Length-Based Reference Points for Data-Limited Situations: Applications and Restrictions

Authors: Cope, Jason M., and Punt, André E.

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JASON M. COPE*

*National Oceanic and Atmospheric Administration Fisheries, Northwest Fisheries Science Center,
Fishery Resource Analysis and Monitoring Division, 2725 Montlake Boulevard East,
Seattle, Washington 98112-2097, USA; and School of Aquatic and Fishery Sciences,
University of Washington, Box 355020, Seattle, Washington 98195-5020, USA*

ANDRÉ E. PUNT

*School of Aquatic and Fishery Sciences, University of Washington,
Box 355020, Seattle, Washington 98195-5020, USA*

Abstract.—Current fisheries management policies generally require an assessment of stock status, which is a difficult task when population and fisheries data are limited. Three simple metrics based on catch length compositions (i.e., that reflect exclusive take of mature individuals, P_{mat}; that consist primarily of fish of optimal size, the size at which the highest yield from a cohort occurs, P_{opt}; and that demonstrate the conservation of large, mature individuals, P_{mega}) can be used to monitor population status relative to exploitation. The metrics (collectively referred to as P_x) were intended to avoid growth and recruitment overfishing, but there was no quantitative linkage to stock status and calculation of future sustainable catches. We attempt to make this connection by exploring the relationship of P_x measures to fishing mortality and spawning biomass (SB). The relationships are compared specifically to the current target reference point (0.4 times the virgin, or unfished, SB [SB_0]) and limit reference point ($0.25SB_0$) used for the U.S. West Coast groundfish fishery by using simulations based on a deterministic age-structured population dynamics model. Sensitivity to fishery selectivity, life history traits, and recruitment compensation (steepness) is explored. Each P_x measure showed a wide range of possible values depending on fishery selectivity, steepness, and the ratio of the length at maturity (L_{mat}) to the optimal fishing length (L_{opt}). Although the values of P_x may be compatible with sustainable fishing, these values are not always sufficient to ensure stock protection from overfishing. Moreover, values for P_x cannot be interpreted adequately without knowledge of the selectivity pattern. A new measure, P_{obj} (the sum of P_{mat}, P_{opt}, and P_{mega}), is introduced to distinguish selectivity patterns and construct a decision tree for development of stock status indicators. Heuristic indicator values are presented to demonstrate the utility of this approach. Although several caveats remain, this approach builds on the recommendations of previous literature by giving further guidance related to interpreting catch length composition data under variable fishery conditions without collecting additional information. It also provides a link to developing harvest control rules that inform proactive fisheries management under data-limited conditions.

The Magnuson–Stevens Fishery Conservation and Management Act (reauthorized in 2006) mandates sustainable fishery actions in the United States, with a particular goal of continuing resource use while avoiding overfishing, maintaining healthy stocks, and rebuilding overfished stocks (Restrepo and Powers 1999). Achieving these goals generally requires the ability to identify when overfishing is occurring and when a stock has reached an overfished state. Life histories, environmental complexity, and resource removal context combine to complicate the "true" definition of overfishing and being overfished, neces-

sitating the use of reference points (RPs; Caddy and Mahon 1995). Reference points often attempt to buffer uncertainty in maximum sustainable removals, thus promoting a risk-based trade-off between resource use (e.g., yield) and conservation (Mace 1994). The precautionary behavior of this trade-off, however, is usually poorly understood (Hilborn 2002).

Reference points, by definition, rely on some measure of the stock in question that relates (or refers) to status. Reference points can either be targets (levels that management attempts to maintain the stock at or around) or limits (levels that are to be avoided; Caddy and Mahon 1995; Caddy 2004). Target RPs (TRPs) therefore reflect desired biological or ecological states, whereas limit RPs (LRPs) relate to resource protection and persistence (Caddy and Mahon 1995; Botsford et al. 2004).

Current quantitative stock assessment techniques, ranging from surplus production models to age-

structured statistical catch-at-age models, provide an array of outputs that can be used when defining RPs, with estimates of fishing mortality (F) and biomass (relative to unfished or optimal conditions) the most widely applied (Quinn and Deriso 1999; Walters and Martell 2002). Although theoretically informative, conventional stock assessment techniques based on fitting population dynamics models to data cannot be applied to a large fraction of the world's exploited fishery resources because of data limitations. The challenge thus becomes devising alternative assessment methods that require limited data but are capable of revealing stock status so as to fulfill the requirements of fishery management mandates.

Contemporary approaches to inform stock vulnerability or status for data-poor situations take the form of state indicators (Garcia and Staples 2000; Jennings 2005), qualitative risk assessments (Stobutzki et al. 2001), and inferences about vulnerability based on life history characteristics (Musick et al. 2000; King and McFarlane 2003). Such approaches strive to apply transparent protocols to simple or limited data. However, the ability to validate these methods and use them to inform future catches remains a formidable task (Rochet and Trenkel 2003; Jennings and Dulvy 2005; Smith et al. 2007).

Froese (2004) introduced a method that relies on well-established relationships between fisheries management and life history theory (Reynolds et al. 2001) as applied to catch length composition data. Its straightforward approach has gained attention (Jennings 2005; Lewin et al. 2006; Francis et al. 2007) and is based on three simple ideas: (1) catch length compositions should reflect almost exclusive take of mature individuals (P_{mat}; Leaman 1991; Myers and Mertz 1998); (2) catch length compositions should consist primarily of fish of the size at which the highest yield from a cohort occurs (P_{opt}; Beverton 1992); and (3) catch length compositions should demonstrate the conservation of large, mature individuals (P_{mega}; Berkeley et al. 2004). These proposed metrics are meant to capture catch characteristics indicative of sustainable catches, such as avoidance of growth (Beverton and Holt 1957) and recruitment (Ricker 1954) overfishing, while using easily collected fisheries data (e.g., length frequencies of catch). We will hereafter refer to these three ideas as "Froese's (2004) sustainability recommendations." While the approach is intuitively appealing, it has not been formally explored to see how these proportional measures relate to currently used RPs.

Our aim for this article is to develop the concepts of Froese (2004) further and to explore how they relate to F, spawning biomass (SB), and current RPs based on SB. Specifically, we ask, "Can informative RPs be developed by using P_{mat}, P_{opt}, and P_{mega} that correspond to the current SB-based RPs commonly used in U.S. fisheries management?" Froese (2004) provided general guidelines regarding target values for P_{mat}, P_{opt}, and P_{mega}, and we explore how these values perform as the basis for fishery RPs. As a point of comparison, the analyses are based, to the extent possible, on management and biological scenarios typical of those related to the U.S. West Coast groundfish fishery.

Methods

Defining catch composition proportions.—The three length-based catch proportions of interest (hereafter referred to collectively as P_x) are calculated as follows:

$$P_{mat} = \sum_{L_{mat}}^{L_{max}} P_L, \tag{1}$$

$$P_{opt} = \sum_{0.9L_{opt}}^{1.1L_{opt}} P_L, \tag{2}$$

and

$$P_{mega} = \sum_{1.1L_{opt}}^{L_{max}} P_L, \tag{3}$$

where P_L is the proportion of the catch that is in length-class L, L_{mat} is the length at 50% maturity, L_{max} is the maximum length, and L_{opt} is the length at which the biomass of a cohort is maximized (defined here as the length corresponding to the age [A_{opt}] at which the product of weight at age and numbers at age under zero F is maximized; Beverton 1992). Calculation of P_{mat}, P_{opt}, and P_{mega} requires information on the catch length composition for the fishery, an estimate of L_{mat}, and an estimate of L_{opt}. This catch length composition is not dependent on the species in question being targeted by a fishery; it is equally relevant to species in the bycatch as well. The major assumption is that the catch length composition is representative of the fishery catch at length.

Population dynamics model.—A deterministic age-structured population dynamics model is used to explore the implications of fishery selectivity, recruitment compensation (quantified by steepness h; Mace and Doonan 1988), and life history traits on P_{mat}, P_{opt}, and P_{mega}. The stable age structure for this model is given by:

$$N_A^g$$

$$= \begin{cases} R_F & \text{if } A = 0 \\ N_{A-1}^g e^{-(M+FS_{A-1})} & \text{if } 0 < A < \omega \\ N_{A-1}^g e^{-(M+FS_{A-1})} / \left[1 - e^{-(M+FS_A)}\right] & \text{if } A = \omega, \end{cases} \tag{4}$$

TABLE 1.—Life history (LH) parameter values used for simulation testing, base case analyses, and sensitivity tests. Asterisks denote changes to the base case (LH2).

	Life history				M/k sensitivity	
Parameter	LH1	LH2	LH3	LH4	$M/k = 1$	$M/k = 1.5$
Growth curve (Von Bertalanffy growth function)						
Average asymptotic length (L_∞)	45	45	45	45	45	45
Growth coefficient (k)	0.0625*	0.125	0.25*	0.5*	0.125	0.125
Age at length 0 (A_0)	0	0	0	0	0	0
Longevity (ω)	100*	50	30*	15*	50	50
Natural mortality (M)	0.05*	0.10	0.20*	0.40*	0.125*	0.1875*
M/k	0.80	0.80	0.80	0.80	1*	1.5*
Length–weight relationship						
Intercept	0.001	0.001	0.001	0.001	0.001	0.001
Slope	3	3	3	3	3	3
Length at maximum biomass (L_{opt})	35.90*	35.60	35.00*	35.00*	35.60	35.60
Length at maturity (L_{mat})						
$0.65L_{opt}$	23.34*	23.14	22.75*	22.75*	23.14	23.14
$0.75L_{opt}$	26.93*	26.70	26.25*	26.25*	26.70	26.70
$0.9L_{opt}$	32.31*	32.04	31.50*	31.50*	32.04	32.04

where N_A^g is the number of animals of age A and gender g, M is the instantaneous rate of natural mortality (assumed to be independent of age and gender), F is the fully selected fishing mortality, S_A is the selectivity of animals of age A to the fishery, ω is the longevity and plus-group age (i.e., age at which older-aged individuals are accumulated in the population dynamics model), and R_F is the number of recruits based on a modified Beverton–Holt stock–recruit relationship (Mace and Doonan 1988) when fully selected fishing mortality

TABLE 2.—Estimates of the ratio of the proportion of mature fish in an unfished population ($P_{mat,F=0}$), the ratio of the length at maturity (L_{mat}) to length at optimal yield (L_{opt}), and the ratio of the age at maturity (A_{mat}) to age at optimal yield (A_{opt}) for assessed U.S. West Coast groundfish species. Summary statistics across species are provided at the bottom of the table.

| Species ($N = 21$)	$P_{mat,F=0}$	L_{mat}/L_{opt}	A_{mat}/A_{opt}
Arrowtooth flounder *Atheresthes stomias*	0.48	0.70	0.56
Black rockfish *Sebastes melanops*	0.24	1.06	1.13
Blue rockfish *Sebastes mystinus*	0.55	0.86	0.67
Cabezon *Scorpaenichthys marmoratus*	0.37	0.77	0.58
Canary rockfish *Sebastes pinniger*	0.57	0.84	0.69
Chilipepper *Sebastes goodei*	0.62	0.63	0.43
Cowcod *Sebastes levis*	0.56	0.64	0.50
Darkblotched rockfish *Sebastes crameri*	0.59	0.91	0.75
Dover sole *Microstomus pacificus*	0.47	0.78	0.61
English sole *Parophrys vetulus*	0.46	0.75	0.60
Gopher rockfish *Sebastes carnatus*	0.50	4.95	7.00
Pacific hake *Merluccius productus*	0.50	0.90	0.75
Kelp greenling *Hexagrammos decagrammus*	0.24	1.08	1.38
Lingcod *Ophiodon elongates*	0.45	0.78	0.56
Longspine thornyhead *Sebastolobus altivelus*	0.55	0.68	0.45
Petrale sole *Eopsetta jordani*	0.50	0.64	0.44
Sablefish *Anoplopoma fimbria*	0.76	0.85	0.50
California scorpionfish *Scorpaena guttata*	0.42	0.84	0.70
Shortspine thornyhead *Sebastolobus alascanus*	0.70	0.30	0.18
Starry flounder *Platichthys stellatus*	0.55	0.51	0.40
Yelloweye rockfish *Sebastes ruberrimus*	0.52	0.82	0.63
All species			
Mean	0.50	0.99	0.93
Third quartile	0.56	0.90	0.75
Median	0.50	0.78	0.60
First quartile	0.45	0.69	0.50
Harmonic mean	0.47	0.74	0.55
Without gopher rockfish			
Mean	0.50	0.77	0.62
Third quartile	0.56	0.85	0.69
Median	0.51	0.78	0.59
First quartile	0.46	0.67	0.49
Harmonic mean	0.46	0.71	0.53
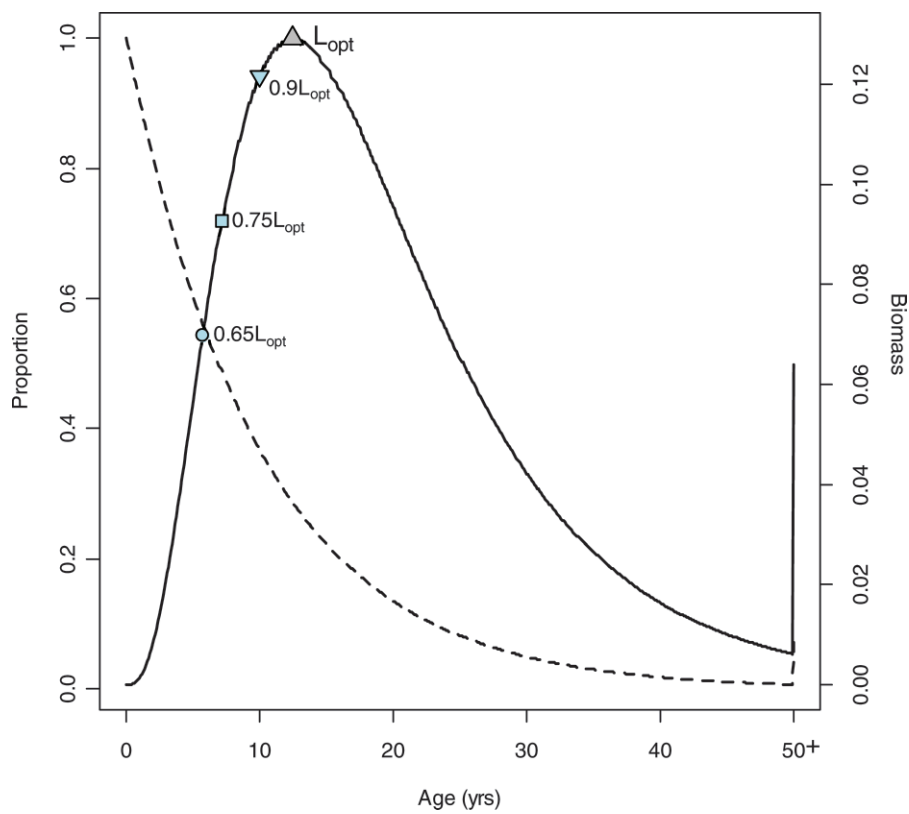
FIGURE 1.—Stable age proportions under no fishing (broken line) and cohort biomass (solid line) for life history 2 (LH2; see Table 1 for parameter values). Values for optimal fishing length (L_{opt}) and the three alternatives for length at maturity ($L_{mat} = 0.65L_{opt}$, $0.75L_{opt}$, or $0.9L_{opt}$) are provided for context.

TABLE 3.—Summary of the categories of uncertainty considered in this study. The additional sensitivities are based on the specifications for the base case (LH2) in Table 1. A qualitative description of the fish sampled by each selectivity curve is given in parentheses.

| Category	Levels
Life history (LH)	LH1, LH2, LH3, LH4 (see Table 2 for details)
Ratio of length at maturity to optimal fishing length (L_{mat}/L_{opt})	0.65, 0.75, 0.90
Selectivity curves (see also Figure 2)	Logistic (fish maturity ogive)
	$>0.9L_{opt}$ (optimally sized and larger fish)
	L_{opt} (optimally sized fish)
	$<0.9L_{opt}$ (small and immature fish)
	$<1.1L_{opt}$ (small and optimally sized fish)
	Reverse logistic (all but the very largest fish)
Fishing mortality (F)	LH1: 0.0 to 0.3 in increments of 0.012, F at maximum sustainable yield (MSY; F_{MSY}), F that reduces the population to 40% of unfished spawning biomass (F_{40}), F that reduces the population to 25% of unfished spawning biomass (F_{25})
	LH2: 0.0 to 0.6 in increments of 0.024, F_{MSY}, F_{40}, F_{25}
	LH3: 0 to 1 in increments of 0.04, F_{MSY}, F_{40}, F_{25}
	LH4: 0.0 to 1.5 in increments of 0.06, F_{MSY}, F_{40}, F_{25}
Steepness (h)	0.25, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0
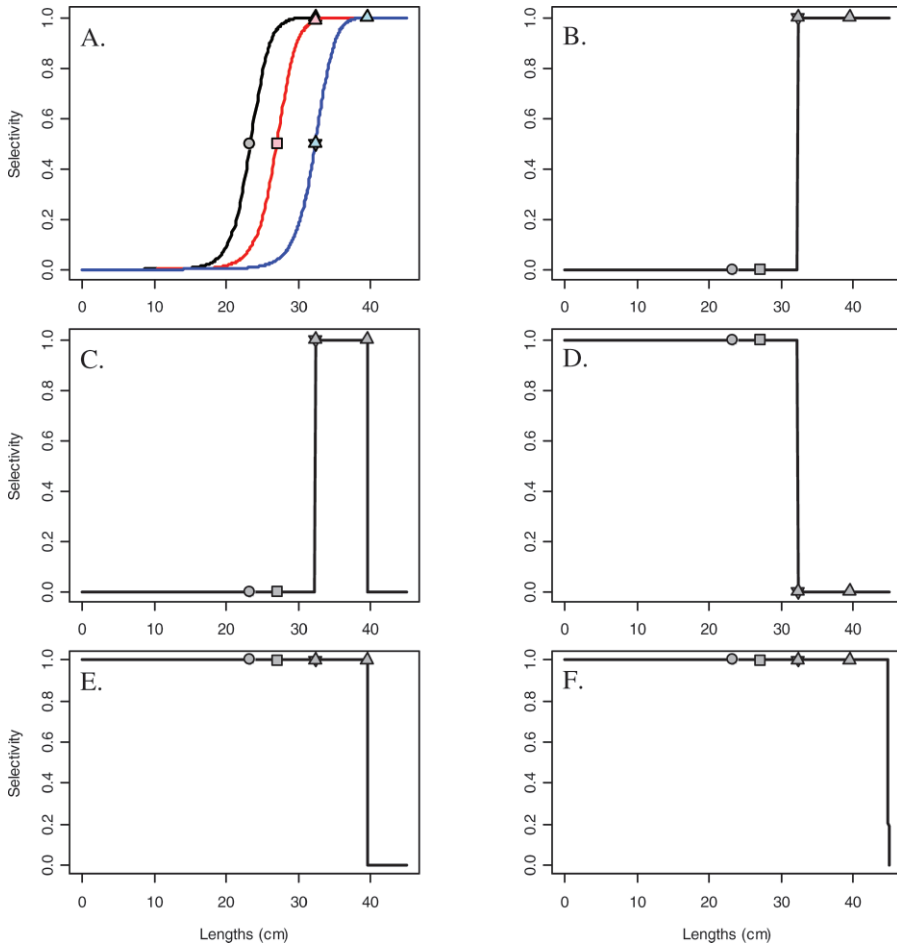
FIGURE 2.—Fishery selectivity patterns: (**A**) logistic (fish maturity ogive); (**B**) greater than 0.9 times the optimal fishing length (L_{opt}; i.e., optimally sized and larger fish); (**C**) L_{opt} (optimally sized fish); (**D**) less than $0.9L_{opt}$ (small and immature fish); (**E**) less than $1.1L_{opt}$ (small and optimally sized fish); and (**F**) reverse logistic (all fish but the very largest). Circles represent $0.65L_{mat}/L_{opt}$ (where L_{mat} is length at maturity); squares represent $0.75L_{mat}/L_{opt}$; and inverted triangles represent $0.9L_{mat}/L_{opt}$. The triangles indicate the ages spanning $0.9L_{opt}$ to $1.1L_{opt}$.

equals F:

$$R_F = \frac{R_{F=0}\left[4h\tilde{S}_F - \tilde{S}_{F=0}(1-h)\right]}{\tilde{S}_F(5h-1)}, \qquad (5)$$

where $R_{F=0}$ is recruitment in the absence of fishing (arbitrarily set to 1) assuming a 50:50 sex ratio, h is the steepness of the stock–recruitment relationship (the fraction of $R_{F=0}$ when SB is reduced to 20% of the virgin, or unfished, SB [SB_0]), $\tilde{S}_F$ is the SB per recruit when fully selected fishing mortality equals F, and $\tilde{S}_{F=0}$ is the SB per recruit in the absence of fishing.

$$\tilde{S}_F = \sum_{A=1}^{\omega} N_A^F W_A \delta_A, \qquad (6)$$

where δ_A is the fraction of animals of age A that are mature, W_A is the weight of an animal of age A based on the allometric growth model ($W = aL^b$) where length at age is assumed to be governed by the von Bertalanffy growth function (VBGF), rearranged to express age as a function of length:

$$A = A_0 - \frac{1}{k}\log_e\left(1 - \frac{L}{L_\infty}\right), \qquad (7)$$

where L_∞ is the asymptotic length, k is the growth coefficient, and A_0 is the theoretical age at a length of zero.

The maturity function is defined as

$$\delta_A = \{1 + \exp[-\log(19)(A - A_{mat})/\beta]\}^{-1}, \qquad (8)$$

FIGURE 3.—Relationships between the catch-based length proportions (P_x; open circles = P_{mat}; open triangles = P_{opt}; crosses = P_{mega}; each defined in Methods) for life history 2 (LH2; defined in Table 1) and other life histories (LH1, LH3, and LH4) across all selectivity patterns, fishing mortality rates, and steepness values. The solid red line is a 1:1 reference line.
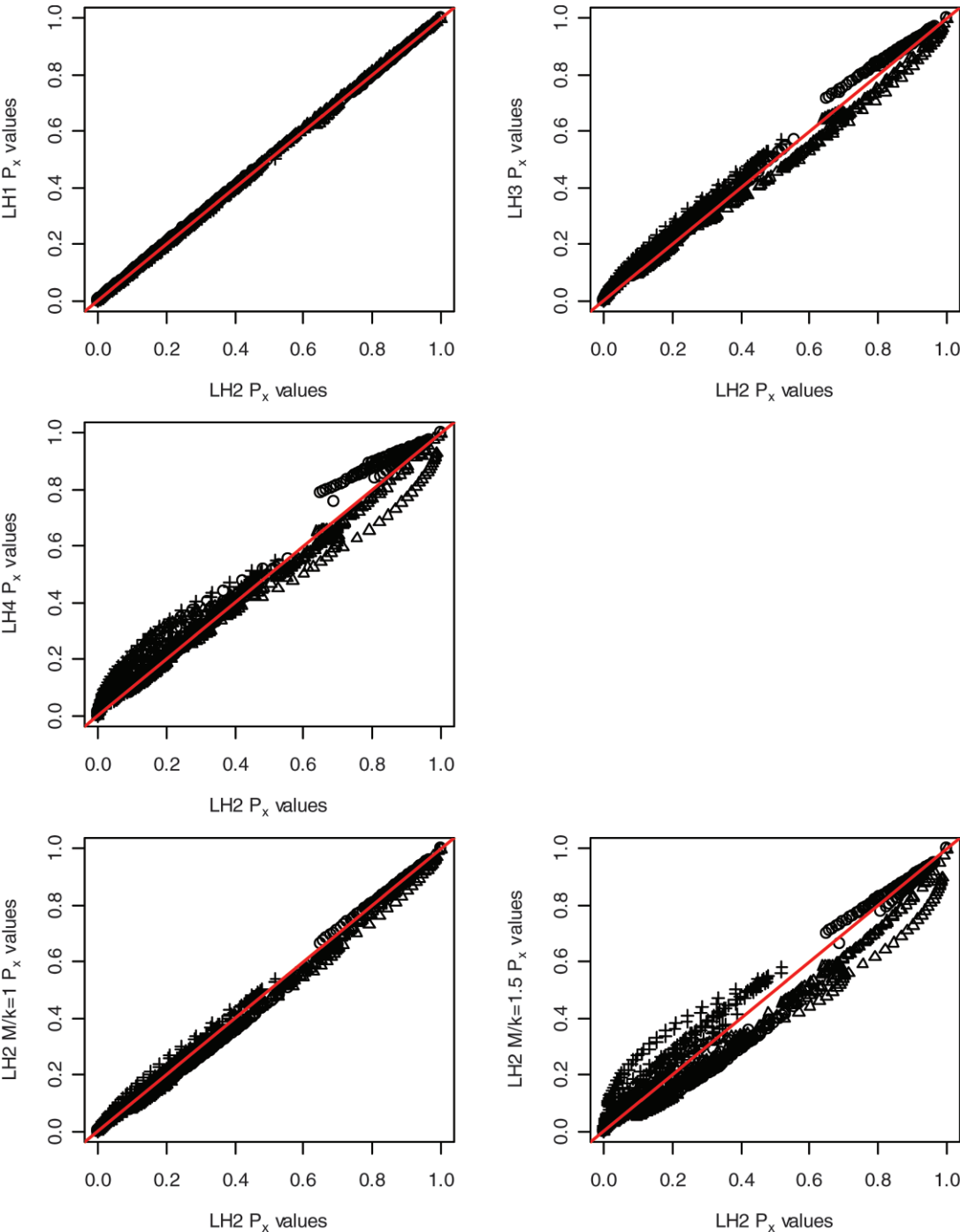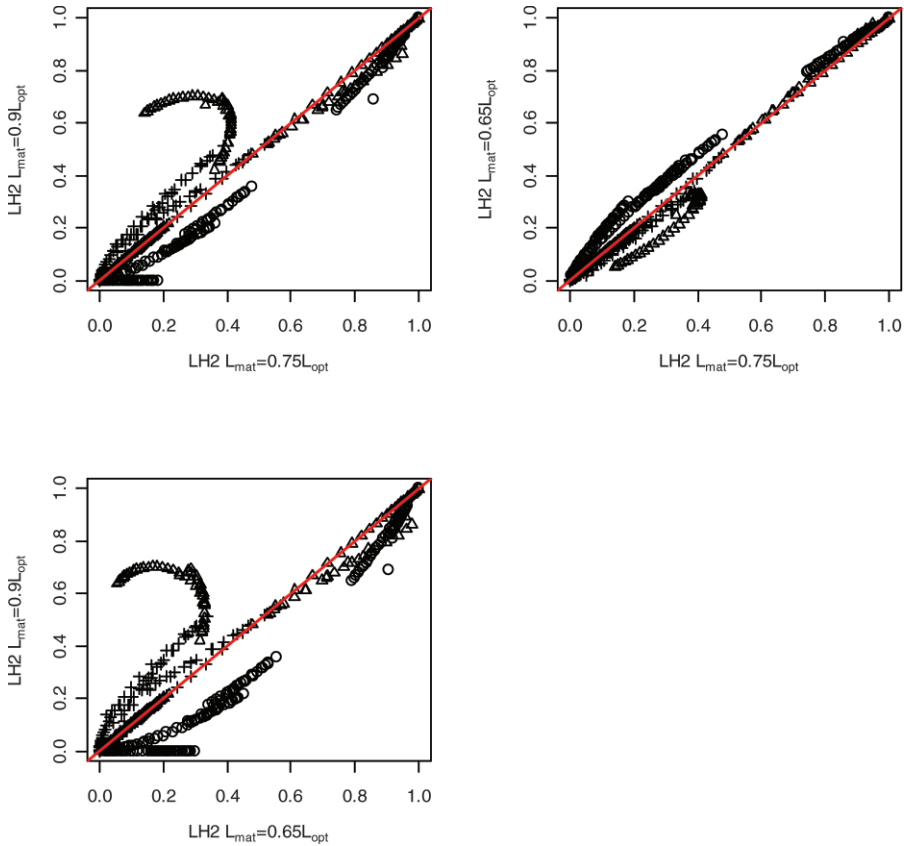
FIGURE 4.—Relationships between the catch-based length proportions (open circles = P_{mat}; open triangles = P_{opt}; crosses = P_{mega}; each defined in Methods) for different ratios of length at maturity (L_{mat}) to optimal fishing length (L_{opt}) for life history 2 (LH2; defined in Table 1) across all selectivity patterns, fishing mortality rates, and steepness values. The solid red line is a 1:1 reference line.

where A_{mat} is the age at 50% maturity and β is the difference between A_{mat} and the age at 95% maturity.

Age is considered at intervals of 0.1 year for greater resolution of lengths, but mortality rates are reported on an annual basis. Although this model is gender structured, the life history parameter values are set equal between genders to reduce complexity.

Defining life histories and parameter values.—The simulated lengths on which the catch length proportions are based depend on the values assigned to the parameters of the age-structured population dynamics model. These values (Table 1) were chosen to capture correlations commonly found among life history characteristics (Adams 1980; Winemiller and Rose 1992), were scaled based on data for species composing the U.S. West Coast groundfish fishery, and were selected to allow key areas of parameter uncertainty to be explored.

Three additional life history relationships relevant to defining P_x values were calculated from 21 assessed West Coast groundfish species as a way to represent the biological scenarios of West Coast groundfishes and maintain consistent relationships among life history parameters when simulating populations (Table 2): (1) P_{mat} at unfished levels ($P_{mat,F=0}$); (2) L_{mat}/L_{opt}; and (3) A_{mat}/A_{opt}. The $P_{mat,F=0}$ measure represents P_{mat} prior to fishing (equation 1) and calculated from the virgin age structure:

$$P_{mat,F=0} = \sum_{A \geq A_{mat}} N_{A,F=0} \Big/ \sum_{A \geq 0} N_{A,F=0}. \qquad (9)$$

The estimates of L_{mat}/L_{opt} and A_{mat}/A_{opt} for gopher rockfish were outliers, so summary statistics with gopher rockfish excluded are also provided in Table 2.

The base case choice for the relationship between age and length (i.e., VBGF parameters L_∞, k, and A_0; life history LH2, Table 1) was taken from a meta-analysis of growth curves for the genus *Sebastes*
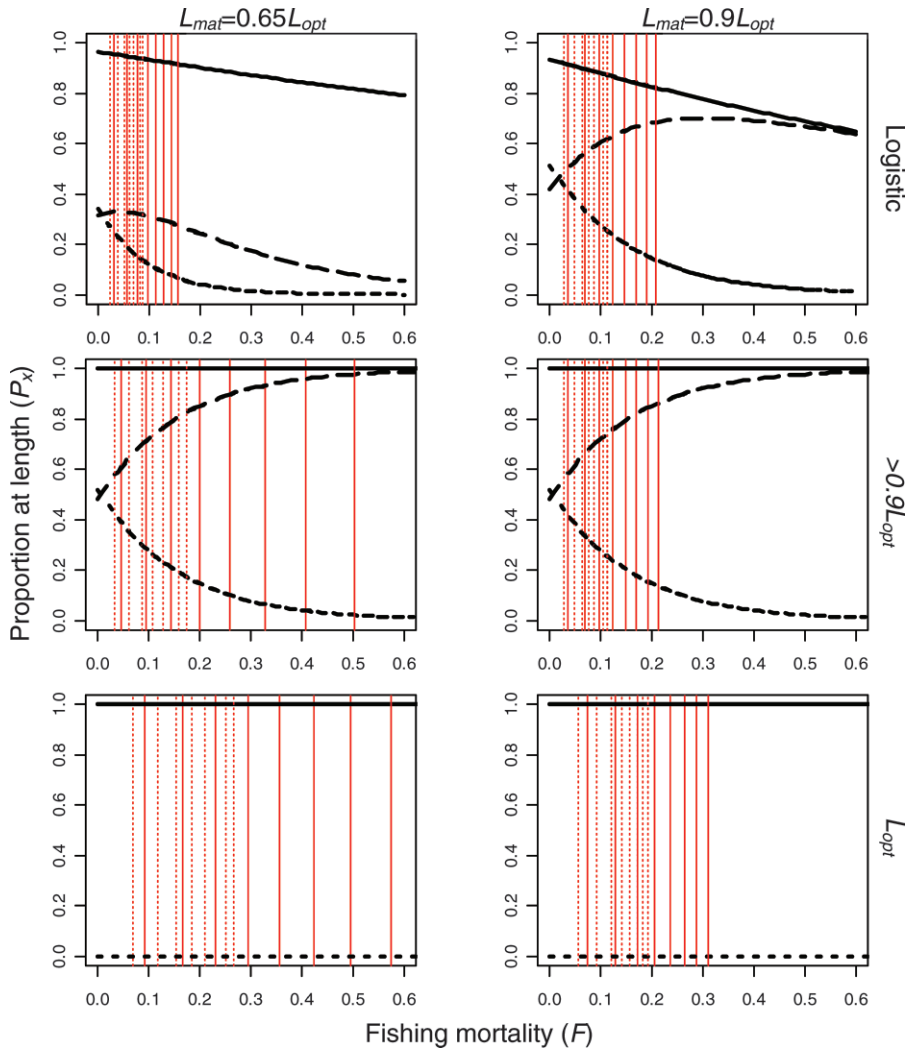
FIGURE 5.—Catch-based length proportions (P_x; solid black line = P_{mat}; dashed black line = P_{opt}; dotted black line = P_{mega}; each defined in Methods) versus fishing mortality (F) for two values of length at maturity (L_{mat}; equal to 0.65 or 0.9 times optimal fishing length [L_{opt}]) and the three selectivity patterns (defined in Methods) that satisfy Froese's (2004) recommendations across nine steepness (h) values. Black lines are a composite trajectory of length proportions for all h-values, where the highest value ($h = 1$) covers a larger range of the trajectory and the lowest value ($h = 0.25$) covers a smaller range per F. The vertical red dashed and solid lines represent, respectively, the F corresponding to the target reference point (TRP; 0.4 times the unfished spawning biomass [SB_0]) and limit reference point (LRP; $0.25SB_0$) for each h. The intersection of the red and black lines corresponds to the F at the TRP or LRP for each value of h (with lower h-values closest to the origin).

(Helser et al. 2007), and sensitivity was explored to three other choices for k (life histories LH1, LH3, and LH4) providing a range of possible life history conditioning among groundfishes, though not representing any one species in particular. Simulation results were insensitive to the choice of L_∞, so this parameter was kept constant among each life history variation. Hoenig's equation (Hoenig 1983) for estimating M from ω was used as a way to establish ω and M for

LH2 (Table 1) consistent with values of $P_{mat,F=0}$ near the median of 0.5 (Table 2). This creates populations that under exponential decay via M and zero F produce mature population proportions consistent with those estimated for virgin populations of assessed West Coast groundfish stocks. Values for M and hence ω for the other life history scenarios (LH1, LH3, and LH4; Table 1) were set so that M/k was a constant, and the parameter values for these scenarios were checked to
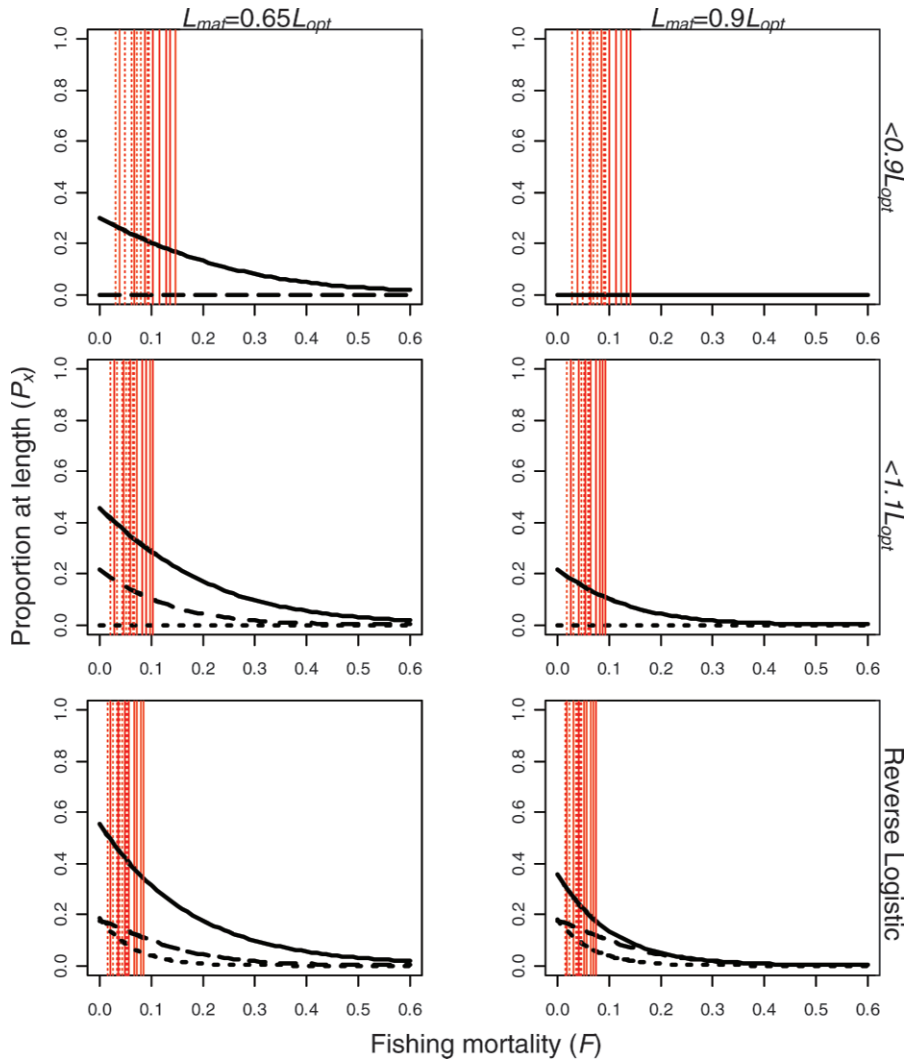
FIGURE 6.—As in Figure 5, except that results are shown for the three selectivity patterns (defined in Methods) that do not satisfy Froese's (2004) recommendations.

ensure that the resulting $P_{mat,F=0}$ values were between the first and third quartiles for $P_{mat,F=0}$ in Table 2. The M/k value that forms the base case for the analyses in this article differs from those values found in other empirical studies (Jensen 1996; Simpfendorfer 1999). Using those literature values for M/k leads to $P_{mat,F=0}$ values near 0.3 (i.e., much lower than most of the values in Table 2). Sensitivity to alternative values for M/k (1.0 and 1.5) was, however, explored (Jensen 1996; Froese et al. 2008). The values for the parameters of the length–weight relationship (intercept a and slope b) were set to be characteristic of those for groundfish species off the U.S. West Coast (0.001 and 3.0, respectively; Burton et al. 2000).

The values for L_{mat} were computed from L_{opt} by using the ratio of L_{mat} to L_{opt} (Froese and Binohlan 2000). The values assumed for this ratio ($L_{mat}/L_{opt} = 0.65$, 0.75, and 0.9; Figure 1) are taken from Table 2 and from additional estimates given by Froese and Binohlan (2000) and reported by Froese et al. (2008). The low and high values for L_{mat}/L_{opt} capture the first and third quartiles for this ratio in Table 2, while the central value is close to the harmonic mean of L_{mat}/L_{opt} based on all species. Conversion of L_{mat} to A_{mat} was accomplished by using the VBGF, and β was set to $A_{mat}/4$ (a general relationship consistent with values seen for West Coast groundfish).
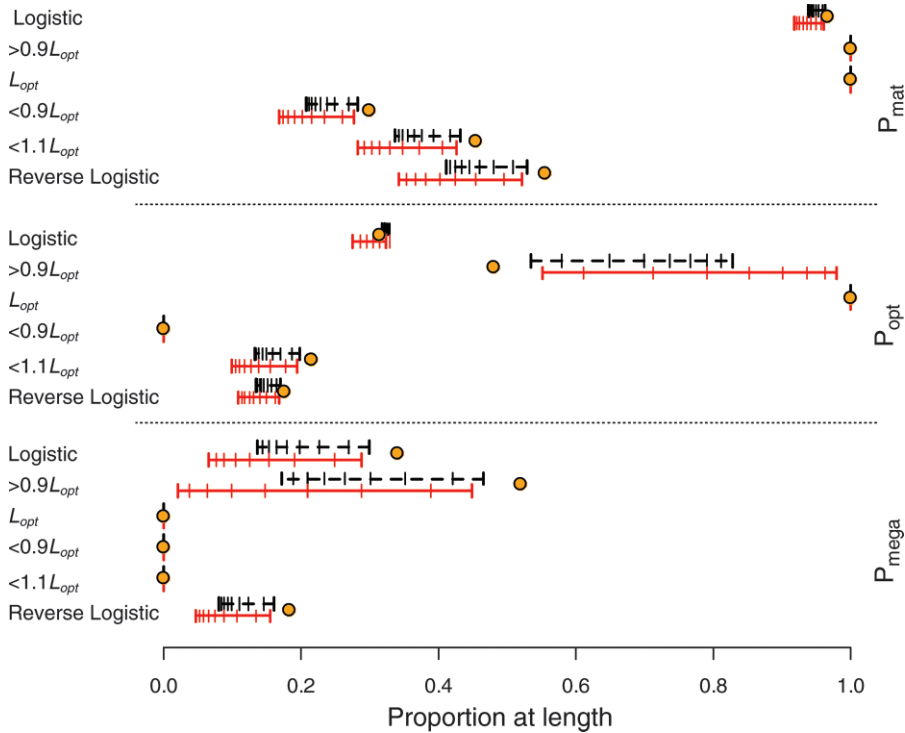
Nine values of h (Table 3) were considered. The

FIGURE 7.—Catch-based length proportions (P_{mat}, P_{opt}, and P_{mega}; defined in Methods) at unfished spawning biomass (SB_0; filled circles), $0.4SB_0$ (black dashed lines), and $0.25SB_0$ (red solid lines) for six selectivity patterns (defined in Methods) when length at maturity equals 0.65 times the optimal fishing length. Each vertical bar within a line segment indicates the results for a given steepness (h) value. The vertical bar closest to the circle is for h equal to 0.25, and the bar farthest from the circle is for h equal to 1.

lowest h-value was set to 0.25 following He et al. (2006), who argued that values less than this are highly unlikely.

Fishing, sampling, and calculating P_x proportions of populations.—Fishing the simulated populations requires defining a fishing rate F and a selectivity-at-age (S_A) curve. Values for F from 0 (unfished) to 0.3, 0.6, 1.0, and 1.5 were considered for each of the four life histories, respectively (Table 3), and the limits to F were defined by the nature of the life history (e.g., $F = 0.3$ was the maximum F for LH1 because it had the lowest M; conversely, LH4 had the highest M and thus the highest potential F of 1.5). In addition, the F-values corresponding to those that reduced the population to 40% (F_{40}) and 25% (F_{25}) of SB_0 were also calculated. Six selectivity patterns (converting age selectivity to length selectivity via the VBGF) were chosen to explore a wide range of possibilities that might affect resultant P_x values (Figure 2; Table 3). Three selectivity patterns (logistic = maturity ogive [hereafter, "logistic"]; full selectivity of fish larger than $0.9L_{opt}$

[hereafter, ">$0.9L_{opt}$"]; and full selectivity of optimally sized fish [hereafter, "L_{opt}"]) comply with Froese's (2004) sustainability recommendations, while the other three patterns (full selectivity of fish smaller than $0.9L_{opt}$ [hereafter, "<$0.9L_{opt}$"]; full selectivity of fish smaller than $1.1L_{opt}$ [hereafter, "$1.1L_{opt}$"]; and the inverse of the above age-based logistic selectivity [hereafter, "reverse logistic"]) violate Froese's (2004) sustainability recommendations. Given that three values of L_{mat} are considered, three equivalent logistic selectivity curves (and the resultant reverse logistic selectivity) were also considered (Figure 2).

The catch-based length proportions were computed by (1) "sampling" the catch age compositions (without error) by using the selectivity pattern used to drive the population dynamics and then (2) converting the age compositions to length compositions. The proportion of the catch in age-class A, P_A, was given by:

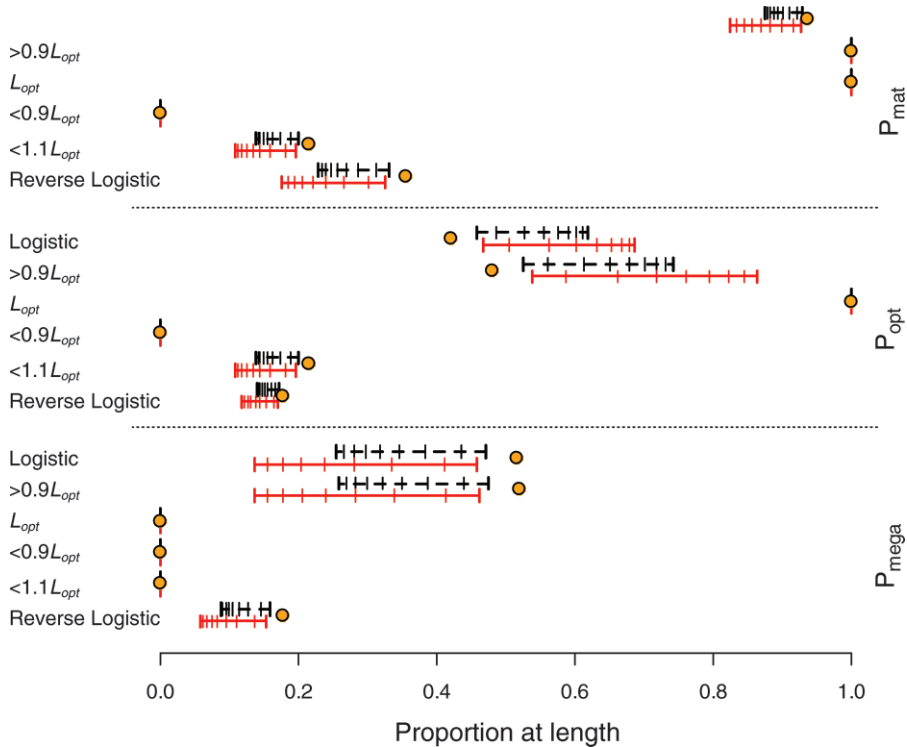$$P_A = N_A S_A \Big/ \sum_{A'=0}^{\omega} N_{A'} S_{A'}. \qquad (10)$$

FIGURE 8.—As in Figure 7, except that the results pertain to length at maturity equal to 0.9 times the optimal fishing length (L_{opt}).

The values for P_{mat}, P_{opt}, and P_{mega} were then compared to identify patterns with selectivity, F, and h that would indicate whether the population was below either the TRP ($0.4SB_0$) or the LRP ($0.25SB_0$) for consistency with how West Coast groundfish are managed (Punt 2003).

Results

Sensitivity of Length Proportions to Life Histories and Ratio of Length at Maturity to Optimal Fishing Length

Differences in the values for the catch-based length proportions (P_{mat}, P_{opt}, and P_{mega}) among the four life histories and two M/k ratios were insufficient (i.e., demonstrating a strong linear trend along the 1:1 comparison line) to permit further consideration of the additional life histories (Figure 3); all subsequent results are therefore only reported for life history LH2. However, the catch proportions (particularly P_{mat}) were sensitive to the assumed value for L_{mat}/L_{opt} (Figure 4). This sensitivity was caused when L_{mat}/L_{opt} was equal to 0.9, which is the same value as the lower length ($0.9L_{mat}$) used to calculate P_{opt}. When these two values are equivalent, all measures of P_x are affected. Consequently, sensitivity to L_{mat}/L_{opt} was retained throughout the rest of the analyses.

Sensitivity of Length Proportions to Selectivity

The catch-based length proportions do not depend greatly on h given F within a selectivity pattern, but they do depend on the value assumed for L_{mat}/L_{opt} and vary among selectivity patterns (Figure 5). Values for P_{mat} and P_{opt} are greater for the selectivity patterns that satisfy Froese's (2004) sustainability recommendations (Figure 5) than for those selectivity patterns that do not (Figure 6), as expected. However, the length proportions and their trends with F differ among the selectivity patterns that satisfy Froese's (2004) sustainability recommendations (Figure 5). Such differences also occur for the selectivity patterns in Figure 6, but the effect is much smaller.

Using Length Proportions as Reference Points

The values for P_x at which the TRP and LRP for SB are obtained depend on h (Figures 5, 6; with the lowest F corresponding to the lowest h). Higher values of F are obtained at TRPs and LRPs when the selectivity pattern satisfies Froese's (2004) sustainability recommendations (Figure 5, intersection of black and red lines). These selectivities also demonstrate the largest sensitivities to h and associated F at the RPs.
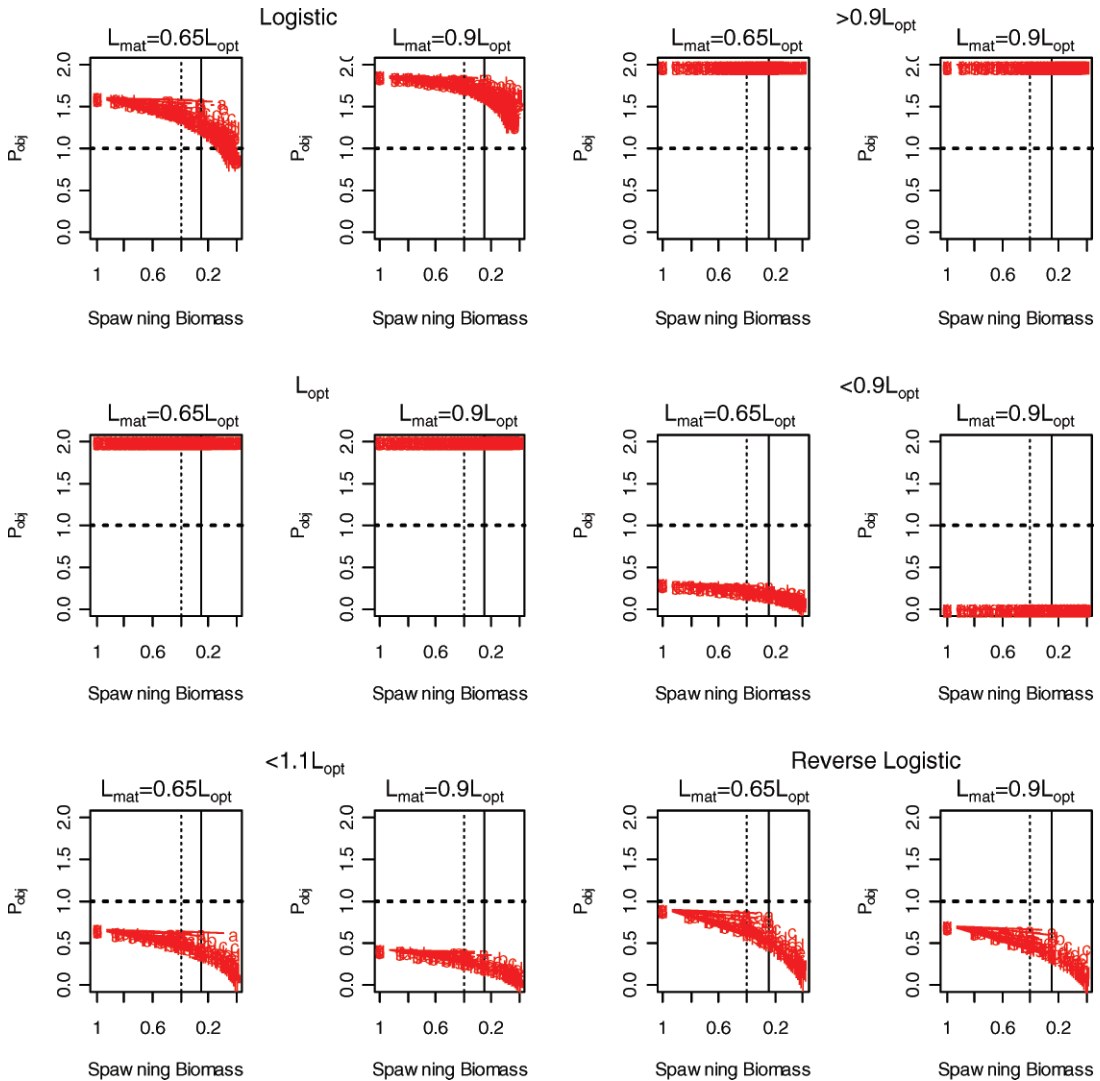
The values for P_x are often not very sensitive to stock

FIGURE 9.—Simulated spawning biomass (SB; relative to unfished SB) versus P_{obj} ($=P_{mat}+P_{opt}+P_{mega}$; defined in Methods) for six selectivity patterns (defined in Methods), two values for length at maturity (L_{mat}; equal to 0.65 or 0.9 times optimal fishing length [L_{opt}]), and nine values for steepness (represented by letters a to i).

status (Figures 7, 8). For example, the ranges of values for the proportions corresponding to an overfished stock (SB = 0.25SB$_0$), a stock at the target level (SB = 0.4SB$_0$), and an unfished stock (SB$_0$) often overlap to a substantial extent (Figures 7, 8). Only when the productivity of a stock is very high (e.g., h approaches 1.0) is there meaningful contrast between the length-based catch proportions at 0.25SB$_0$, 0.4SB$_0$, and SB$_0$. In other cases, there is no contrast in the values of P_{mat}, P_{opt}, or P_{mega}, such as when fishing occurs at L_{opt} (by definition the optimal fishing pattern).

Also troubling is the wide range of possible values for the catch-based length proportions. For example, values of P_{mat} that indicate that the stock is at 0.25SB$_0$ range from 1.0 to approximately 0.2 when L_{mat}/L_{opt} is 0.65 (Figure 7) and from 0 to 1 when L_{mat}/L_{opt} is 0.9 (Figure 8), with the range primarily reflecting the impact of the selectivity pattern. The same holds true for P_{opt}, while P_{mega} could range from 0.5 to 0.0. These results challenge the notion that values for P_{mega} between 0.3 and 0.4 or at 0 will indicate healthy stocks (Froese 2004). Moreover, these results indicate that
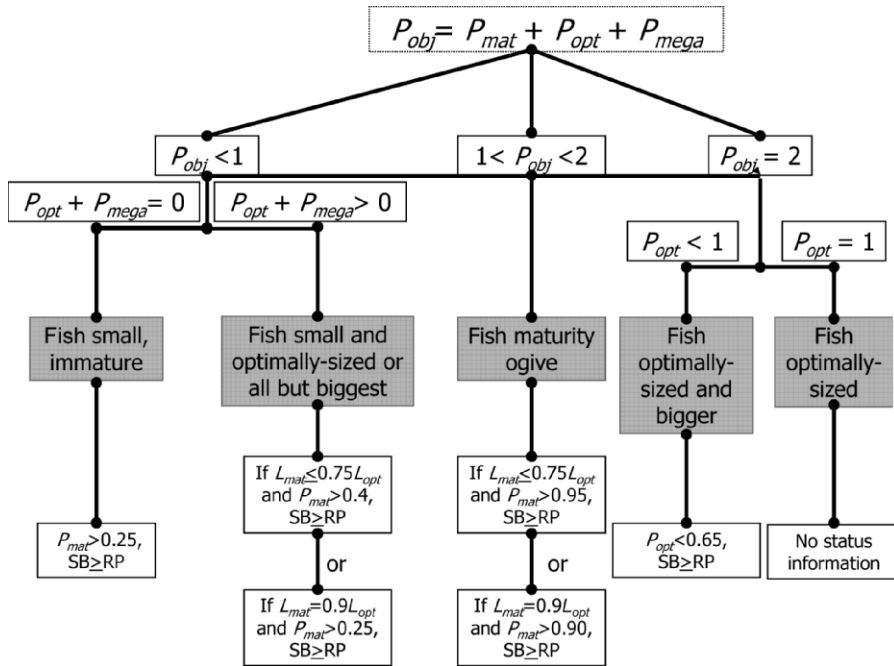
FIGURE 10.—Decision tree for defining indicator values (boxes) of stock status above spawning biomass (SB) reference points (RPs) by using length composition data. The main decisions relate to selectivity type (distinguished by the P_{obj} value), the ratio of length at maturity (L_{mat}) to optimal fishing length (L_{opt}), and recruitment compensation (measured by steepness). To use the decision tree, the P_{mat}, P_{opt}, and P_{mega} (collectively referred to as P_x; each defined in Methods) are calculated by using length composition and life history values (see text for details). The sum of the P_x values gives the P_{obj} value, which describes the selectivity of the fishery (noted in gray boxes). Following the tree down from that branch, the corresponding value of either P_{mat} or P_{opt} is interpreted to determine whether the SB is at or above the target RP.

distinguishing selectivity is critical to establishing RPs based on catch length compositions.

The sum of the catch-based length proportions (P_{mat}, P_{opt}, and P_{mega}), herein referred to as P_{obj}, provides a means to distinguish selectivity patterns. There is a more consistent relationship between P_{obj} and SB across h-values and between values for L_{mat}/L_{opt} (Figure 9) than using P_{mat}, P_{opt}, or P_{mega} alone. Two strong relationships are apparent from Figure 9: (1) a P_{obj} value less than 1 is indicative of selectivity patterns that do not follow Froese's (2004) sustainability recommendations; and (2) a P_{obj} value greater than 1 is indicative of selectivity patterns that follow Froese's (2004) recommendations. Within the latter distinction, a P_{obj} value between 1 and 2 clearly distinguishes selectivity patterns containing some immature and suboptimally sized fish (e.g., the logistic selectivity pattern) from those for which P_{obj} is equal to 2 (e.g., the $>0.9L_{opt}$ and L_{opt} selectivity patterns). Within the former, the $<1.1L_{opt}$ (small and optimally sized fish) and reverse logistic (all but the largest fish) selectivity patterns can be distinguished by using P_{mega} values. Finally, if P_{obj} is less than 1 and if $P_{opt} + P_{mega}$

= 0, the fishery is one that fishes only immature individuals and is considered highly undesirable under Froese's (2004) sustainability recommendations (see also Myers and Mertz 1998).

The results in Figures 7–9 allow the construction of a decision tree (Figure 10) for indicators based on P_x values. Given values for P_{obj}, P_{mat}, and P_{opt} and the relationship between L_{mat} and L_{opt}, Figure 10 provides a set of rules for defining when a stock is below the TRP or LRP that does not require knowledge of F, SB, and h.

Table 4 illustrates the trade-offs of the indicators suggested in Figure 10. It is clear from Table 4 that the catch-based length proportions are not sensitive enough across all h-values to reliably determine when the stock is at the TRP or below the LRP, so any assigned indicator values should be considered trigger points and should be determined under case-specified risk analysis. The proposed indicator values offered here are used only as examples to explain the basic approach.

In general, the example decision tree allows stocks that are below $0.25SB_0$ to be identified as such unless h

TABLE 4.—Values of catch-based length proportions P_x (P_{mat} or P_{opt}; defined in Methods) given depletion (spawning biomass [SB]) and steepness (h) for different values of length at maturity ($L_{mat} = 0.65$ or 0.9 times optimal fishing length [L_{opt}]) and P_{obj} (sum of P_{mat}, P_{opt}, and P_{mega}), and selectivity patterns (defined in Methods; RevLog = reverse logistic pattern). When P_{obj} is less than 1, only selectivities for which $P_{opt} + P_{mega}$ is greater than 0 are given. Asterisks indicate P_x values outside the trigger point (see also Figure 10).

		$L_{mat} = 0.65L_{opt}$				$L_{mat} = 0.75L_{opt}$			
		$P_{obj} < 1$		$2 > P_{obj} > 1$	$P_{obj} = 2$	$P_{obj} < 1$		$2 > P_{obj} > 1$	$P_{obj} = 2$
		$<1.1L_{opt}$	RevLog	Logistic	$>0.9L_{opt}$	$<1.1L_{opt}$	RevLog	Logistic	$>0.9L_{opt}$
Depletion	h	P_{mat}	P_{mat}	P_{mat}	P_{opt}	P_{mat}	P_{mat}	P_{mat}	P_{opt}
SB_0		0.45	0.55	0.97	0.48	0.36	0.48	0.96	0.48
Trigger P_x		>0.40	>0.40	>0.95	<0.65	>0.40	>0.40	>0.95	<0.65
$0.4SB_0$	0.25	0.43*	0.53*	0.96*	0.53*	0.34	0.45*	0.95*	0.53*
	0.30	0.42*	0.51*	0.96*	0.58*	0.33	0.43*	0.95*	0.57*
	0.40	0.39	0.48*	0.95	0.65	0.31	0.40	0.94	0.64*
	0.50	0.38	0.46*	0.95	0.70	0.29	0.38	0.93	0.68
	0.60	0.36	0.45*	0.95	0.74	0.28	0.37	0.93	0.72
	0.70	0.36	0.43*	0.94	0.77	0.27	0.36	0.93	0.75
	0.80	0.35	0.42*	0.94	0.79	0.27	0.35	0.92	0.77
	0.90	0.34	0.42*	0.94	0.81	0.26	0.34	0.92	0.79
	1.00	0.34	0.41*	0.94	0.83	0.26	0.34	0.92	0.80
$0.25SB_0$	0.25	0.43*	0.52*	0.96*	0.55*	0.34	0.45*	0.95*	0.55*
	0.30	0.40	0.50*	0.96*	0.61*	0.32	0.42*	0.94	0.60*
	0.40	0.37	0.45*	0.95	0.71	0.29	0.38	0.93	0.70
	0.50	0.35	0.42*	0.94	0.79	0.27	0.35	0.92	0.77
	0.60	0.33	0.40	0.94	0.85	0.25	0.33	0.91	0.82
	0.70	0.31	0.38	0.93	0.90	0.24	0.31	0.91	0.87
	0.80	0.30	0.37	0.93	0.94	0.23	0.29	0.90	0.90
	0.90	0.29	0.35	0.92	0.96	0.22	0.28	0.89	0.93
	1.00	0.28	0.34	0.92	0.98	0.21	0.27	0.89	0.95

is less than 0.3. For example, following one branch of the tree, let us consider the case when P_{obj} is less than 1, $P_{opt} + P_{mega}$ is greater than 0, and L_{mat} equals $0.65L_{opt}$ (Table 4). As long as the P_{mat} value is above the suggested trigger point of 0.4, the stock is correctly assessed to be (1) above $0.25SB_0$ unless h is 0.25 or less and (2) above $0.4SB_0$ unless h is 0.3 or less when selectivity is governed by the $<1.1L_{opt}$ pattern. However, under the reverse logistic selectivity pattern, this trigger point fails to detect a stock that is below $0.4SB_0$ (but still above $0.25SB_0$) for any value of h or a stock that is below $0.25SB_0$ if h is less than 0.5. Alternatively, one could separate the $<1.1L_{opt}$ and reverse logistic selectivity patterns by using P_{mega} values (Figures 7, 8), so an additional trigger point based on P_{mega} could be included to reduce error in detection between these selectivities.

The probability that the stock is below the SB-based TRP, LRP, or both for all possible values of a P_x trigger point is listed in Table 5. Table 5 integrates the uncertainty across h-values and the selectivity patterns for each P_{obj} branch of the decision tree. For instance, given complete uncertainty in h, there is a 26% chance that the true SB is below $0.4SB_0$ (the TRP) and a 17% chance that it is below $0.25SB_0$ (the LRP) if P_{obj} is less

than 1, L_{mat} is less than $0.75L_{opt}$, and P_{mat} equals 0.4 (Tables 4, 5).

Discussion

Length-Based Reference Points and Harvest Control Rules

Size-related measures (e.g., mean length or weight; length compositions) have long been used as indicators of response to population decline (Beverton and Holt 1957; Smith 1994b). Recent extensions of this idea demonstrate that size composition changes with increased F (Gislason and Rice 1998; Bianchi et al. 2000), although such studies, as applied mostly to fish communities and ecosystems, illustrate general trends rather than linking size-related measures to RPs (Rochet and Trenkel 2003). Given that catch length frequencies are among the easiest data to collect, it is valuable to know how to interpret such information in the context of providing directed fishery management advice.

Froese (2004) advanced this approach by providing simple but fundamentally sound guidance for how to interpret fishery length composition data to avoid overly depleting stocks. However, translating the broad suggestions of Froese (2004; i.e., to target the mature

TABLE 4.—Extended.

Depletion	h	$L_{mat} = 0.9L_{opt}$			
		$P_{obj} < 1$		$2 > P_{obj} > 1$	$P_{obj} = 2$
		$<1.1L_{opt}$	RevLog	Logistic	$>0.9L_{opt}$
		P_{mat}	P_{mat}	P_{mat}	P_{opt}
SB_0		0.22	0.36	0.94	0.48
Trigger P_x		>0.25	>0.25	>0.90	<0.65
$0.4SB_0$	0.25	0.20	0.33*	0.93*	0.53*
	0.30	0.19	0.31*	0.92*	0.56*
	0.40	0.17	0.29*	0.91*	0.61*
	0.50	0.16	0.27*	0.90	0.65
	0.60	0.16	0.26*	0.89	0.68
	0.70	0.15	0.25	0.89	0.70
	0.80	0.15	0.24	0.88	0.72
	0.90	0.14	0.23	0.88	0.73
	1.00	0.14	0.23	0.87	0.74
$0.25SB_0$	0.25	0.20	0.32*	0.93*	0.54*
	0.30	0.18	0.30*	0.92*	0.59*
	0.40	0.16	0.26*	0.90	0.66
	0.50	0.15	0.24	0.88	0.72
	0.60	0.13	0.22	0.87	0.76
	0.70	0.13	0.21	0.86	0.79
	0.80	0.12	0.19	0.84	0.82
	0.90	0.11	0.18	0.83	0.85
	1.00	0.11	0.18	0.82	0.86

and optimally sized individuals) into practical management advice can be problematic (Rochet and Trenkel 2003; Link 2005), especially given the strong interaction between selectivity and stock status. Punt et al. (2001) formally evaluated size-based indicators and their potential use as RPs, offering cautionary advice on the potentially imprecise but informative nature of using mean size and size compositions as proxies of population depletion.

This article continues such thoughts, related specifically to the measures offered by Froese (2004), and shows that fish stocks with P_{mat} and P_{opt} values much less than 1.0 can theoretically be sustainably fished, while also demonstrating that major decreases in population biomass can occur even when P_{opt} equals 1.0, the theoretically ideal situation. We also illustrate how Froese's (2004) original suggestion of targeting a P_{mega} value either between 0.30 and 0.40 or at 0 may encourage overfishing under certain circumstances.

The approach outlined in this article offers a way to interpret length composition data even if direct information on mortality, fishery selectivity, and recruitment compensation (i.e., h) is unknown. The decision tree (Figure 10) can provide context-specific guidance for interpreting stock status when a fishery is not operating at an optimal fishing selectivity (L_{opt}), thus providing more flexible management advice. Noting that the sensitivity to different life histories is low (Figure 3), these results are germane to a wide range of stocks and fisheries.

Identifying a link between a trigger point and stock status (by using Figure 10) is the first step to using catch length composition data to inform future catch recommendations via harvest control rules (HCRs). Harvest control rules define the functional response of removals to the current state of the resource as reflected by indicators or RPs (Restrepo and Powers 1999; Smith et al. 2008). The decision tree (Figure 10) and risk assessment (Tables 4, 5) suggest ways in which catch-based length proportions can be used to provide advice regarding harvest regulation within the context of existing management RPs. Specifically, an HCR could act on both P_{obj} and the related P_x indicator(s) (Figure 10) to adjust catches up or down. However, a full examination of P_x-based HCRs requires a management strategy evaluation (MSE; Smith 1994a; Sainsbury et al. 2000; Smith et al. 2007) and is hence beyond the scope of this study.

Using Froese's (2004) P_x values to interpret catch-based length compositions in the context of status determination remains less than ideal in several ways. For example, it is not possible to evaluate stock status when selectivity contains only "optimal" individuals (i.e., when $P_{mat} = 1$; represented here by the $>0.9L_{opt}$ and L_{opt} selectivity patterns). There are two main ways of transitioning from a selectivity pattern that includes all optimally sized and larger individuals (e.g., $>0.9L_{opt}$) to the "most optimal" selectivity pattern that encompasses all optimally sized individuals (L_{opt}): (1) stop fishing individuals that are counted in P_{mega}; or (2) increase F until there are no more fish of P_{mega} size. The former would be considered conservative and the latter reckless with respect to maintaining stock status above RPs, yet both strategies result in the same P_x values during monitoring. This suggests that if a fishery is taking only mature individuals, but not just at P_{opt}, it may be most precautionary to assign an HCR that forces the L_{opt} strategy. This would be carried out by ensuring that a P_{obj} equal to 2 and a P_{mat} equal to 1 are both heavily enforced in an HCR. In a similar approach, it may be wise to have a large penalty on catch for a fishery that takes only immature fish (far left branch of Figure 10) unless there is additional evidence that the M/F relationship is much smaller than 1 (Figure 6).

One major drawback with the simulation approach we took is the assumption that there is no variation in length at age. This assumption helps to simplify the analyses and helps one discern general patterns, but it

TABLE 5.—Probability (p) of being below the target (0.4 times unfished spawning biomass [SB_0]) and limit ($0.25SB_0$) spawning biomass reference points given trigger values for catch-based length proportions P_x (either P_{mat} or P_{opt}; defined in Methods) for different values of P_{obj} (sum of P_{mat}, P_{opt}, and P_{mega}) and length at maturity ($L_{mat} \leq 0.75 \times$ optimal fishing length [L_{opt}] or $L_{mat} = 0.9L_{opt}$) integrated across steepness values. Probabilities assigned to P_{obj} values less than 1 are integrated over the $<1.1L_{opt}$ and reverse logistic selectivity patterns (defined in Methods); probabilities assigned to P_{obj} values between 1 and 2 are based on the logisitic selectivity pattern; and probabilities assigned to P_{obj} values equal to 2 are based on the $>0.9L_{opt}$ selectivity pattern.

	$P_x = P_{mat}$								$P_x = P_{opt}$	
	$P_{obj} < 1$				$1 < P_{obj} < 2$				$P_{obj} = 2$	
	$p < 0.4SB_0$		$p < 0.25SB_0$		$p < 0.4SB_0$		$p < 0.25SB_0$		$p < 0.4SB_0$	$p < 0.25SB_0$
Trigger P_x	$\leq 0.75L_{opt}$	$0.9L_{opt}$	$\leq 0.75L_{opt}$	$0.9L_{opt}$	$\leq 0.75L_{opt}$	$0.9L_{opt}$	$\leq 0.75L_{opt}$	$0.9L_{opt}$	All L_{mat} values	
1.00	0	0	0	0	0	0	0	0	100	100
0.95	0	0	0	0	22	0	11	0	100	93
0.90	0	0	0	0	100	44	83	22	100	74
0.85	0	0	0	0	100	100	100	67	100	63
0.80	0	0	0	0	100	100	100	100	89	52
0.75	0	0	0	0	100	100	100	100	74	37
0.70	0	0	0	0	100	100	100	100	48	30
0.65	0	0	0	0	100	100	100	100	33	22
0.60	0	0	0	0	100	100	100	100	22	15
0.55	0	0	0	0	100	100	100	100	11	7
0.50	4	0	2	0	100	100	100	100	0	0
0.45	9	0	6	0	100	100	100	100	0	0
0.40	26	0	17	0	100	100	100	100	0	0
0.35	39	0	26	0	100	100	100	100	0	0
0.30	56	7	44	7	100	100	100	100	0	0
0.25	70	19	61	11	100	100	100	100	0	0
0.20	83	37	76	22	100	100	100	100	0	0
0.15	87	52	87	44	100	100	100	100	0	0
0.10	100	67	96	67	100	100	100	100	0	0
0.05	100	67	100	67	100	100	100	100	0	0
0.00	100	67	100	67	100	100	100	100	0	0

loses realism and therefore the power of the decision rule (Table 5) is probably overestimated. Furthermore, deviations from our presented results would be seen if maturity is age based instead of size based, although the exploration of a range of L_{mat}/L_{opt} ratios does address this uncertainty to some extent. Also not considered here is how the L_{mat}/L_{opt} ratio may change with fishing-induced alteration of life history traits (Conover and Munch 2002).

Another challenge associated with using P_x values is the very small difference between expectations of P_x for fished populations at the trigger points and for unfished populations, especially those with low h. The contrast between P_x at SB_0 and $0.4SB_0$ or $0.25SB_0$ increases with h, but h is unknown for most fishes. This contrast, or the lack thereof, will affect the functionality of subsequent HCRs, particularly when trying to adjust catch upwards. Although this ability is almost negligible when h is low, this is not surprising given low recruitment compensation and yield potential in such instances (Punt et al. 2008). Additionally, the responsiveness of P_x values to population status change could not be determined in this study. Other studies using different forms of size-based indicators imply weak (Piet and Jennings 2005) to moderate (Punt et al. 2001) linkages. Such responsiveness could affect the reliability of P_x measures as indicators of stock status on time scales that are germane to management and thus needs examination via MSE.

Finally, the evaluation of power in Table 5 does not account for sampling error, which can be substantial for many data-poor fisheries. Again, an MSE approach will ultimately show the utility of the basic approach when fisheries monitoring data are limited.

Conclusions

The approach of this article enhances the recommendations of Froese (2004) by giving further guidance related to interpreting catch-based length composition data under a range of fishery conditions without the collection of information other than basic biological parameters related to growth and maturity. It also lays the groundwork from which HCRs that use length composition data could be developed and tested to inform fishery management decisions. Finally, the progress made with these simple measures hints at the value of identifying additional alternative measures based on length- or age-composition information (e.g.,

indicators measuring age truncation; Longhurst 1998; Rochet and Trenkel 2003) that may increase the ability of management to interact proactively with fisheries under variable fishing and data-limited conditions.

Acknowledgment

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