Abstract—We estimated size-specific depth distributions and commercial bottom trawl fishery selectivities for Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus)*, longspine thornyhead (*S. altivelis*), and sablefish (*Anoplopoma fimbria*) along the U.S. west coast. Depth distributions are size-specific because fish migrate ontogenetically to deep water. With ontogenetic migration, fishery selectivities of commercial bottom trawls depend on depth of fishing because large fish are most common in deep water. Depth distributions were similar for northern and southern areas and for males and females. Results show ontogenetic migration in sablefish, suggest a possible weak ontogenetic migration in longspine thornyhead, and confirm ontogenetic migration patterns already reported for Dover sole and shortspine thornyhead. Fishery selectivities varied among species, between areas, and changed dramatically over time for most species as fishing effort moved into deep water. Our approach used biological data collected during research bottom trawl surveys but was generally not affected by size selectivity of bottom trawl survey gear. Uncertainty in our commercial bottom trawl selectivity estimates was mostly from length-specific capture probabilities (or vulnerabilities) for fish in the path of commercial bottom trawls. Our estimates complement selectivity estimates from stock assessment models. The approach may be useful whenever the geographic distribution of fish depends on size or age, fishing effort is not randomly distributed geographically, and survey estimates of fish density, bathymetric data, and commercial fishing effort information are available.

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Depth distributions and time-varying bottom trawl selectivities for Dover sole (*Microstomus pacificus*), sablefish (*Anoplopoma fimbria*), and thornyheads (*Sebastolobus alascanus* and *S. altivelis*) in a commercial fishery

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In our study, we estimated depth distributions and fishery selectivities for four demersal fish species taken in commercial bottom trawls: Dover sole (*Microstomus pacificus*), shortspine thornyhead (*Sebastolobus alascanus)*, longspine thornyhead (*S. altivelis*), and sablefish (*Anoplopoma fimbria*). The fishes in our study were all valuable components of the deep-water commercial bottom trawl fishery off Washington, Oregon, and California (Pacific Fishery Management Council, 1998). Depth distributions for many fishes in the deep-water fishery depend on length and age because of ontogenetic migration (movement to deep water as fish grow and age, Jacobson and Hunter, 1993; Jacobson and Vetter, 1995). Depth distributions and ontogenetic migration are important because they affect many aspects of the deep-water fishery, including selectivity of commercial bottom trawls, which are the primary fishing gear.

Fishery selectivities measure the relative intensity of fishing mortality on fish of different size or age (Megrey, 1989). Fishery selectivities depend on size for fishes in the deep-water bottom trawl fishery (Perez-Comas, 1996) because of factors that include size and shape of mesh, size and shape of fish, orientation of netting, twine material (Wileman et al., 1996), and (as shown below) depth of fishing. In many length-structured stock assessment models, for example, the size-specific fishing mortality rate ($F_{y,L}$) in year y for fish in length class L is separated into the product of year-specific fishing mortality (F_y) and size-specific selectivity parameters (s_L), so that $F_{y,L} = F_y\ s_L$ (Megrey, 1989). Selectivities are typically scaled so that the selectivity for a reference size or age is one (Deriso et al., 1985; Methot, 1990). By convention, we scaled selectivities so that the length group with the highest fishing mortality rate had a selectivity of one.

Selectivities determine how fishing affects the size and age structure of a fish stock. They are used in stock assessment models to relate length and age composition data from catch samples to length and age composition of the stock. They are important in predicting effects of harvest rates (Legault, 1998) and in calculating biological reference points (e.g. $F_{0.1}$, F_{rep}, $F_{35\%}$, F_{max}, see Clark, 1991) used to recommend catch levels. At the policy and legal levels, they are often involved in defining overfishing and rebuilding overfished stocks as required under U.S. law (Restrepo et al., 1998).

Estimating selectivity patterns for commercial fishing is a central issue in use of most stock assessment models based on forward simulation calculations (e.g. Deriso et al., 1985; Methot, 1990; Fournier and Archibald, 1982; Jacobson et al., 1994). Changes in fishery selectivity patterns over time may be difficult to measure if length or age composition data are not available for some years. When fishery length or age composition data are available, they can often be explained equally well by many different assumptions about fishery selectivity and population length or age composition. To understand this, consider the catch in number (C_L) of a single size group (length L) from a population. If the fishing mortality rate (F) is low and the selectivity for the size group is s_L, then $C_L \approx N_L F_y s_L$. Even if F_y is known, the resulting catch C_L could be from a high N_L and low s_L, low N_L and high s_L, or an infinite number of intermediate combinations. Problems are compounded if the operation of the commercial fishery and selectivity parameters have changed over time (Sampson, 1993; Brodziak et al., 1997; Rogers et al., 1997) or if natural mortality is also a function of size or age. For example, Tagart et al. (1997) found that scarcity of large female fish in fishery length-composition data was explained equally well by two models. One model had constant natural mortality and fishery selectivity decreased with size. The other model had constant fishery selectivity and natural mortality increased with size.

In our study, we estimated fishery selectivities for the commercial bottom trawl fishery using a new approach that complements estimates from stock assessment models. Our approach is based on information available in many fisheries, including data from bottom trawl surveys, information about bathymetry of fishing grounds, fishing effort data from logbooks, and length- or age-specific vulnerabilities to commercial fishing gear from field experiments. First, we used Jacobson and Hunter's (1993) method with our bottom trawl survey and bathymetric data to estimate depth distributions for fish of different lengths. Next, we used a new method based on commercial fishing logbook data, bathymetric information, length-specific vulnerabilities (from field experiments with commercial fishing gear) and depth distributions to estimate fishery selectivities in the commercial bottom trawl fishery. Our approach may be useful whenever the geographic distribution of fish depends on size or age, when fishing effort is not randomly distributed geographically, and when both survey densities and commercial fishing effort data are available.

Our results show clear differences in commercial fishery selectivities among species, areas, and over time. In addition, our analysis provides new information on depth distributions of sablefish and more precise understanding about depth distributions of Dover sole and shortspine and longspine thornyheads.

Materials and methods

All depths in this study are measured in fathoms (fm). Our study area was the continental shelf and upper continental slope at depths of 100–700 fm (equivalent to 183–1280 m) along the west coast of the U.S. between 36°00′ and 48°30′N (Fig. 1). We divided the study area near the Oregon–California border into southern (36°00′N to 43°00′N) and northern (43°00′N to 48°30′N) subareas to account for geographic differences in groundfish habitat, bottom trawl fishery and logbook data, and to accommodate areas defined for management of the groundfish fishery. The boundary 43°00′N separates the Eureka and Columbia INPFC (International North Pacific Fisheries Commission) management areas.

Areas (km^2) of each 100-fm stratum (estimated from spherical projections at sea level) were the same as those used by the National Marine Fisheries Service (NMFS) to estimate fish density and swept area abundance (Lauth[1]). The shallowest depth stratum in our study (100–199 fm) was relatively larger in the northern subarea (24%) than in the southern subarea (16%, Fig. 1; Tables 1 and 2). Fishing effort shifted into deep water earlier in the south (Tables 1 and 2). Fishing effort data from the southern subarea were collected mostly from California logbooks, whereas fishing effort data from the northern subarea were mostly collected from Oregon and Washington logbooks.

Survey data

Data from eight NMFS bottom trawl surveys on the upper continental slope in our study area were used to estimate depth distributions (Table 3). Each survey was conducted during October–December from the National Oceanic and Atmospheric Administration (NOAA) ship *Miller Freeman* (e.g. Lauth, 1997a, 1997b; Lauth, 1999). As a group, the surveys covered the entire study area (Fig. 1). A NMFS standard Nor'eastern otter trawl net with a 27.2-m headrope, 37.4-m groundgear, 89-mm codend mesh and a 32-mm mesh liner was used in each bottom trawl survey. In each survey, bottom trawl stations were allocated roughly in proportion to the area of 100-m depth strata (100–199, 200–299, 300–399, 400–499, 500–599, and 600–699 fm). Tows with poor gear performance, outside the study area, and at depths greater than 699 fm or less than 100 fm were excluded from our study. Lengths of Dover sole captured in surveys were recorded as total length (TL) in mm. Lengths of other species were recorded as fork length (FL) in mm.

Fishing effort data

Bottom trawl fishing effort data (hours towed) for the northern (Table 1) and southern area (Table 2) were obtained from logbooks submitted by commercial vessels operating out of ports in Washington (1985–97), Oregon (1978–97), and California (1978–96). The fishing effort data in our study were nominal (as reported) hours towed for bottom trawl tows in which the catch of Dover sole, thornyheads, or sablefish was greater than zero.

[1] Lauth, R. 1998. Personal commun. Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way, BIN C15700, Seattle, WA 98115-0070.

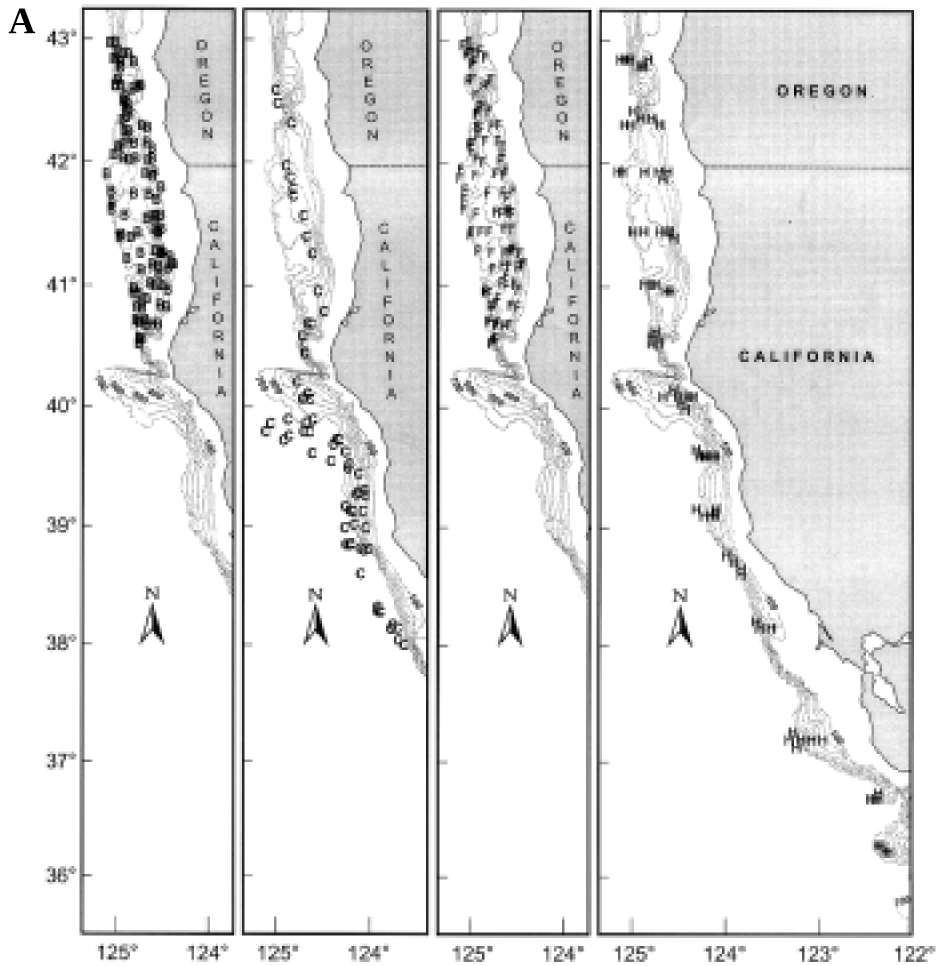

Figure 1

(**A–C**): study areas, 100–199, 200–299, 300–399, 400–499, 500–599, and 600–699 fm depth contours, and location of National Marine Fisheries Service bottom trawl survey tows used to estimate gear selectivities in the commercial bottom trawl fishery. Letters A–H are map symbols defined in Table 3 that identify locations of tows from different bottom trawl surveys.

Depth distributions

All calculations were based on fish length (two centimeter length groups), rather than fish age, because insufficient survey age data (see below) were available. The smallest and largest length groups in our analysis were "plus" groups. For example, a plus group of 20 cm at the low end of length composition would include fish 20 cm FL and smaller. We chose the largest and smallest length groups to use the widest possible range in lengths and to achieve reasonable precision and smoothness in commercial bottom trawl selectivity and depth distribution estimates for large and small fish.

For each species, depth distributions in the total population were estimated by conditional probabilities ${}^{s}p(d \mid L)$ which gave the odds, based on data from bottom trawl survey s, of finding a fish of length L at depth d in the population (Jacobson and Hunter, 1993). Following Jacobson and Hunter (1993), we used Bayes's theorem and data from a single bottom trawl survey in the estimator:

$$ {}^{s}p(d \mid L) = \frac{p_s(L,d)}{p_s(L)} = \frac{p_s(L \mid d)\, p_s(d)}{p_s(L)}, \quad (1) $$

where the joint probability distribution $p_s(L,d)$ gives the probability that a randomly selected fish taken in bottom trawl survey s was length L and from depth stratum d. $P_s(L)$ is the probability that a randomly selected fish taken in the survey was length L. Other terms are defined below.

It is important to note that ${}^{s}p(d \mid L)$ refers to an estimate for the total population based on data from survey s (leading superscript notation), and terms on the right-hand side of the equation refer to the portion of the population selected by the gear used for survey s (trailing subscript notation). The total and surveyed populations differ because survey bottom trawls tend to select fish of certain size or ages and, depending on a variety of conditions, length composition data from survey catches will differ

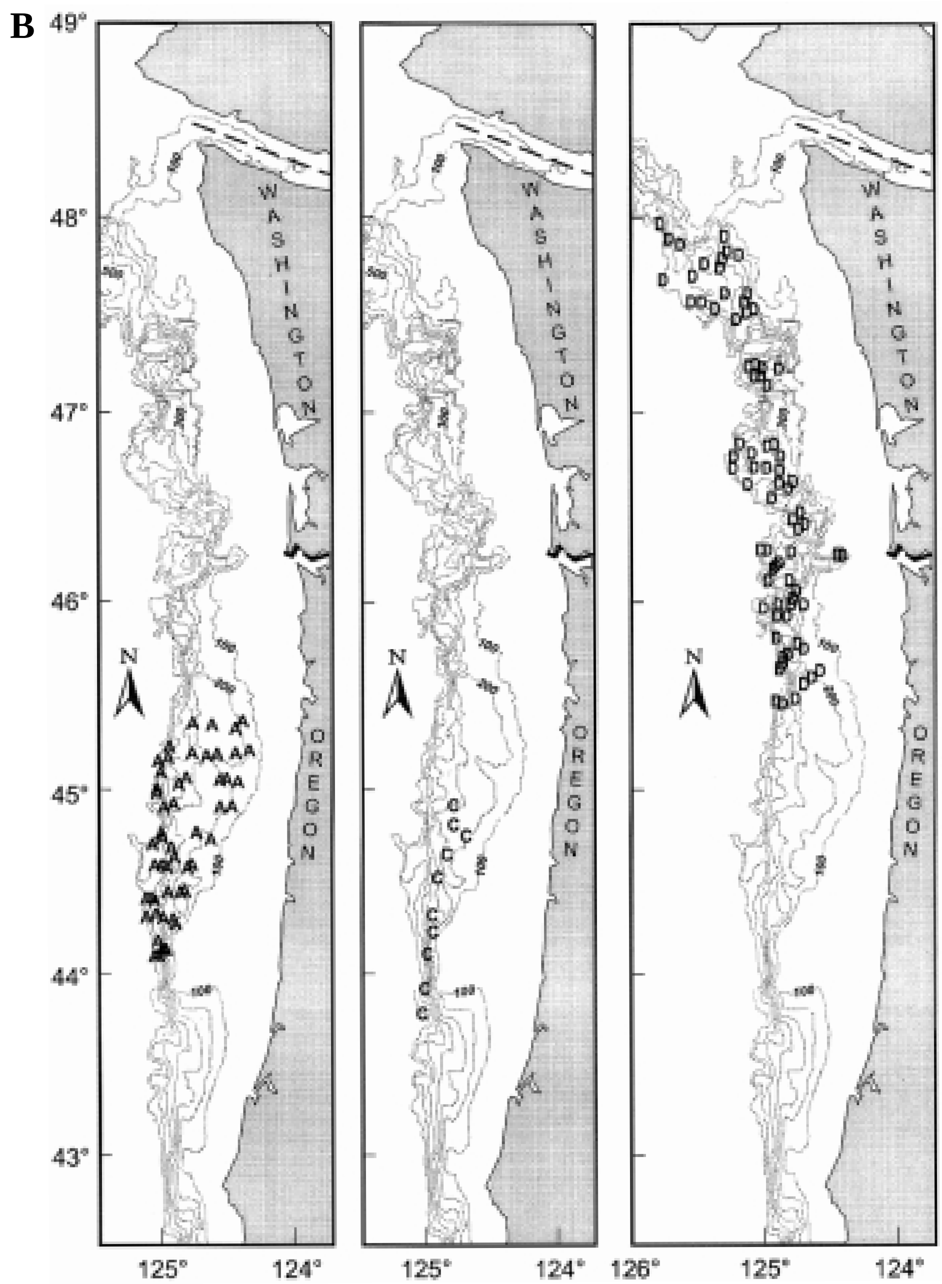

Figure 1 (continued)

from the length composition of the population (Gunderson, 1993). Our estimates of depth distributions for the total population ${}^{s}p(d \mid L)$ were generally unaffected by bottom trawl survey gear selectivity because selectivity of the survey gear affects both $P_s(L,d)$ and $P_s(L)$ equally and "cancels out." This important point is explained further below, after other terms in Equation 1 are defined.

For each bottom trawl survey, species, and depth stratum, length composition of the surveyed population $p_s(L \mid d)$ was calculated as a weighted average of length composition data from each tow in the stratum:

$$p_s(L \mid d) = \frac{\sum_t p_{s,t}(L \mid d)\, w_{s,d,t}}{\sum_t w_{s,d,t}}, \quad (2)$$

where $p_{s,t}(L \mid d)$ = the length distribution from tow t, and
$w_{s,d,t}$ = the tow catch rate (fish/m^2).

Tow catch rates were computed as $w_{s,d,t} = n_{s,d,t} / a_{s,d,t}$, where $n_{s,d,t}$ is the total number of fish caught and $a_{s,d,t}$ is the area swept (width of the net times distance towed).

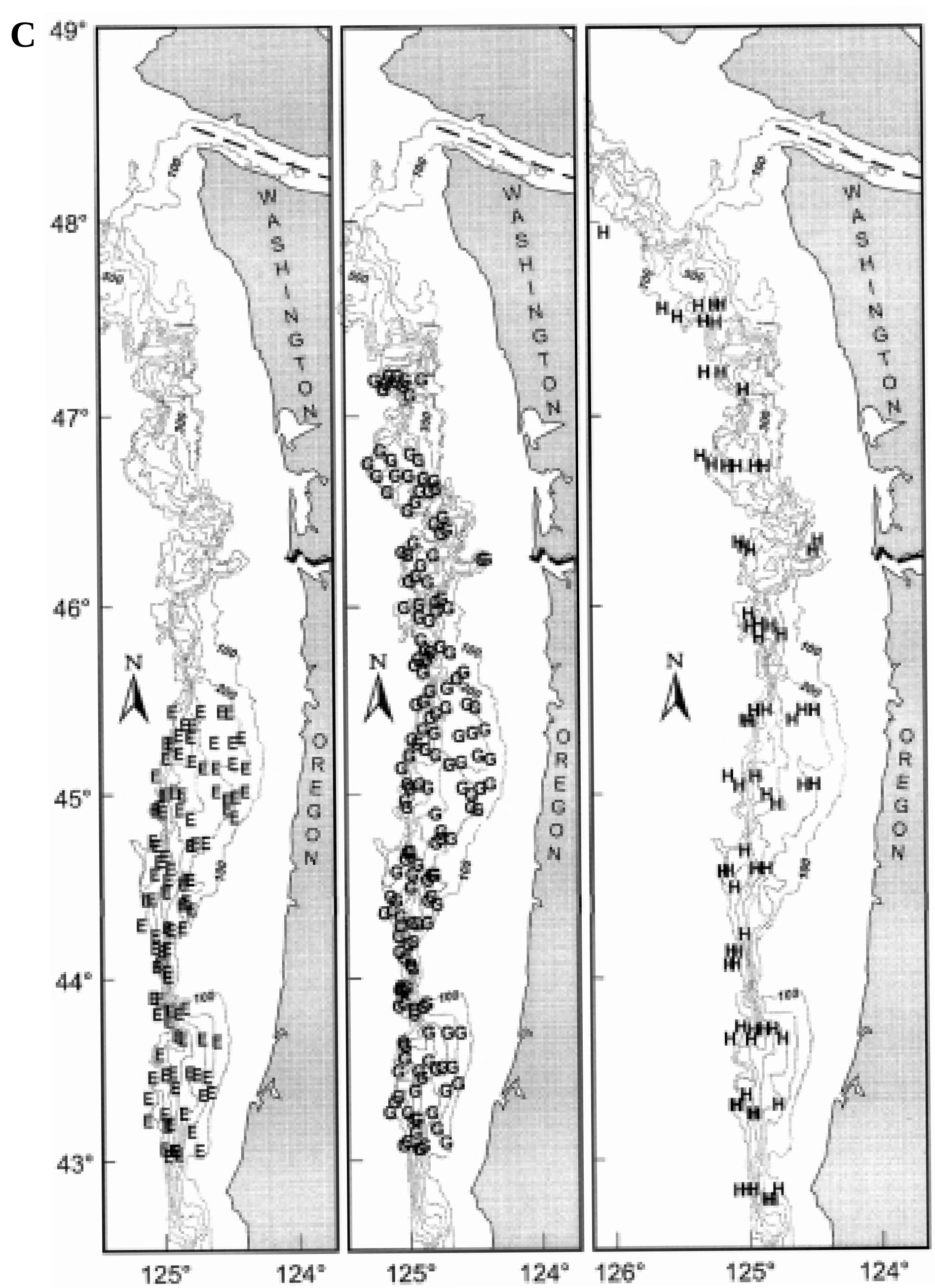

Figure 1 (continued)

The marginal distribution $p_s(d)$ gives the proportion of the surveyed population (all sizes and ages) in depth stratum d based on data from the bottom trawl survey:

$$p_s(d) = \frac{\overline{W}_{s,d}\, A_{s,d}}{\sum_d (\overline{W}_{s,d}\, A_{s,d})}, \tag{3}$$

where $\overline{W}_{s,d}$ = the average (weighted by area swept) catch rate in stratum d; and
$A_{s,d}$ = the total area (km^2) of the survey stratum.

The length distribution of the surveyed population $p_s(L)$ was calculated by summing the joint distribution for depth and length across depth strata:

$$p_s(L) = \sum_d p_s(L, d). \tag{4}$$

Data collected from the surveyed population on the right-hand side of Equation 1 can be used to estimate depth distributions for the total population because bot-

Table 1

Depth stratum area (in 1000 km^2), percentage of total area, and nominal fishing effort (h/yr) by depth stratum for bottom trawls in the northern subarea (43°00′N–48°30′N) during 1978–96. Nominal fishing effort was calculated from Oregon and Washington bottom trawl logbook data as total hours trawled for trips catching any thornyheads, Dover sole, or sablefish.

		Depth (fm)					
		100–199	200–299	300–399	400–499	500–599	600–699
	Area	5.213	4.159	3.131	2.970	3.055	2.925
Year	% total area	24	19	15	14	14	14
1978		4224	1059	269	6	0	0
1979		4808	2991	1744	117	0	0
1980		1910	1277	811	46	5	0
1981		3669	1725	1215	118	0	0
1982		6955	5172	2252	263	16	0
1983		5942	4211	2089	354	23	0
1984		4845	4542	2026	235	0	0
1985		9086	6568	3017	1224	14	0
1986		6541	5680	1934	237	0	0
1987		9083	7639	2864	425	0	0
1988		12,762	12,874	5293	706	31	6
1989		15,125	17,458	7609	1792	1793	45
1990		13,820	14,070	8571	7020	4674	314
1991		19,346	20,148	13,346	7547	2976	221
1992		15,063	15,191	12,977	12,233	5467	595
1993		22,571	20,027	14,144	13,202	10,498	2262
1994		13,531	13,569	10,239	12,773	10,531	1634
1995		13,318	10,225	8502	11,117	15,580	2578
1996		13,539	10,867	8745	9831	12,831	1673

tom trawl survey gear selectivity cancels out. To prove this important point algebraically, note that

$$p_s(L,d) = \frac{{}^s\Pi(L,d)\,\sigma_{s,L}}{\sum_d \sum_L {}^s\Pi(L,d)\,\sigma_{s,L}} \tag{5}$$

and

$$p_s(L) = \frac{{}^s\Pi(L)\,\sigma_{s,L}}{\sum_d \sum_L {}^s\Pi(L,d)\,\sigma_{s,L}}, \tag{6}$$

where ${}^s\Pi(L,d)$ = the joint probability of depth and length in the total population when the bottom trawl survey was carried out;

${}^s\Pi(L)$ = the marginal probability distribution for length in the total population; and

$\sigma_{s,L}$ = the length specific selectivity for the survey bottom trawl gear (assumed the same in all depth strata, see "Discussion" section).

Use Equation 1, substitute terms from Equations 5 and 6, and simplify to get ${}^sp(d\,|\,L) = {}^s\Pi(L,d)/{}^s\Pi(L) = {}^s\Pi(d\,|\,L)$, where ${}^s\Pi(d\,|\,L)$ is for depth distributions in the total population. This proof shows that selectivities ($\sigma_{L,s}$) for bottom trawl survey gear cancel out, and that length-specific depth distributions ${}^sp(d\,|\,L)$ from Equation 1, based on bottom trawl survey data, are algebraically equivalent to length-specific depth distributions in the total population ${}^s\Pi(d\,|\,L)$. Of course, depth distributions are statistics that include uncertainty (measured by CVs in our analysis) due to survey data measurement errors and natural variability in survey selectivities (particularly natural variability that depends on depth).

Effects of survey gear selectivity on depth distribution estimates can be understood intuitively. Consider a hypothetical bottom trawl survey in our study area designed to measure abundance of a fish stock that consists of a single, 1-cm length group. As long as the selectivity of the survey bottom trawl was the same in each depth interval, the survey would measure the relative abundance of the length group in each depth stratum (N_d) and the relative abundance in the whole study area $N = \sum_d N_d$. The depth distribution for the hypothetical stock could be computed simply as ${}^sp(d\,|\,L)=N_d/N$ and the selectivity of the survey bottom trawl would not matter.

We averaged depth distributions estimated from different bottom trawl surveys ${}^sp(d\,|\,L)$ to use all available information. Preliminary results showed that survey-specific depth distributions were similar but relatively noisy. Aver-

Table 2

Depth stratum area (in 1000 km^2), percentage of total area, and nominal fishing effort (h/yr) by depth stratum for bottom trawls in the southern subarea (36°00′N –43°00′N) during 1978–96. Nominal fishing effort was calculated from California and Oregon bottom trawl logbook data as total hours trawled for trips catching any thornyheads, Dover sole, or sablefish.

		Depth (fm)					
		100–199	200–299	300–399	400–499	500–599	600–699
	Area	3.472	3.293	3.732	3.733	3.716	3.158
Year	% total area	16	16	18	18	18	14
1978		8584	4606	8673	3533	743	46
1979		11,707	6980	11,792	4035	1973	50
1980		8200	4992	6765	3171	817	95
1981		9346	7518	11,163	3635	1246	6
1982		10,941	7997	10,698	5142	1559	15
1983		19,481	13,375	17,037	9382	1662	62
1984		10,471	7972	8262	6090	2031	5
1985		13,642	8599	9603	7629	4782	41
1986		8914	10,861	11,228	8184	5262	60
1987		7496	8890	7712	5057	4001	191
1988		10,143	8839	5384	7575	9843	206
1989		8646	9120	6834	10,016	11,533	398
1990		7615	8630	6297	8459	12,717	345
1991		9408	15,428	11,660	8493	6776	567
1992		8327	14,616	12,602	10,356	10,873	512
1993		8424	13,488	15,861	9170	13,142	1241
1994		5999	9522	10,444	8452	13,743	3649
1995		8892	12,556	13,966	13,588	14,573	1542
1996		9825	13,766	15,608	13,549	9688	1887

Table 3

National Marine Fisheries Service (NMFS) bottom trawl slope survey data used to estimate depth distributions for Dover sole, shortspine thornyhead, longspine thornyhead, and sablefish. The National Oceanic and Atmospheric Administration ship *Miller Freeman* and standard bottom trawl survey gear (NMFS poly Nor'eastern otter trawl with small mesh liner, see text) were used in all surveys. Only tows with satisfactory performance were used. "Cruise ID" gives codes used in NMFS cruise reports. "Map symbols" are used in Figure 1.

Cruise ID	Start and end	Min and max latitude (°N lat.)	Min and max depth (fm)	Number of tows used	Map symbols
889	Nov 1988	44.11	121	53	A
	Dec 1988	45.37	682		
9011	Oct 1990	40.52	122	101	B
	Nov 1990	42.97	680		
9112	Oct 1991	38.39	108	83	C
	Nov 1991	45.34	684		
9210	Oct 1992	45.51	109	76	D
	Nov 1992	48.00	692		
9312	Oct 1993	43.07	101	110	E
	Nov 1993	45.50	683		
9512	Oct 1995	40.53	120	105	F
	Nov 1995	42.96	672		
9615	Oct 1996	43.09	102	199	G
	Nov 1996	48.07	690		
9711	Oct 1997	36.31	103	151	H
	Nov 1997	48.07	689		

aging depth distributions was reasonable because effects of survey bottom trawl selectivities (that may have differed because of area or year) were removed. Uncertainty in depth distributions was measured with coefficients of variation (CV) for average depth distributions from standard formulas for weighted means (see "Discussion" section for other approaches).

Fishery selectivities for commercial bottom trawls

The catch equation (C=F$\overline{N}$, Ricker, 1975) holds for each depth stratum. Consequently, total catch by the fishery is the sum of catches in all depth strata

$$C_{y,L} = \sum_{d} F_{y,d}\, V_L\, \overline{N}_{y,d,L}, \tag{7}$$

where $F_{y,d}$ = a year- and depth-specific instantaneous fishing mortality rate multiplier;
V_L = length-specific vulnerability to commercial bottom trawl gear (the probability that a fish in the path of the fishing gear is captured); and
$\overline{N}_{y,d,L}$ = average abundance during year y.

Vulnerabilities, like selectivities, were scaled to a maximum of one. Thus, the fishing mortality rate in a depth stratum for length groups fully vulnerable to the gear (V_L=1) is $F_{y,d}$ and the corresponding rate for other length groups is $F_{y,d}V_L$.

Depth-specific fishing mortality rates $F_{y,d}$ are related to nominal fishing effort at depth divided by the area of the depth stratum:

$$F_{y,d} = \frac{cE_{y,d}}{A_d}, \tag{8}$$

where $E_{y,d}$ = nominal effort (hours towed) for bottom trawls in depth stratum d during year y; and
c = a constant proportional to average area swept per unit time (Paloheimo and Dickie, 1964).

Depth-specific fishing mortality ($F_{y,\,d}$) is inversely proportional to stratum area (A_d) because the fraction of the stock harvested after an hour of fishing in a small area will be larger than the fraction harvested after an hour of fishing in a large area (Jacobson and Hunter, 1993).

Vulnerabilities (V_L) measure the probability of capture for a fish of length L given that the fish is in the path of the trawl. For this study, we calculated vulnerabilities using the logistic function based on length:

$$\eta_L = 2\log_e(3)\left(L - \frac{L_{50}}{R}\right), \tag{9}$$

so that

$$V_L = \frac{e^{\eta_L}}{1+e^{\eta_L}}, \tag{10}$$

and L_{50} = the length at which vulnerability is 50%. R is the difference between the predicted lengths at V_L=75% and V_L=25% for commercial bottom trawls with 4½-inch mesh codends (i.e. L_{75}–L_{25} in Perez-Comas, 1996). Four and one-half inch mesh is the current legal minimum in bottom trawls along the west coast. We rescaled values from Equation 10 so that the largest value was one.

For Dover sole and shortspine thornyhead, we used species-specific vulnerability parameter estimates (Table 4) from Perez-Comas (1996). For sablefish, we used unpublished estimates (Perez-Comas[2]) estimated in the same manner. Perez-Comas's estimates were from paired bottom trawl experiments. The experiments measured vulnerability of fish of different sizes in commercial bottom trawls in relation to vulnerability in bottom trawls with 3-inch (between knots) mesh codends as a reference standard (see "Results" and "Discussion" sections for information about possible bias due to escapement of small fish from commercial bottom trawls with 3-inch mesh codends).

We assumed that vulnerability estimates for longspine thornyhead were the same as for shortspine thornyhead because no other information was available for longspine thornyhead. The two species are similar in shape and their size ranges overlap (shortspine thornyhead grow larger), but their depth distributions differ (Jacobson and Vetter, 1995).

Given vulnerabilities at length for commercial bottom trawls, an expression for commercial fishery selectivities at length can be derived because $p(d\,|\,L)\ N_{y,L} = N_{y,d,L}$, where $p(d\,|\,L)$ is for the total population computed as the average of ${}^{s}p(d\,|\,L)$ from each of the surveys. Substituting

Table 4

Parameter estimates from Perez-Comas (1996) and Perez-Comas[1] for logistic vulnerability models. All estimates are from alternate haul experiments and for commercial bottom trawls with 4½-inch diamond mesh codends fished from commercial trawlers in the west coast groundfish fishery off northern California, Oregon, and Washington (34°40′N–48°30′N and east of 126°W) during 1988–90. L_{50} is the length at which vulnerability is 50% and R is the difference between the predicted lengths at 75% and 25% vulnerability. SE is the estimated standard error for a statistic. Parameter estimates for shortspine thornyhead were also used for longspine thornyhead.

	L_{50} (cm)	SE (cm)	R (cm)	SE (cm)
Dover sole	33.8	1.01	3.96	1.22
Shortspine thornyhead	30.1	1.90	9.81	1.85
Sablefish	33.6	2.43	8.53	2.36

[1] Perez-Comas, J. A. 1998. Personal commun. Columbia Basin Research, School of Fisheries, Univ. Washington, Puget Sound Building, 1325 Fourth Ave., Seattle, WA 98101.

[2] Perez-Comas, J. A. 1998. Personal commun. Columbia Basin Research, School of Fisheries, Univ. Washington, Puget Sound Plaza Building, 1325 Fourth Ave., Seattle, WA, 98101.

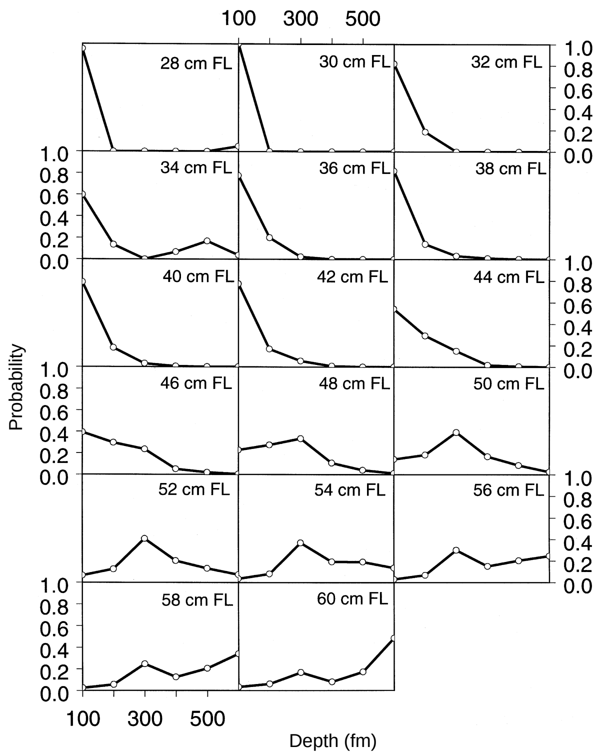

Figure 2

Average depth distributions for sablefish (Table 5) from October to December by length group.

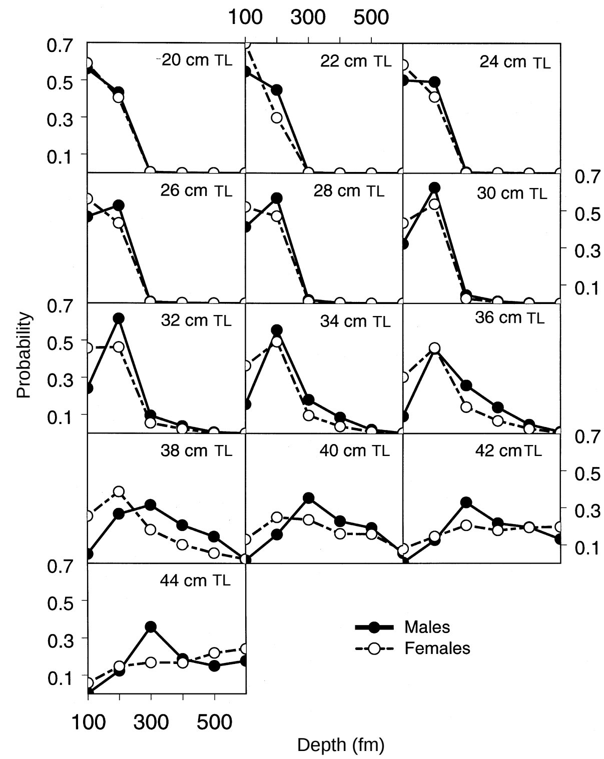

Figure 3

Average depth distributions for male and female Dover sole (Table 6) from October to December by length group.

this and the expression from Equation 8 for $F_{y,d}$ into Equation 7 gives

$$\frac{C_{y,L}}{N_{y,L}} = cV_L \sum_d \frac{E_{y,d}}{A_d} p(d \mid L). \tag{11}$$

The commercial fishery selectivity for fish length L in year y is proportional to $C_{y,L} / N_{y,L}$ in Equation 11 because $C_{y,L} = N_{y,L} F_y s_{y,L}$. Thus, commercial fishery selectivities $s_{y,L}$ were proportional to

$$s_{y,L} \propto V_L \sum_d \frac{E_{y,d}}{A_d} p(d \mid L). \tag{12}$$

Following our convention, we rescaled commercial bottom trawl fishery selectivity estimates from Equation 12 so that the largest was one.

We computed preliminary sex and subarea-specific depth distributions for each species by averaging depth distributions for each sex from bottom trawl surveys in each subarea. Depth distributions for male and female sablefish and thornyheads were similar, but male Dover sole appear to move into deep water at smaller sizes than female Dover sole. There were no clear differences between subareas for any species or sex. We therefore calculated "best estimates" (Tables 5–8; Figs. 2–5) of depth distributions for sablefish and thornyheads by combining subareas and sexes (i.e. by computing survey-specific depth distributions for males and females combined, and then averaging over all surveys). For Dover sole, we calculated sex-specific depth distributions based on combined subareas (i.e. by computing survey-specific depth distributions for males and females separately and then averaging over all surveys). Depth distributions for male and female Dover sole combined (not shown) can be approximated by averaging sex-specific values (e.g. averaging values and rescaling the averages to a maximum of one).

Our best estimates of commercial bottom trawl fishery selectivities for each subarea, year, and species were based on subarea-specific fishing effort data (Tables 1–2) and our best estimates of depth distributions for the whole coast and sexes combined. Preliminary calculations suggested that commercial bottom trawl selectivities for male and female Dover sole were similar (even though depth distributions were different); therefore we combined sexes for final selectivity calculations. Apparently, selectivity calculations for Dover sole were relatively insensitive to differences in depth distributions for males and females because of the overwhelming effects of changes over time in the distribution of commercial fishing effort. Additional data may be required to identify clearly differences in selectivity patterns for male and female Dover sole in the commercial bottom trawl fishery.

Results and discussion

Our best estimates of depth distributions (Tables 5–8; Figs. 2–5) during October–December (when the surveys were conducted) confirm ontogenetic migration patterns of Dover sole (Jacobson and Hunter, 1993), shortspine thornyhead (Jacobson and Vetter, 1995), and sablefish (Parks and Shaw, 1990; Saunders et al., 1997; Sigler et

Table 5

Average depth distributions, i.e. probabilities of depth given length or $p(d\,|\,L)$, and CVs for sablefish (sexes combined) between 36°00′N and 48°30′N and between 100 and 699 fm during October–December based on eight National Marine Fisheries Service bottom trawl surveys. The largest and smallest length groups are "plus" groups (i.e. include larger or smaller fish). Length groups (2 cm) are identified by the lower bound (e.g. 30 cm means 30–31.99 cm). For example, the 28-cm group includes all specimens <29.9 cm. Four surveys took sablefish 28–30 cm sablefish, three surveys took 32-cm sablefish, six surveys took 34-cm sablefish, seven surveys took 36-cm sablefish, and all eight surveys took 38–60 cm sablefish. The symbol "—" means that CV could not be calculated because the average depth distribution was zero.

	Depth intervals (fm)					
Fork length (cm)	100–199	200–299	300–399	400–499	500–599	600–699
Depth distributions						
28	0.9506	0.0000	0.0000	0.0000	0.0000	0.0494
30	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000
32	0.8150	0.1850	0.0000	0.0000	0.0000	0.0000
34	0.5963	0.1334	0.0000	0.0664	0.1667	0.0372
36	0.7767	0.1999	0.0234	0.0000	0.0000	0.0000
38	0.8191	0.1405	0.0304	0.0090	0.0010	0.0000
40	0.7886	0.1764	0.0303	0.0047	0.0000	0.0000
42	0.7707	0.1654	0.0550	0.0079	0.0000	0.0011
44	0.5380	0.2904	0.1490	0.0174	0.0048	0.0004
46	0.3941	0.2965	0.2361	0.0500	0.0194	0.0040
48	0.2301	0.2761	0.3361	0.1073	0.0401	0.0104
50	0.1421	0.1845	0.3947	0.1685	0.0858	0.0244
52	0.0653	0.1239	0.4071	0.2015	0.1301	0.0722
54	0.0344	0.0784	0.3697	0.1922	0.1908	0.1346
56	0.0300	0.0675	0.3007	0.1509	0.2034	0.2476
58	0.0258	0.0567	0.2464	0.1256	0.2051	0.3404
60	0.0333	0.0614	0.1679	0.0806	0.1719	0.4848
CV						
28	0.05	—	—	—	—	1.00
30	0.00	—	—	—	—	—
32	0.23	1.00	—	—	—	—
34	0.23	0.64	—	1.00	1.00	1.00
36	0.15	0.52	0.96	—	—	—
38	0.09	0.42	0.98	0.73	1.00	—
40	0.12	0.43	0.79	1.00	—	—
42	0.12	0.38	0.64	0.58	—	1.00
44	0.19	0.26	0.54	0.47	0.54	1.00
46	0.19	0.21	0.36	0.22	0.32	0.31
48	0.21	0.22	0.21	0.14	0.13	0.46
50	0.22	0.22	0.11	0.12	0.11	0.24
52	0.23	0.21	0.06	0.13	0.10	0.22
54	0.28	0.22	0.07	0.13	0.11	0.16
56	0.17	0.24	0.09	0.15	0.09	0.13
58	0.26	0.14	0.12	0.14	0.16	0.14
60	0.28	0.11	0.16	0.25	0.13	0.11

al., 1997; Methot et al., 1998). For sablefish, Dover sole and shortspine thornyhead, the smallest individuals were found almost entirely in shallow water (100–199 fm for sablefish and 100–299 fm for Dover sole and shortspine thornyhead). The largest individuals occupied the entire range of depths but were relatively rare in the shallowest water and relatively abundant in the deepest water. As indicated by Jacobson and Vetter (1995), depth distributions showed little evidence of ontogenetic migration in longspine thornyhead (but see below).

Our depth distribution results for Dover sole, like results in Jacobson and Hunter (1993, their Figs. 2–3), show that males 22–32 cm TL were most common at depths of 200–299 fm. Female Dover sole of the same size were more often found in shallower water (100–199 fm). Larger Dover sole (38–44 cm FL) of both sexes were more common in deeper water, where males were most common at 300–399 fm. These patterns seem clear, although, as pointed out by a reviewer, there was substantial overlap in 95% confidence intervals for the depth distributions of male and female Dover sole.

Selectivity patterns for groundfish in the deep-water commercial bottom trawl fishery were complex and dynamic (Figs. 6–9). As expected, there were differences in fishery selectivity estimates for commercial bottom trawls among species, between subareas, and over time (Figs. 6–9). Selectivities for species with strong ontogenetic migration (sablefish, shortspine thornyheads and Dover sole) changed most over time. For these fishes, commercial bottom trawl selectivity curves were dome-shaped with peaks that shifted towards larger sizes in later years as the relative amount of fishing effort increased on deep-water fishing grounds where large fish were most common.

Shifts in commercial bottom trawl selectivity patterns towards larger sizes (Figs. 6–9) were most pronounced in the north because the proportion of total commercial bottom trawl fishing effort in deep water over the continental slope was higher in the southern subarea during the early years of our study than in the northern subarea (Tables 5–6). Higher proportions of total commercial bottom trawl effort in deep water (where large fish are most common) during the early years caused relatively high selectivities for large fish in the southern subarea.

Changes in commercial bottom trawl selectivity patterns over time in sablefish, shortspine thornyhead, and Dover sole (Figs. 6–8) were large enough to be important in stock assessment work (Rogers et al., 1997), particularly if assessments are carried out for northern fishing areas. Most of the changes in selectivity patterns over time were for relatively large fish on the right-hand side of the selectivity curves. Commercial bottom trawl selectivities for smaller fish on the left-hand side of the selectivity

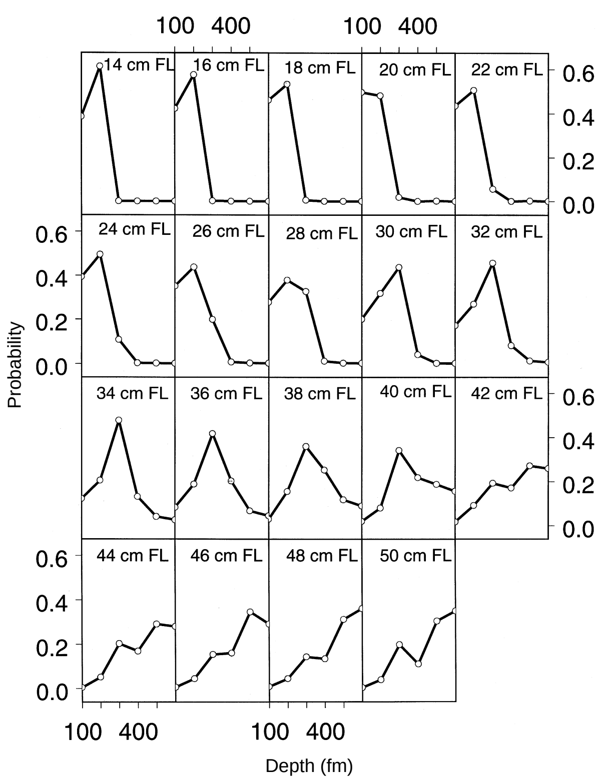

Figure 4

Average depth distributions for shortspine thornyhead (Table 7) from October to December by length group.

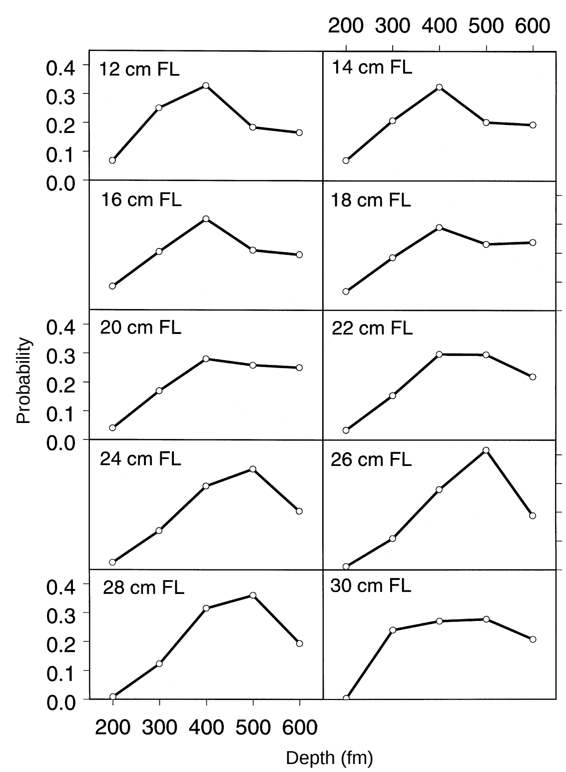

Figure 5

Average depth distributions for longspine thornyhead (Table 8) from October to December by length group.

Table 6

Average depth distributions, i.e. probabilities of depth given length or $p(d \mid L)$, and CVs for male and female Dover sole between 36°00′N and 48°30′N Lat and between 100 and 699 fm during October–December based on eight National Marine Fisheries Service bottom trawl surveys. Length groups and depth intervals defined as in Table 5. All eight surveys took 20–44 cm male and female Dover sole. The symbol "—" means that CV could not be calculated because the average depth distribution was zero.

	Depth intervals (fm)					
Total length (cm)	100–199	200–299	300–399	400–499	500–599	600–699
Depth distributions (males)						
20	0.5616	0.4333	0.0051	0.0000	0.0000	0.0000
22	0.5479	0.4491	0.0031	0.0000	0.0000	0.0000
24	0.5018	0.4928	0.0053	0.0000	0.0000	0.0000
26	0.4652	0.5256	0.0080	0.0010	0.0001	0.0000
28	0.4116	0.5664	0.0185	0.0033	0.0003	0.0000
30	0.3212	0.6225	0.0447	0.0111	0.0006	0.0000
32	0.2412	0.6175	0.0956	0.0392	0.0065	0.0000
34	0.1565	0.5560	0.1802	0.0859	0.0201	0.0014
36	0.0916	0.4552	0.2575	0.1394	0.0472	0.0092
38	0.0506	0.2654	0.3139	0.2052	0.1444	0.0205
40	0.0174	0.1560	0.3527	0.2276	0.1916	0.0548
42	0.0046	0.1248	0.3282	0.2167	0.1951	0.1305
44	0.0041	0.1239	0.3592	0.1859	0.1497	0.1772
CV (males)						
20	0.20	0.27	1.00	—	—	—
22	0.20	0.24	0.87	—	—	—
24	0.16	0.16	0.57	—	—	—
26	0.18	0.15	0.51	0.66	1.00	—
28	0.18	0.13	0.27	0.58	1.00	—
30	0.20	0.10	0.24	0.29	0.57	—
32	0.20	0.08	0.19	0.39	0.43	—
34	0.24	0.09	0.18	0.35	0.40	0.52
36	0.28	0.15	0.19	0.22	0.28	0.33
38	0.36	0.21	0.08	0.18	0.24	0.13
40	0.39	0.33	0.07	0.14	0.21	0.20
42	0.56	0.21	0.07	0.18	0.22	0.25
44	0.66	0.28	0.10	0.22	0.22	0.23

continued

curves resemble the underlying vulnerability curves. These results imply that temporal changes in the right-hand side of the curve should be of greatest concern to stock assessment scientists.

Commercial bottom trawl selectivities for large longspine thornyhead may have increased slightly over time as the fishery moved into deeper water (Fig. 9). This result implies a small amount of ontogenetic migration in longspine thornyhead not evident in our length-specific depth distributions (Fig. 5). Selectivity calculations, which are based on the full suite of depth distributions and fishing effort data, may be a more sensitive indicator of ontogenetic migration patterns not clearly visible in plots showing length-specific depth distributions for longspine thornyhead. It is also possible that the hint of ontogenetic migration in longspine thornyhead was due to estimation errors in depth distributions, lack of species-specific vulnerability parameters, or other factors.

As described above, differences between sexes in length-specific commercial bottom trawl selectivities were minor. This implies little need for sex-specific selectivity parameters in stock assessment models if selectivity is calculated as a function of length. If selectivity is modeled as a function of age, and growth rates of males and females are different (often the case for west coast groundfish), then sex-specific selectivity parameters may be required. Sex-specific length-based selectivity parameters would be required if ontogenetic migration is more closely related to age than length.

Clear trends in our fishery selectivity estimates for commercial bottom trawls suggest a reasonable level of preci-

Table 6 (continued)

	Depth intervals (fm)					
Total length (cm)	100–199	200–299	300–399	400–499	500–599	600–699
Depth distributions (females)						
20	0.5897	0.4066	0.0037	0.0000	0.0000	0.0000
22	0.6982	0.2988	0.0030	0.0000	0.0000	0.0000
24	0.5842	0.4119	0.0016	0.0022	0.0000	0.0000
26	0.5609	0.4304	0.0068	0.0019	0.0000	0.0000
28	0.5189	0.4687	0.0100	0.0025	0.0000	0.0000
30	0.4331	0.5347	0.0248	0.0075	0.0000	0.0000
32	0.4580	0.4632	0.0549	0.0217	0.0020	0.0002
34	0.3635	0.4930	0.0967	0.0375	0.0079	0.0015
36	0.3025	0.4605	0.1421	0.0670	0.0241	0.0038
38	0.2540	0.3860	0.1811	0.1006	0.0550	0.0235
40	0.1294	0.2488	0.2352	0.1598	0.1578	0.0691
42	0.0800	0.1455	0.2052	0.1784	0.1934	0.1975
44	0.0580	0.1481	0.1680	0.1662	0.2185	0.2412
CV (females)						
20	0.27	0.40	0.74	—	—	—
22	0.18	0.41	1.00	—	—	—
24	0.17	0.25	0.65	0.80	—	—
26	0.15	0.19	0.49	0.64	—	—
28	0.13	0.13	0.71	0.35	—	—
30	0.19	0.16	0.40	0.32	—	—
32	0.15	0.14	0.25	0.22	0.60	1.00
34	0.19	0.16	0.32	0.26	0.48	0.73
36	0.19	0.14	0.27	0.24	0.37	0.73
38	0.20	0.17	0.21	0.19	0.23	0.32
40	0.31	0.14	0.15	0.19	0.39	0.24
42	0.26	0.13	0.15	0.14	0.25	0.20
44	0.30	0.20	0.10	0.14	0.20	0.14

sion (see below for a discussion of possible bias). A simple approach to measuring precision would be to fit smooth lines to the estimates and calculate variation of the residuals. Variances might also be computed analytically, on the variance of depth distributions, or by bootstrapping (Efron, 1982).

Depth distributions and commercial bottom trawl selectivities could be estimated from surveys with different types of survey bottom trawls because the selectivity of the survey gear cancels out in estimation of depth distributions for the population. It is important, however, not to simply pool survey data collected with different types of trawls. Estimates of depth distribution from individual surveys ${}^{s}p(d \mid L)$ should be averaged or combined instead.

Our methods could be used to calculate depth distributions and commercial bottom trawl selectivities as a function of age if sufficient age data from bottom trawl surveys were available. In fact, the approach could be extended to include both length and age simultaneously. This procedure might be useful for species such as sablefish, where the relationship between age, length, and depth is complex (Norris, 1997; Methot et al., 1998). In the absence of survey age data, an inverted von Bertalanffy growth model could be used to convert selectivities for commercial fishing based on length to selectivities based on age.

Our approach to estimating fishery selectivities complements traditional approaches using stock assessment models because our assumptions were different. In particular, our approach did not involve assumptions about relationships between fish size and natural mortality that were made either implicitly (natural mortality assumed constant for all size groups) or explicitly (e.g. Tagart, et al., 1997) in most stock assessment models. As described above, size-dependent natural mortality rates and size-dependent fishery selectivities tended to be confounded in fishery length-composition or age-composition data (e.g. Tagart et al., 1997). It is possible that estimates of fishery selectivity for commercial bottom trawls might be useful in stock assessment models as a basis for estimating trends in length-specific natural mortality. Another approach would be to use estimates of fishery selectivity from our method

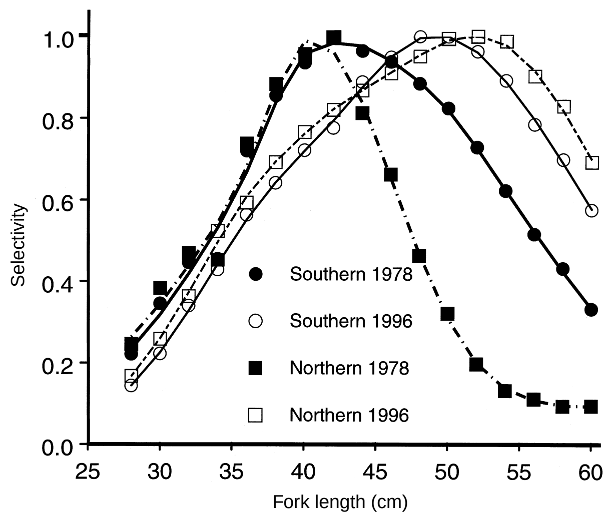

Figure 6

Commercial bottom trawl (4½-inch mesh codend) fishery selectivity estimates for sablefish (sexes combined) in the northern and southern subareas during 1978 and 1996. Selectivity curves for other years were intermediate. Estimates for 1978 are biased owing to commercial trawls in the fishery with smaller mesh codends. Smooth lines show trends and were fitted to estimates by locally weighted regression smoothing (LOESS).

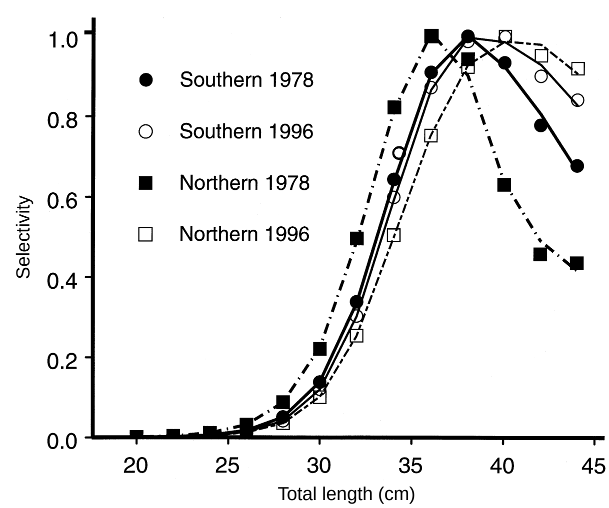

Figure 7

Commercial bottom trawl (4½-inch mesh codend) fishery selectivity estimates for Dover sole (sexes combined) in the northern and southern subareas during 1978 and 1996. Selectivity curves for other years were intermediate. Estimates for 1978 are biased due to commercial trawls in the fishery with smaller mesh codends. Smooth lines show trends and were fitted to estimates by locally weighted regression smoothing (LOESS).

as Bayesian priors for selectivity parameters estimated by stock assessment models (Methot, 1990).

Our estimates of depth distributions reflect conditions during the autumn (October–December). Our study did not include data collected during other seasons that could be used to test hypotheses about seasonal migrations between deep and shallow water (Alverson, 1960). Additional bottom trawl survey data collected at different times of the year with a variety of vessels and trawl gears are available (Lauth[3]) and could be used to measure seasonal differences in depth distributions.

Our analysis used data from bottom trawl surveys to estimate depth distributions. Our approach might be applicable to other types of surveys as long as densities of organisms in each strata can be calculated on an relative or absolute basis. Although survey gear selectivities cancel out in calculations, it is important that the survey gear be relatively efficient for length groups used in calculations. Otherwise, density estimates used to calculate depth distributions may be too variable.

The assumption that survey bottom trawl selectivities are constant with depth is important in calculating depth distributions $p(d \mid L)$ because the proof that survey selectivities cancel out depends on the assumption. It is possible for example, that small fish might evade bottom trawls by hiding in rubble or depressions. If there were more rubble or depressions in deep water than in shallow water, then bottom trawl survey selectivities would change with depth, and depth distribution estimates (as well as commercial fishery bottom trawl selectivity calculations) would be affected. The magnitude of any possible problem would depend on a variety of factors (e.g. the relative abundance of small fish at depths with more or less rubble) and cannot be predicted in general. However, factors that affect selectivity of survey bottom trawls (including herding, escapement under the footrope, escapement over the top of the net, and escapement through meshes) are not important in calculating depth distributions, even if they depend on fish size, as long as they remain the same for all depth strata.

Sensitivity of selectivity estimates to errors in fishing effort data

Our estimator for fishery selectivities does not depend on knowing total effective commercial fishing effort ($E_{y,d}$) for each depth stratum. It does depend on knowing the proportion of total effective fishing effort (which is proportional to fishing mortality) in each stratum. This means that unreported fishing effort would not affect our calculations unless there were differences in depth of fishing among fishermen who did and did not turn in log data, differences among states in depth of fishing and proportion of fishermen who submit log data, or differences in logbook reporting rates among fishermen who fish in different areas or at different depths.

[3] Lauth, R. 1998. Personal commun. Alaska Fisheries Science Center, National Marine Fisheries Service, 7600 Sand Point Way, BIN C15700, Seattle, WA 98115-0070.

Our approach to calculating fishery selectivities for commercial bottom trawls is based on the assumption that nominal fishing effort data in each stratum from logbooks is a relative measure of commercial fishing mortality. Bias in fishing effort data as a measure of relative fishing mortality (e.g. due to differences among depth strata in average fishing power) would affect our estimates of fishery selectivities for commercial bottom trawls. It would be better to use a standardized measure of fishing effort for each stratum adjusted for differences in season, gear, vessel size, engine size, skipper skill, target species, bycatch, or other operational characteristics of the vessels (Hilborn and Walters, 1992). We hypothesize that this is a minor problem in interpretation of our results, however, because the nominal fishing effort data we used showed clear and substantial shifts towards deep water (Tables 1–2).

Sensitivity of selectivity estimates to vulnerability estimates from field studies

Vulnerability estimates were the most important uncertainty in our estimates of fishery selectivities for commercial bottom trawls (but did not affect estimates of depth distributions because they were not used to calculate depth distributions). We conducted extensive sensitivity analysis for each species and determined that a 1-cm change in the assumed length at 50% vulnerability (L_{50} in Table 4) shifted the commercial bottom trawl selectivity curves in the same direction by about 1 cm.

The vulnerability parameters used in our analysis were for $4^1/_2$-inch mesh which is the current legal minimum mesh size in bottom trawls along the west coast, but smaller mesh was used by some vessels during earlier years (Pacific Fishery Management Council, 1998). Changes over time in commercial mesh size would affect our calculations for early years and small fish. The extent of the potential problem is unknown because no vulnerability parameters were available for small mesh gear (e.g. 3-inch mesh) and because there is no information about proportions of total fishing effort by trawls with different mesh size during early years. The potential problem is not important in estimating selectivity of commercial bottom trawls during recent years because recent mesh size regulations make $4^1/_2$-inch mesh standard in the fishery.

Results from Perez-Comas (1996) were valid estimates of selectivities (as defined in his study) but likely underestimate vulnerability (as defined in our analysis) and bias our estimates for small fish. Precise definition of terms is important in this regard.

According to Perez-Comas (1996), his estimates measured "the differential retention of certain sizes of fish after they come in contact with the gear" (Gulland, 1983). In our words, Perez-Comas measured "the relative probability of capture given that a fish entered the mouth of the trawl." These definitions are similar but not identical to our definition of vulnerabilities as "the relative probability of capture given that a fish is in the path of the trawl." In particular, Perez-Comas's (1996) definition differs from ours to the extent that fish of different sizes have different probabilities of moving

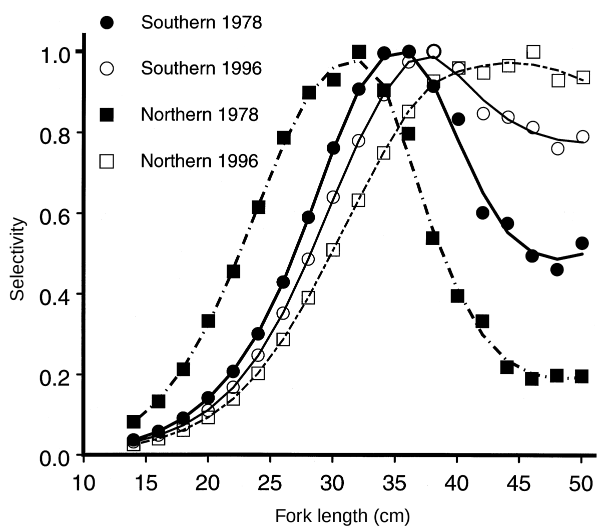

Figure 8

Commercial bottom trawl ($4^1/_2$-inch mesh codend) fishery selectivity estimates for shortspine thornyhead (sexes combined) in the northern and southern subareas during 1978 and 1996. Selectivity curves for other years were intermediate. Estimates for 1978 are biased owing to commercial trawls in the fishery with smaller mesh codends. Smooth lines show trends and were fitted to estimates by locally weighted regression smoothing (LOESS).

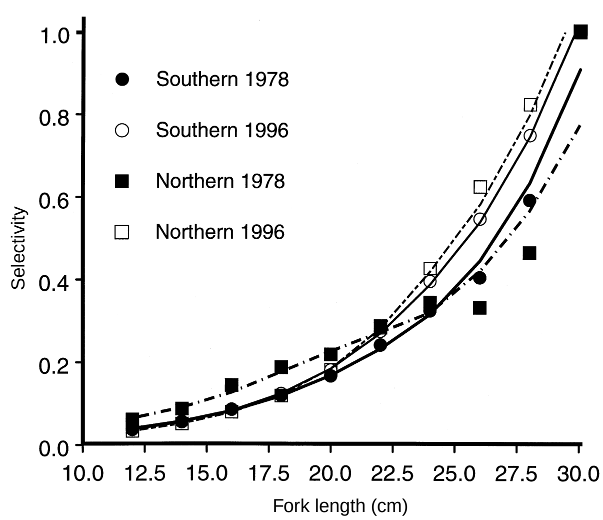

Figure 9

Commercial bottom trawl ($4^1/_2$-inch mesh codend) fishery selectivity estimates for sablefish (sexes combined) in the northern and southern subareas during 1978 and 1996. Selectivity curves for other years were intermediate. Estimates for 1978 are biased owing to commercial trawls in the fishery with smaller mesh codends. Smooth lines show trends and were fitted to estimates by locally weighted regression smoothing (LOESS).

away from or into the path of the net and to the extent that escape after entering the net depends on fish size.

Perez-Comas (1996) used a sophisticated estimation procedure but, conceptually, his vulnerability estimates were proportional to the length-specific ratios of catch rates in 4½-inch and 3-inch mesh (i.e. V_L proportional to C_L/K_L, where C_L and K_L are catch rates with 4½ and 3-inch gear). It is likely that catch rates for small fish in 3-inch mesh

Table 7

Average depth distributions, i.e. probabilities of depth given length or $p(d\,|\,L)$, and CVs for shortspine thornyhead (sexes combined) between 36°00′N and 48°30′N lat and between 100 and 699 fm during October–December based on eight National Marine Fisheries Service bottom trawl surveys. Length groups and depth intervals defined as in Table 5. All eight surveys took 14–50 cm shortspine thornyhead. The symbol "—" means that the CV could not be calculated because the average depth distribution was zero.

	Depth intervals (fm)					
Fork length (cm)	100–199	200–299	300–399	400–499	500–599	600–699
Depth distributions						
14	0.3863	0.6127	0.0011	0.0000	0.0000	0.0000
16	0.4221	0.5752	0.0027	0.0000	0.0000	0.0000
18	0.4607	0.5330	0.0061	0.0000	0.0003	0.0000
20	0.4969	0.4816	0.0185	0.0006	0.0024	0.0000
22	0.4349	0.5056	0.0567	0.0002	0.0025	0.0002
24	0.3920	0.4944	0.1079	0.0028	0.0025	0.0006
26	0.3506	0.4383	0.1989	0.0075	0.0028	0.0019
28	0.2780	0.3779	0.3271	0.0117	0.0032	0.0021
30	0.2011	0.3174	0.4373	0.0405	0.0020	0.0016
32	0.1718	0.2694	0.4564	0.0824	0.0130	0.0070
34	0.1214	0.2042	0.4773	0.1309	0.0404	0.0259
36	0.0826	0.1874	0.4169	0.2025	0.0662	0.0445
38	0.0291	0.1544	0.3592	0.2522	0.1168	0.0884
40	0.0190	0.0797	0.3410	0.2175	0.1868	0.1560
42	0.0164	0.0906	0.1919	0.1709	0.2713	0.2589
44	0.0039	0.0518	0.2034	0.1698	0.2908	0.2804
46	0.0056	0.0437	0.1539	0.1608	0.3453	0.2907
48	0.0080	0.0440	0.1429	0.1342	0.3108	0.3602
50	0.0034	0.0386	0.1970	0.1095	0.3033	0.3482
CV						
14	0.18	0.11	0.45	—	—	—
16	0.14	0.10	0.44	—	—	—
18	0.06	0.05	0.25	—	1.00	—
20	0.08	0.08	0.26	0.45	0.91	—
22	0.09	0.07	0.25	0.66	1.00	1.00
24	0.10	0.06	0.21	0.27	0.76	0.74
26	0.11	0.09	0.11	0.15	0.43	0.65
28	0.10	0.07	0.03	0.20	0.75	0.52
30	0.12	0.07	0.04	0.22	0.67	0.69
32	0.15	0.08	0.05	0.17	0.31	0.35
34	0.19	0.14	0.09	0.14	0.23	0.59
36	0.18	0.16	0.10	0.12	0.34	0.27
38	0.23	0.21	0.10	0.13	0.27	0.25
40	0.43	0.23	0.12	0.09	0.11	0.17
42	0.57	0.25	0.15	0.17	0.11	0.17
44	0.69	0.11	0.12	0.15	0.11	0.13
46	0.66	0.28	0.13	0.16	0.07	0.12
48	0.41	0.26	0.18	0.15	0.11	0.09
50	0.46	0.26	0.15	0.12	0.08	0.13

(K_L) were reduced by escapement of small fish through 3-inch meshes so that vulnerabilities estimates for small fish were biased high as well. The extent of the potential bias is unknown but bias was probably low for large fish.

It might be possible to refine estimates of vulnerability parameters by carrying out field studies similar to those analyzed by Perez-Comas, but by using small mesh liners in the codends of commercial bottom trawls as the reference standard. Small mesh can cause problems under commercial fishing conditions (Erickson et al., 1996) and it might therefore be preferable to use codend covers to capture small fish as they escape through codends with commercial-size mesh instead.

As described above, fish may move away from or into the path of a commercial bottom trawl (herding) to an extent that depends on size (Gunderson, 1993). Herding is complex and depends on net design, size, towing speed, and other factors (Ramm and Xiao, 1995). These variables would affect our calculations of size-specific selectivities in commercial bottom trawls to the extent that the vulnerability estimates used in our study would fail to measure the relatively probability of capture for fish of different size in front of commercial bottom trawls. We have little information on this topic for west coast groundfish.

Loss of small fish through 3-inch codends during the paired bottom trawl experiments used to estimate vulnerabilities likely biased our estimates of bottom trawl selectivities in commercial fisheries. Length-composition data for sablefish, Dover sole, and thornyheads from commercial gear with 3-inch codends include fewer small fish than length-composition data from survey bottom trawls with small mesh (3.2 cm) liners (Lauth[3]). We have no other information about size-specific probabilities of escape of small fish, but studies with survey bottom trawls and a variety of species (e.g. Engås and Godø, 1989a; 1989b; Walsh, 1992) show that small fish do escape. We recommend field studies with commercial bottom trawls and video equipment.

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Table 8

Average depth distributions, i.e. probabilities of depth given length or $p(d \mid L)$, and CVs for longspine thornyhead (sexes combined) between 36°00′N and 48°30′N lat and between 200 and 699 fm (longspine thornyhead were seldom taken at 100–199 fm) during October–December based on eight National Marine Fisheries Service bottom trawl surveys. Length groups and depth intervals defined as in Table 5. All eight surveys took 12–30 cm longspine thornyhead.

	Depth intervals (fm)				
Fork length (cm)	200–299	300–399	400–499	500–599	600–699
Depth distributions					
12	0.0684	0.2512	0.3288	0.1845	0.1671
14	0.0701	0.2082	0.3252	0.2028	0.1938
16	0.0817	0.2024	0.3155	0.2078	0.1925
18	0.0652	0.1831	0.2875	0.2289	0.2353
20	0.0401	0.1701	0.2801	0.2590	0.2509
22	0.0334	0.1545	0.2970	0.2957	0.2195
24	0.0250	0.1344	0.2894	0.3488	0.2024
26	0.0112	0.1081	0.2784	0.4152	0.1871
28	0.0080	0.1225	0.3151	0.3610	0.1934
30	0.0034	0.2403	0.2711	0.2777	0.2076
CV					
12	0.34	0.09	0.09	0.07	0.09
14	0.38	0.11	0.13	0.09	0.13
16	0.37	0.14	0.10	0.12	0.13
18	0.33	0.14	0.09	0.10	0.11
20	0.25	0.12	0.09	0.11	0.11
22	0.27	0.13	0.07	0.07	0.13
24	0.34	0.09	0.06	0.04	0.14
26	0.26	0.13	0.08	0.03	0.17
28	0.69	0.15	0.15	0.07	0.23
30	0.46	0.19	0.23	0.16	0.25

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