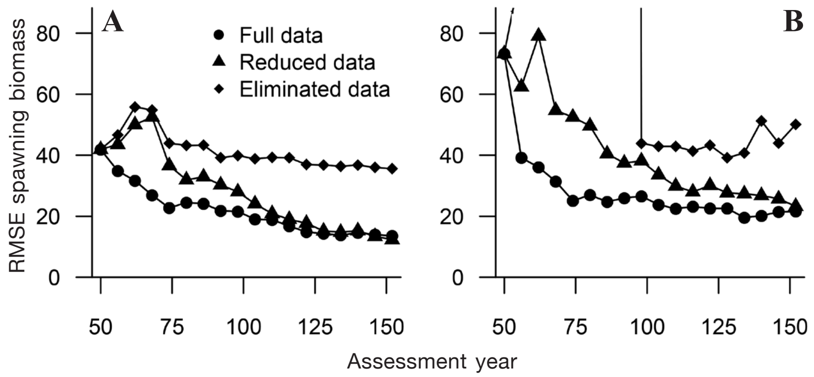

Figure 4

The root mean square error (RMSE) for spawning biomass (SB) by assessment year for each case, (**A**) time invariant and (**B**) time varying, and for each data scenario (full data, reduced data, eliminated data). The scale of the y-axis is the same for comparability of results between the time-invariant and the time-varying simulations. The time-varying eliminated data scenario peaked in year 68 at 221% RMSE.

the end of the management period (Fig. 3G; note that the term *median unbiased* is used to define cases in which the median of the relative errors equals zero). In contrast, the median of the estimates of steepness for the reduced data scenario were greater than the true steepness during the management period (Fig. 3H). The eliminated data scenario had the highest among-simulation variability among estimates of steepness during the management period (Fig. 3I) as a result of the mixture of simulations in which stocks had rebuilt and not rebuilt.

Reduction or elimination of data during rebuilding increased the among-simulation variability in estimates of the size at maximum fishery selectivity and the median estimates were generally equal to the true value for all data scenarios (Fig. 3, J–L). The among-simulation variability of the estimates for the reduced and eliminated scenarios improved when the majority of the simulated stocks were estimated to be rebuilt and fishery composition sample sizes returned to historical levels. The full and reduced data scenarios were allowed to estimate dome-shaped selectivity during the rebuilding period and resulted in median estimates of the width at maximum selectivity that exceeded the true values and were highly variable among simulations at the start of the management period (Fig. 3, M and N). The eliminated data scenario did not allow estimation of dome-shaped selectivity because of the absence of fishery composition data. The estimates from the full and reduced data scenarios for the width at maximum selectivity that exceeded the true values for this parameter indicated that the data available were not sufficient to inform the estimation method about the severity of the dome shape in the selectivity curve during rebuilding. A higher estimated value indicates that the dome in selectivity occurs at larger sizes with a higher proportion of the population in relation to the operating model at full selectivity. The full data scenario resulted in markedly improved estimates of the shape of the dome over the management period, compared with estimates in the reduced data scenario (Fig. 3, M and N).

The RMSE for the estimated spawning biomass for each assessment year shows the increased precision of the full data scenario during the rebuilding period compared with that of the reduced and eliminated data scenarios (Fig. 4A). The eliminated data scenario resulted in the highest RMSE over the entire management period (Fig. 4A). However, the RMSE for the reduced data scenario improved over the management period as simulated stocks began to be assessed as rebuilt to the target biomass and as sample sizes returned to historical levels. The limited improvement in the RMSE for the eliminated data scenario was driven by the simulations in which the stocks never were projected to rebuild to the target biomass (35 out of 100 simulations).

In the absence of data collection, the performance of the estimation method was dependent upon the ability of the historical data to inform parameter estimates. An examination of the eliminated data scenario more closely revealed a pattern in the performance of the estimation method based on the estimation of steepness in the first assessment year. The eliminated data scenario simulations were divided and plotted on the basis of whether the estimation method projected the stock in the simulation to rebuild (65 simulations) or to fail to rebuild (35 simulations) by the end of the management period. To allow comparison between the eliminated and the full data scenarios, the estimates from the full data scenario were also divided into the same 2 groups and plotted. The estimates of spawning

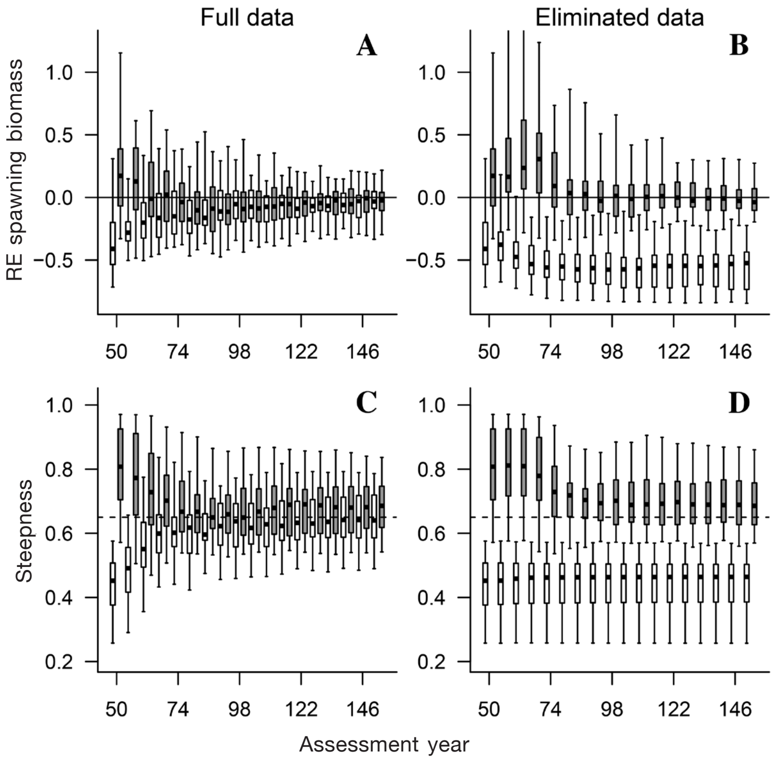

Figure 5

Relative error (RE) of spawning biomass and the estimates of steepness for the full and eliminated data scenarios for the time-invariant case; results are divided by whether the simulated stock was estimated to be rebuilt (65 simulations [gray]) or not (35 simulations [white]) for the eliminated data scenario. The black lines in the gray boxes denote the median of the estimates, the gray boxes cover the 25–75% simulation interval, and the boxplot whiskers indicate the 95% simulation interval for each assessment year.

biomass were considerably less than the true values in the first assessment year (Fig. 5B) for the 35 simulations in which the stocks were estimated not to rebuild by the end of the management period. The underestimates of spawning biomass (Fig. 5B) were driven by estimates of steepness that were much less than the true value in the first assessment (Fig. 5D). In the absence of new data, the underestimates of steepness resulted in the estimation method perceiving a less productive stock that required an extended period to rebuild to the target biomass. However, with full data present, estimated quantities (spawning biomass and steepness) improved for this subset of simulations and were median unbiased by the end of the management period (Fig. 5, A and C).

The median number of years estimated for the simulated stocks to recover to the target biomass for the full data scenario was longer than the median time required to rebuild the stock within the operating model simulations (Table 2). In contrast, both the reduced and eliminated data scenarios had shorter median recovery times than those of the operating model (Table 2). The contrast in estimated recovery times across the data scenarios was related to the average catch obtained during rebuilding along with the bias and variability of estimates. The median error associated with relative spawning biomass for the full data scenario was less than zero, and there was low among-simulation variability (compared with those of the other data scenarios) for all assessment years, which resulted in estimates that predicted constant rebuilding but at a slower rate than the true rate of the simulated stock in the operating model (Fig. 3D). In contrast, the reduced data scenario had higher variability over time (i.e., within-simulation) across the estimates of error associated with relative spawning biomass (Fig. 3E). The variability of estimates between assessments resulted in simulated stocks that were estimated to be recovered to the target stock size when the populations in the operating model were not yet recovered because of estimation error driven by the limited number of composition samples during rebuilding.

Table 2

The median and 90% simulation interval (SI) for the estimated number of years needed for simulated rockfish stocks to rebuild to the target biomass, the operating model number of years needed for the stocks to rebuild to target biomass, and the number of stocks that failed to rebuild to the target biomass determined by the estimation method (EM) and the operating model (OM) for each case and data scenario.

	Estimated number of rebuilding years		Operating model number of rebuilding years		Number of stocks that failed to rebuild	
Selectivity/data scenario	Median	90% SI	Median	90% SI	EM	OM
Time-invariant						
Full data	43	(13–87)	34	(16–73)	7	4
Reduced data	31	(19–61)	34	(14–83)	1	5
Eliminated data	25	(14–72)	37	(14–87)	35	4
Time-varying						
Full data	31	(13–91)	35	(13–85)	13	4
Reduced data	25	(13–79)	32	(12–74)	8	2
Eliminated data	25	(13–77)	36	(12–79)	32	5

Table 3

The median and 90% simulation intervals (SI) for the average catch of simulated rockfish stocks during rebuilding, the annual average variability of the catches (AAV) during rebuilding, and the AAV over all years for each case and data scenario.

	Average catch during rebuilding		AAV during rebuilding		AAV all years	
Selectivity and data scenario	Median	90% SI	Median	90% SI	Median	90% SI
Time-invariant						
full data	44.0	(15.3–78.9)	6.0	(3.7–11.5)	3.2	(2.1–4.7)
reduced data	28.1	(14.6–57.9)	7.7	(4.0–14.5)	3.5	(2.3–5.3)
eliminated data	41.3	(19.9–83.8)	2.6	(1.3–4.4)	2.2	(1.3–3.9)
Time-varying						
full data	31.7	(11.0–75.4)	7.3	(4.4–17.5)	4.2	(2.7–5.9)
reduced data	25.1	(15.6–68.0)	8.9	(4.5–20.7)	4.5	(2.6–9.8)
eliminated data	36.3	(15.7–79.4)	2.3	(1.2–4.8)	2.8	(1.3–5.3)

The reduced data scenario had the lowest median average catch during rebuilding (Table 3), and the median rebuilding time was estimated to be shorter than the true time to recovery within the operating model (Table 2). The eliminated data scenario, which was entirely dependent upon historical data until the simulated stocks were projected to rebuild, essentially projected the population forward with each assessment on the basis of the initial parameter estimates from the historical data and resulted in high median average catches during rebuilding and the lowest median AAV during rebuilding and across the entire management period (Table 3).

The effect of time-varying parameters

Time-varying annual deviations in natural mortality and fishery selectivity generally resulted in increased among-simulation variation in estimation errors than with the time-invariant case. The median error of estimates of spawning biomass at the time of the first assessment exceeded the true values and were highly variable among simulations (Fig. 6, A–C). The among-simulation variance in errors of estimates of spawning biomass decreased markedly for the full data scenario after the first assessment (Fig. 6A). However, this variability remained high for approximately the first 25 years of the management period (assessments were performed every fourth year between years 50–74 approximately) for both the reduced and eliminated data scenarios, until approximately 50% of the simulated stocks were estimated to be recovered and the fishery sample sizes increased to historical levels (Fig. 6, B and C). The full and reduced data scenarios resulted in median spawning biomass estimates that were generally smaller than the operating model values (Fig. 6, A and B). However, the medians of the errors for relative spawning biomasses were variable over the manage-

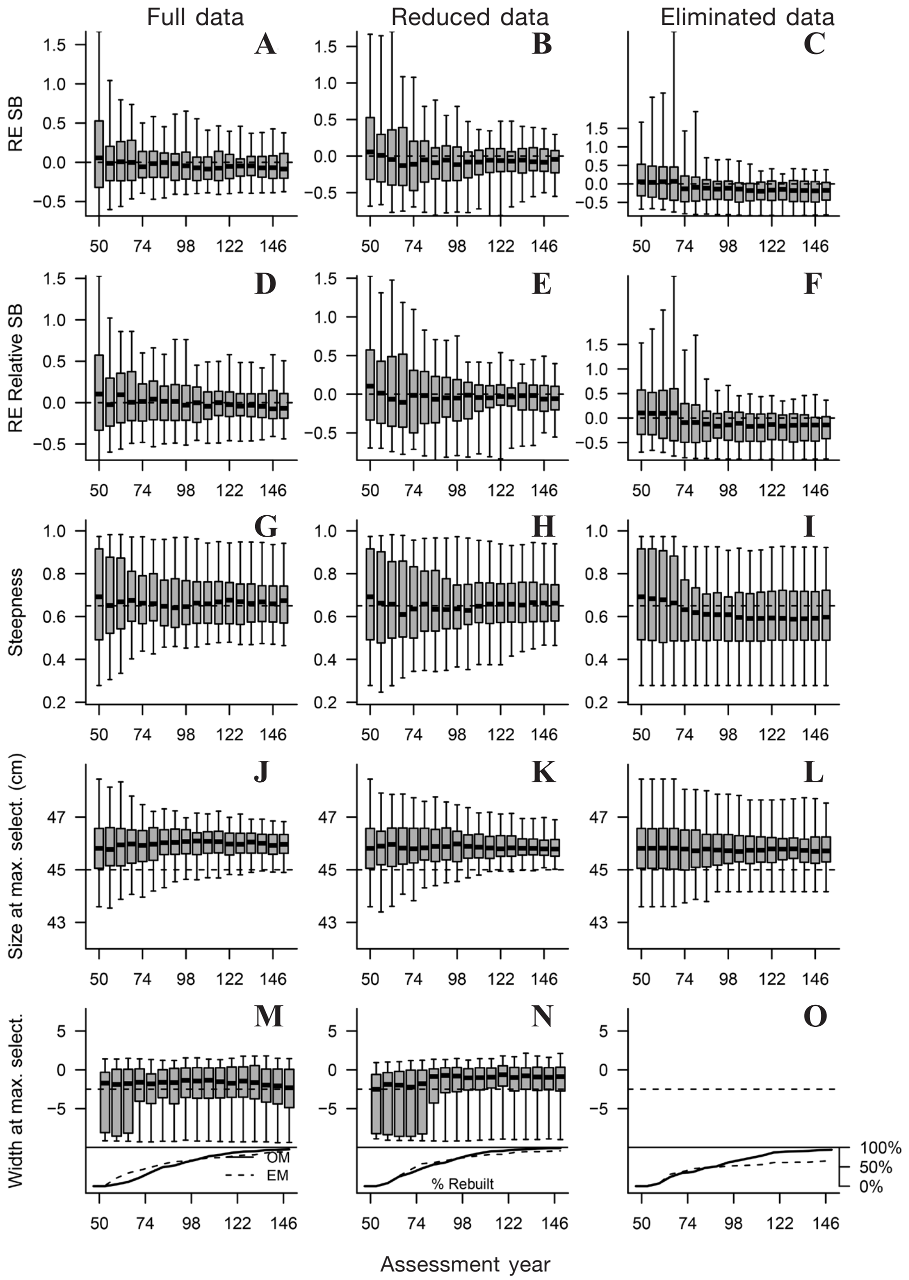

Figure 6

Relative error (RE) of estimated spawning biomass (SB) and relative SB, estimates of steepness, size at maximum selectivity, and the width of at maximum selectivity in each assessment year for the time-varying case and all 3 data scenarios (full data, reduced data, and eliminated data) for all simulations used to examine the effect of data availability on the ability to monitor rebuilding of an overfished stock of rockfish species. The eliminated data scenario in the absence of composition data had selectivity fixed at the asymptotic assumption and hence did not estimate the width at maximum selectivity parameter. The percentage of stocks that had rebuilt to the target biomass during the management period within the operating model (OM, solid black line) and with the estimation method (EM, dashed black line) is shown in the bottom panels. Data collection consequently returned to historical levels when the EM determined that the stock was rebuilt. The black lines in the gray boxes denote the median of the estimates, the gray boxes cover the 25–75% simulation interval, and the boxplot whiskers cover the 95% simulation interval for each assessment year ment period (Fig. 6, D and E). The medians of the estimates of relative spawning biomass for the eliminated data scenario were larger than operating model values at the start of the management period but became smaller than the values as simulated stocks rebuilt to target biomass levels and data collection resumed (Fig. 6F).

Inclusion of time-varying selectivity resulted in the median estimates of the size at maximum selectivity (the earliest size at which selectivity reaches a maximum value) across all data scenarios exceeding the mean of the operating model values (Fig. 6, J–L), although the full data scenario resulted in the lowest among-simulation variation. The full and reduced data scenarios, which were allowed to estimate dome-shaped selectivity (width at maximum selectivity) during the recovery period, resulted in highly variable among-simulation estimates at the start of the management period and the variability for the estimates decreased earlier for the full data scenario (Fig. 6, M and N).

Compared with the case with time-invariant parameters, the RMSE was higher for all data scenarios when time-varying parameters were present within the operating model (Fig. 4). The RMSE for the estimated spawning biomass for the full data scenario was lower than that of the other scenarios for the entire management period (Fig. 4B). Similar to the time-invariant results, the RMSE of spawning biomass for the eliminated data scenario was the highest between the scenarios across the entire management period, peaking in assessment year 68 at 221% (a single simulation for the eliminated data scenario, with extreme outliers for 2 assessment years, was removed for a more informative summary of the RMSE).

The time-varying results for the eliminated data scenario were qualitatively similar to those for the time-invariant case, in which stocks were not projected by the estimation method to be rebuilt for a large number of simulations (32 simulations). As was observed in the time-invariant case, the simulations with time-varying parameters and stocks projected to fail to rebuild biomass had median estimates of spawning biomass and relative spawning biomass below the operating model values at the time of the first assessment, which were driven by estimates of steepness that were considerably lower than the true value (not shown).

The inclusion of time-varying parameters in the operating model resulted in shorter median estimated recovery times in relation to the time-invariant case for the full and reduced data scenarios (Table 2). However, the median number of years to rebuild for stocks in the operating model were similar between the time-varying and time-invariant cases. The estimation method produced earlier recovery times for the time-varying case because of the increased variability in the estimates of relative spawning biomass and resulted in the estimation method having an increased frequency of erroneous estimation of the biomass to be above the target stock size (Fig. 3, D–F, versus Fig. 6, D–F).

The eliminated data scenario had the highest median average catch during the recovery period because of the subset of simulated stocks that were estimated to be less depleted than the population in the operating model, resulting in more aggressive catch estimates from the estimation method (Table 3; Fig. 6, D–F). Additionally, the eliminated data scenario had the lowest median AAV during the rebuilding period (Table 3). The eliminated data scenario also resulted in the highest number of simulated stocks that never reached the target biomass (Table 2) as a result of incorrect parameter estimates at the start of the management period that resulted in catch estimates exceeding the harvest that would allow rebuilding within the population in the operating model (Table 3).

Estimation performance when survey data are also available

The estimates of spawning biomass (Fig. 7, A–C) and relative spawning biomass (Fig. 7, D and E) for the time-invariant case were median unbiased at the time of the first assessment in year 50. The addition of a survey index and composition data for all data scenarios led to less among-simulation variability and reduced median bias over the management period in relation to the simulations without survey data (Fig. 3, A–F). The presence of survey data when fishery data were eliminated (eliminated data scenario) allowed the majority of the simulated stocks to be estimated as rebuilt by the end of the management period (Fig. 7) compared with the large fraction of simulations in which the stocks failed to be estimated as rebuilt when only historical data were available from the fishery (Fig. 3). Similar to what was observed in the time-invariant case, reduced among-simulation variability in the estimates of spawning biomass and relative spawning biomass (not shown) were observed when the inclusion of survey data, in addition to fishery data when time-varying parameters were present.

The full data scenario had the lowest RMSE for relative spawning biomass during the early portion of the management period for both cases (time-invariant and time-varying), when the majority of simulations were estimated to be rebuilding for both cases (Fig. 8). However, midway through the management period, after a majority of the simulated stocks had rebuilt and data restrictions were removed, the data scenarios resulted in similar RMSEs (Fig. 8). The inclusion of survey data for all data scenarios resulted in similar estimates of the median number of years required to recover to the target biomass, and these estimates were similar to the median rebuilding time from the operating model.

Discussion

Maintaining fishery data at historical levels during rebuilding reduced the variation in estimates for spawning biomass, relative spawning biomass, and steepness

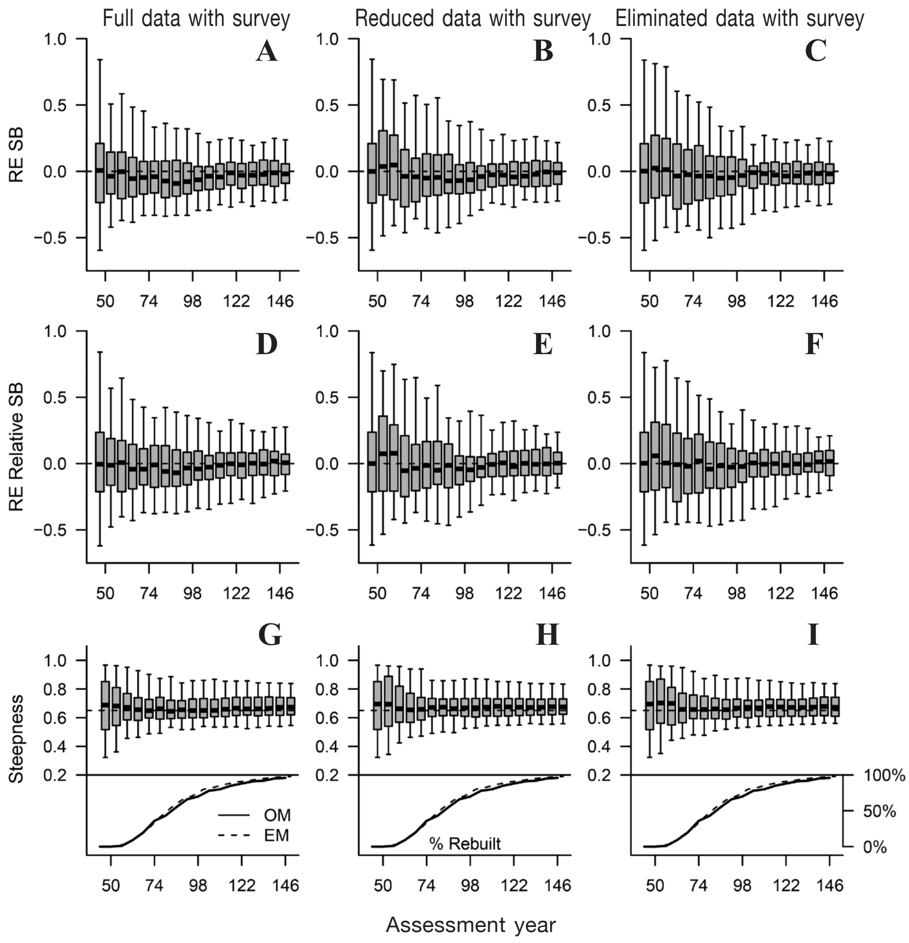

Figure 7

Relative error (RE) of estimated spawning biomass (SB) and relative SB and estimates of steepness in each assessment year when survey data are present during stock rebuilding for the time-invariant case and all 3 data scenarios (full data, reduced data, and eliminated data) for all simulations (top panels). The percentage of stocks that had rebuilt to the target biomass during the management period is shown in bottom panel within the operating model (OM, solid black line) and the estimation method (EM, dashed black line); data collection consequently returned to historical levels for the fishery when the EM determined that the stock was rebuilt. The black lines in the grey boxes denote the median of the estimates, the gray boxes cover the 25–75% simulation interval, and the boxplot whiskers cover the 95% simulation interval for each assessment year.

between assessments (i.e., over time within a simulation). Although the full data scenario had less variation, the median estimates of spawning biomass (over simulations) and relative spawning biomass were consistently below the operating model values for much of the management period. This result is contrary to what might be expected when additional data are available. Simulations in which there was a fishery-independent survey that provided an index of abundance and composition data (length and age) determined that this underestimation of the true spawning biomass was eliminated if survey composition data were available along with fishery composition data. The underestimation was driven by 2 key factors: the shape of fishery selectivity curve and data quantity. The specification of a fishery selectivity curve as greater than the maturity-at-length curve, with the fishery selecting only mature fish, resulted in a lag between recruitment to the population and recruitment to the fishery. However, conducting a fishery-independent survey that selects fish at smaller sizes yields information about recruitment to the population earlier than using data from the fishery that selects larger, mature fish. Additionally, an increase in the number of length- and age-composition

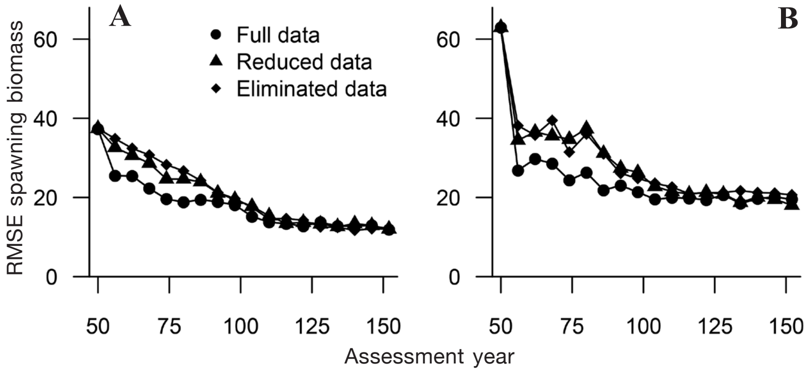

Figure 8

The root mean square error (RMSE) when survey data are available during rebuilding of a stock for relative spawning biomass in the assessment year for each case, (**A**) time invariant and (**B**) time varying, and data scenario (full data, reduced data, eliminated data).

samples from multiple data sources can improve estimates of recruitment, spawning biomass, and relative spawning biomass (Yin and Sampson, 2004; Wetzel and Punt, 2011).

The median relative errors for the relative spawning biomass were negative during the rebuilding period for the full data scenario and resulted in the estimation method failing to determine whether the population in the operating model was at, or above, the target biomass (median number of rebuilding years was greater than those in the operating model, Table 2). Failing to correctly determine that the population has rebuilt would lead to unwarranted extended harvest, a situation to avoid in fishery management. However, the reduced estimation variability (within and among simulations) offered by the full data scenario resulted in an improvement in the consistency of estimates by subsequent assessments, offering a level of stability for fisheries managers and stakeholders. In contrast, the higher between-assessment variation in estimates of spawning biomass for the reduced data scenario resulted in simulated stocks being estimated as rebuilt when the true population was still below the target biomass, a result that could have undesirable outcomes for fisheries management. Overly optimistic estimates of relative spawning biomass can result in overfishing when catch limits are set too high, leading to further reductions in biomass and potentially resulting in an overfished declaration based on a future assessment.

Loss of data during rebuilding resulted in a number of simulations that failed to estimate rebuilding because of poor initial estimates of steepness, a key parameter that controls how quickly a stock can rebuild from low biomass levels. In the absence of new data, the first and subsequent assessments were entirely dependent on the quality of the historical data to inform parameter estimates. The simulations that failed to correctly detect rebuilt stocks were driven by erroneously low estimates of steepness at the time of the first assessment. Therefore, initially identifying a stock as less productive than the true population resulted in lower estimates of spawning biomass and relative spawning biomass, and the assessment predicating harvest levels that were well below the true acceptable biological catch. The reduced harvest allowed the population in the operating model to rebuild to, or above, the target biomass. However, in the absence of new (and informative) data, the estimation method did not detect the correct simulated stock size. The population in the operating model had a 2-way trend of abundance (decline and increase in biomass) with the fishery data available during the fishing down and recovery periods, data that previous studies have found informative in estimating steepness (Magnusson and Hilborn, 2007; Conn et al., 2010). This work showed that a one-way trip scenario in stock size with limited data may not be adequate to correctly estimate steepness, but the inclusion of even limited data can, with a contrast in stock size, improve the estimation of steepness even if the initial assessment produced a poor estimate (Figs. 6C and 7).

The general trend in results when the operating model included time-varying natural mortality and fishery selectivity was similar to the trend in results for the time-invariant case, although the among-simulation estimates were more variable across all data scenarios. Natural mortality was fixed at a single value in the estimation method across all years equal to the mean value that was used to generate the autocorrelated annual deviations in the operating model. This setup was a strategic choice that allowed variation in the composition data that the estimation method would not be able to account for, but it was not anticipated to result in strongly biased estimates due to model misspecification. The processes that control natural mortality rates in real systems over the life span of an individual are likely more complex with extended periods of high or low mortality that is affected by external factors (e.g., predator abundance, climate conditions)—periods that could result in large biases in estimated quantities if they are not accounted for in an assessment (Johnson et al., 2015).

Shifts in the form of selectivity over time and the impact of annual deviations in selectivity led to mixed results. The estimation method consistently overestimated the mean size at maximum selectivity for all data scenarios with time-varying selectivity. The operating model selectivity applied normally distributed deviations to generate the annual shifts in selectivity. One would not a priori predict the estimation method to have a consistent bias in estimates; however, the estimation method was able to identify the change in the selectivity form (asymptotic to dome-shaped through a reduction in the width at peak selectivity) during the rebuilding years with a similar error to that observed in the time-invariant case. Each case led to estimates that overestimated the width at maximum selectivity, the parameter defining the dome in selectivity (dome-shaped selectivity occurring at larger sizes with increased sizes subject to full selectivity compared with that in the operating model). Time blocks were applied within the estimation method defined by the status of the stock to allow shifts in selectivity, ignoring the annual deviations in the selectivity curve. Studies have evaluated other ways of estimating time-varying selectivity by using state-space models (Nielsen and Berg, 2014) or have examined the implications of applying time blocks versus allowing a random-walk component in selectivity parameters or catchability (Wilberg and Bence, 2006; Martell and Stewart, 2014). Further exploration should be conducted to determine whether allowing a random walk or applying an alternative estimation method eliminates the bias detected in the estimated selectivity observed here and how data quantity and quality affect these estimates. Additionally, if shifts in fishery selectivity are anticipated as a result of management actions, increased data collection may be required to achieve a similar level of precision in estimates of fishery selectivity during rebuilding.

As with other simulation studies, simplifying assumptions were used in this study and these can lead to an underestimation of the uncertainty that would be expected in a real-world population. With the estimation method used in this study, the population structure and functional form of biological relationships were assumed correctly—variables that are not known with certainty for a typical assessment. Additionally, the simulated composition data from the historical and management periods were representative of a homogenous population. In reality, one may expect spatial structure in fish populations, and, during a period of limited sampling, composition data may be available only from a subset of the population that may not be representative of the population as a whole. The results from this simulation study should be considered a best-case scenario specifically designed to allow clearer interpretation of the results regarding the availability of data for estimate rebuilding.

The work described here highlights the benefits of continued data collection during stock rebuilding on the precision of estimates, but there are many additional reasons why retaining data streams or creating new data streams are important. Data availability can fluctuate with harvest limits for species for which the fishery is the primary data source. Additionally, the data collected may be more variable because of variations in fishing behavior among fishermen, and the data typically will be available only for mature, larger animals selected by the fishery. The presence of consistent survey data for these stocks could improve the ability to produce a more robust estimate of stock status. Ideally, survey data would provide comparable data across time and space for a large portion of size and age classes for a population when it is collected by using standardized sampling protocols. Traditional trawl survey methods commonly used off the U.S. west coast have failed to capture sufficient samples for some rockfish species because of gear or area restrictions. Creating and maintaining alternative survey sampling methods (e.g., hook and line or underwater camera sampling) that sample representative portions of a stock would be one way to improve the assessment of certain rockfish species (e.g., Harms et al, 2008).

A benefit of continued data collection across multiple data sources is the potential ability to identify misspecification in model assumptions. With the estimation method and operating models applied in this study, similar structural assumptions were generally made. However, the true state of nature is never known with confidence and continued data collection may allow the identification of model misspecification in the structural assumptions (e.g., growth, recruitment), allowing models to better approximate reality. Specifically, there could be long-term changes in stock dynamics that are due to environmental conditions (e.g., Hollowed et al., 2011) or biological forces when a stock is depleted (e.g., Hixon et al., 2014; Legault and Palmer, 2016) that could negatively affect the ability of the stock to rebuild. In such a case additional data would be required to detect a lack of rebuilding despite reduced fishing mortality. Sampling during harvest restrictions will provide continued information that can identify changes in stock dynamics. Additionally, the creation of alternative data streams can buffer against the reliance upon a single and potentially variable data source and, in turn, could provide valuable insights into stock dynamics by the sampling of differing subsections of a population.

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