Abstract—The time series of abundance indices for many groundfish populations, as determined from trawl surveys, are often imprecise and short, causing stock assessment estimates of abundance to be imprecise. To improve precision, prior probability distributions (priors) have been developed for parameters in stock assessment models by using meta-analysis, expert judgment on catchability, and empirically based modeling. This article presents a synthetic approach for formulating priors for rockfish trawl survey catchability (q_{gross}). A multivariate prior for q_{gross} for different surveys is formulated by using 1) a correction factor for bias in estimating fish density between trawlable and untrawlable areas, 2) expert judgment on trawl net catchability, 3) observations from trawl survey experiments, and 4) data on the fraction of population biomass in each of the areas surveyed. The method is illustrated by using bocaccio (*Sebastes paucipinis*) in British Columbia. Results indicate that expert judgment can be updated markedly by observing the catch-rate ratio from different trawl gears in the same areas. The marginal priors for q_{gross} are consistent with empirical estimates obtained by fitting a stock assessment model to the survey data under a noninformative prior for q_{gross}. Despite high prior uncertainty (prior coefficients of variation ≥ 0.8) and high prior correlation between q_{gross}, the prior for q_{gross} still enhances the precision of key stock assessment quantities.

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Using experiments and expert judgment to model catchability of Pacific rockfishes in trawl surveys, with application to bocaccio (*Sebastes paucispinis*) off British Columbia

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Rockfishes (*Sebastes* spp.) are a group of groundfish species on the west coast of North America, many of which are commonly exploited; over 25 stocks are assessed and individually managed in the United States and Canada (DFO, 2008; NPFMC, 2008; PFMC, 2008). Stock assessment models for rockfish are typically fitted to a variety of data, such as estimates of population biomass determined from survey trawl-swept areas. These swept-area biomass estimates are usually treated as relative indices of abundance because of the unknown relationship between the availability of the target population to the survey net. Factors affecting this relationship include the proportion of fish present within the path of the net that on average enter the net, the proportion of the population that is potentially available to be captured by the survey gear and the relative density of rockfish in trawlable and untrawlable areas. Treated as a relative abundance index, a single scalar parameter is typically estimated, called "bulk catchability" or "q_{gross}" to scale the model-predicted population biomass to the swept-area biomass values (Millar and Methot, 2002). Owing to the trawl survey data being available for only a portion of the history of a stock's exploitation and because of moderate to large amounts of variation in interannual error, stock assessment estimates of q_{gross} are often imprecise and may not provide reliable estimates of population biomass (Millar and Methot, 2002).

In order to reduce the large uncertainty common to estimates of q_{gross} and population abundance for rockfishes and many other assessed fishes, stock assessment scientists have quantified Bayesian prior probability density functions (pdfs) for q_{gross}. Among these quantifications, there have been efforts to quantify expert judgment (e.g., Punt et al., 1993; McAllister and Ianelli, 1997; Boyer et al., 2001) on factors affecting survey catchability. Others have performed hierarchical analyses of stock assessments for different rockfish species to quantify the mean and variance in q_{gross} across different populations for surveys, using the same gear (Millar and Methot, 2002). Although these analyses have improved the conceptual understanding of the processes contributing to trawl catchability during surveys and have shown how expert judgment and other information can be used to help form priors, no unifying framework exists that integrates the judgment from multiple experts with other available data on survey catchability.

In this article, we present a synthetic approach for integrating inputs on technical parameters elicited from experts and survey data not used in a stock assessment to form a prior for q_{gross} that can be used to improve the value of biomass estimates from trawl-swept areas for use in stock assessments. This approach can be applied to swept-area abundance estimates across a number of areas and over multiple types of trawl gear (e.g., shrimp and groundfish trawl nets). Each expert is assigned equal prior weight which is then updated from ratios of relative catch rates between different survey gear types. We use estimates of the fraction of the total population biomass that lies within the boundaries of each survey area and that accounts for the fraction of the area within the boundary of each survey that is trawlable. A factor is applied to prevent the expert inputs from being overly certain. Finally, because this method is applied to different surveys of the same stock, these parameters are not independent (in some surveys the same gears were used) and there is spatial covariance in estimates of the fraction of biomass in the different survey areas (the prior pdf formed accounts for the correlations in the q_{gross} parameters between surveys). We illustrate the method with an application to bocaccio (*Sebastes paucispinis*) off British Columbia (B.C.) that relied upon technical information obtained from interviews with a dozen trawl captains. We show the sensitivity of the results to assumptions about potential differences in rockfish density between trawlable and untrawlable substrates, the amount of uncertainty in expert inputs, and how results from different experts should be integrated. The impact on the overall stock assessment results are illustrated by comparing results obtained with and without informative priors for q_{gross}.

Bocaccio in British Columbia were chosen to illustrate the new method to formulate a prior for q_{gross} because this species presents an instance in which the time series of abundance indexes available for stock assessment are mostly too short or imprecise to enable estimation of parameters of population dynamics and abundance trends. An informative prior for survey q is essential to achieve these ends. Bocaccio range from the Alaska Peninsula to Baja California (Love et al., 2002). In British Columbia, adult bocaccio exhibit a widespread distribution mainly on the outer coast (Fig. 1). Most catches are taken close to the bottom over depths of 60–200 m near the break-in-slope of the continental shelf, as well as at the edges of troughs in Queen Charlotte Sound (QCS) and Hecate Strait (HS). Adult bocaccio can be semipelagic and are found over a variety of bottom types, although harvesters suggest they favour proximity to high relief and rocky bottom. In British Columbia, bocaccio are caught by trawl and hook-and-line gear along with many other groundfish species, including Pacific ocean perch (*S. alutus*), yellowtail rockfish (*S. flavidus*), canary rockfish (*S. pinniger*), and lingcod (*Ophiodon elongatus*).

Indices from seven trawl surveys (Fig. 1) were used in our study. Four of the surveys, 1) the west coast of Vancouver Island groundfish (WCVI Gfish), 2) Queen Charlotte Sound groundfish (QCS Gfish), 3) Hecate Strait groundfish (HS Gfish), and 4) west coast of Haida Gwaii groundfish (WCHG Gfish) represent a set of nonoverlapping bottom trawl surveys that were started between 2003 and 2006 to collectively survey most of the B.C. coastal shelf between 50 and 500 m of bottom depth. The focus of these surveys was to provide relative indices of all groundfish species affected by the groundfish bottom trawl fishery in B.C. waters. For all four surveys, the Atlantic Western II groundfish bottom trawl was used and the surveys were conducted by the Canada Department of Fisheries and Oceans (DFO) staff on either the government research trawler (surveys 1 and 2) or chartered trawler (surveys 3 and 4).

Two of the surveys, the WCVI shrimp (survey 5) and QCS shrimp (survey 6) are conducted by DFO staff on board the same DFO research trawler (Boutillier et al., 1998). These surveys use a shrimp trawl and were designed to provide relative indices of shrimp abundance on two specific shrimp fishing grounds. For the seventh survey, the U.S. triennial survey a Nor'Eastern groundfish bottom trawl was used. This survey was designed to monitor groundfish abundance in U.S. waters, but in some years covered a small portion of southern B.C. waters. This survey stopped covering Canadian waters after 2001.

Methods

General model structure for trawl survey catchability (q_{gross})

See Table 1 for descriptions of all symbols used in this paper and Figure 2 for a schematic outline of the inputs, sub-models and outputs of the q prior model. We define catchability (q_{gross}) as the ratio of biomass of rockfish in a particular survey area to the population biomass of a given rockfish population that is on average vulnerable to trawl survey gear on account of gear selectivity (i.e., the fully vulnerable population biomass). q_{gross} is typically considered to be the long-term average value and is applied as a scalar to the fully vulnerable population biomass (B_y) modeled in a stock assessment model to predict the index of biomass obtained from a given trawl survey. The predicted swept-area biomass ($\hat{I}_y$) is obtained from the product of B_y and q_{gross}:

$$\hat{I}_y = q_{gross} \times B_{y.} \tag{1}$$

For rockfish, it has been generally acknowledged that there are three main factors that may cause the value

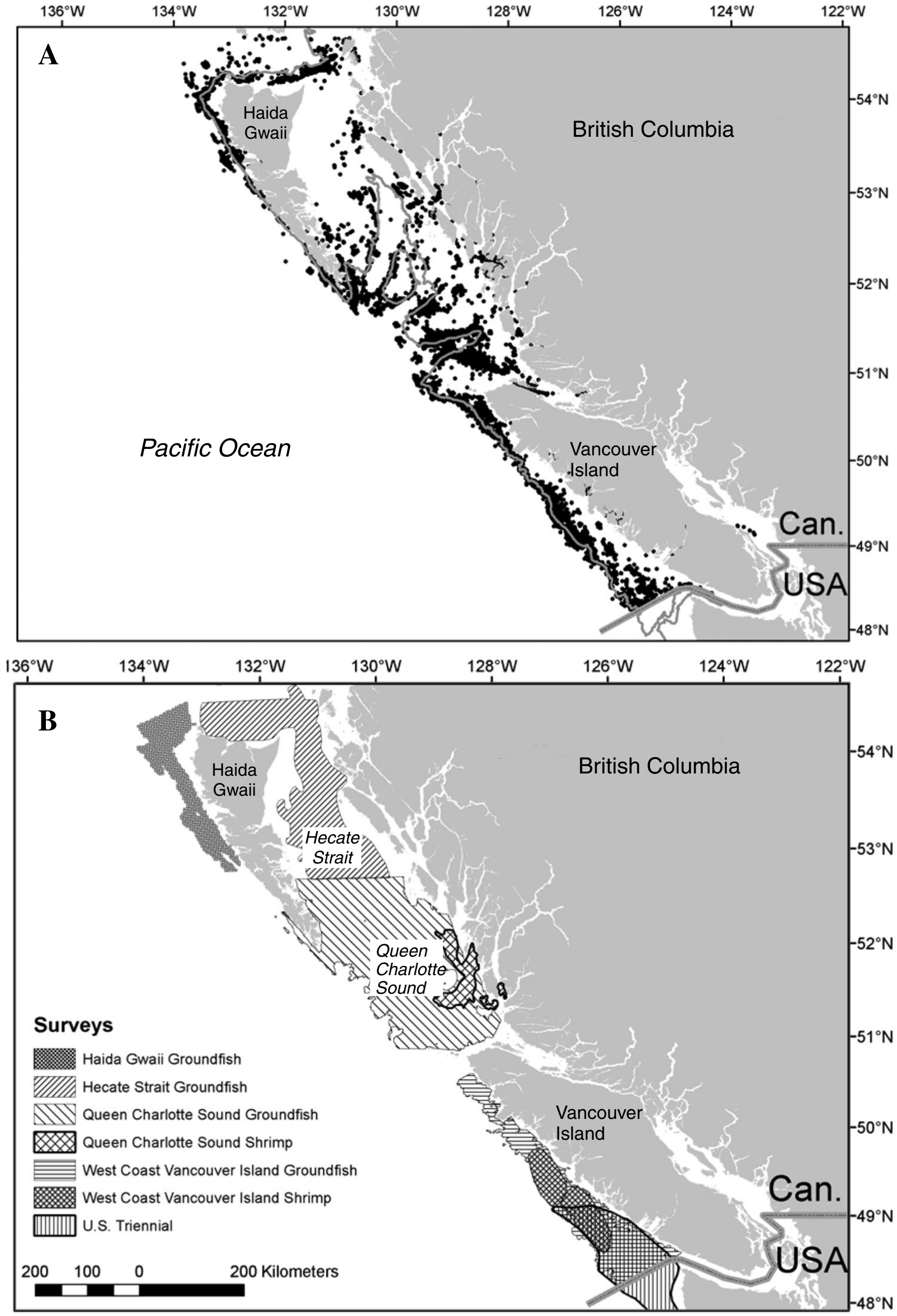

Figure 1

(**A**) Locations where bocaccio (*Sebastes paucispinis*) were caught in commercial and research trawls, 2004–08. The 200-m depth contour is shown by a thin gray line. (**B**) Locations of trawl surveys in outside waters of British Columbia.

for q_{gross} to deviate from unity and may be conceived to act multiplicatively (Millar and Methot, 2002):

$$q_{gross} = q_{net} \times q_{trawlable} \times q_{available}, \qquad (2)$$

where q_{net} = the fraction of exploitable biomass that is within the path (i.e., between the trawl doors) of a given type of survey net and that is on average captured by the net;

Table 1

Definition of symbols for the indices, model parameters, and model variables used to determine trawl catchability for bocaccio (*Sebastes paucispinis*) off British Columbia.

Symbol	Description
Indices	
pop	entire fish population of interest that is potentially susceptible to capture by the survey gear of interest
n	trawl net type, e.g., in study 1=the groundfish AWII used in the Department of Fisheries and Ocean's groundfish trawl surveys, in study 2=the shrimp trawl, in study 3=the Nor' Eastern used in the U.S. triennial groundfish trawl survey
c	interviewed captain
s	survey
Model parameters	
q_{gross}	the parameter that scales the model-predicted population biomass to a trawl survey swept area biomass value
q_{net}	the parameter that reflects the fraction of exploitable biomass within the path (i.e., between the trawl doors) of a given type of survey net that is on average captured by the net
$q_{availability}$	the fraction of total exploitable population biomass indexed by a given survey (the proportion of the population biomass in the survey area)
$q_{trawlable}$	the parameter that accounts for the potential average difference in rockfish density between trawlable and untrawlable areas and the fraction of the surveyed area that is trawlable
S_s	the fraction of total population biomass present in the survey area
f_{Ts}	the fraction of the total survey area A that is trawlable.
α	the ratio of target rockfish density in untrawlable to trawlable habitat.
g_s	the bias correction factor to account for the difference in fish density between trawlable and untrawlable bottoms and the fraction of a survey area that is trawlable
$I_{T,s}$	swept area biomass obtained from trawl samples in the trawlable part of a survey area
n_{areas}	the number of surveyed areas in the range of an assessed fish population
a_1	estimate of the percent of rockfish that would be near-bottom (within 3–4 fm of the bottom, i.e., the kill zone) as the vessel passed overhead (Fig. 3)
a_2	proportion of off-bottom rockfish that "dive" into the kill zone (Fig. 3)
$a_{1.2,c}$	proportion of fish going into path of the net and doors from those in the water column that are in the horizontal path of the net and the doors (Fig. 3)
$a_{3,1,n}$	fraction of distance between the trawl doors that is in the path of the sweeps and bridles but more than 6 m inside of the door path (Fig. 3; Table 3)
$a_{3,2,n}$	fraction of distance between the trawl doors that is in the path of the sweeps and bridles but not more than 6 m inside of the door path, i.e., the fraction of fish in the "dead zone" inside which all fish are deflected out of the path of the net (Fig. 3, Table 3)
$a_{3.6.n,c,i}$	fraction of fish between the doors that end up in front of the net depending on whether the interviewed captain included the "dead zone" in assessing this fraction (i=1 means did not distinguish dead zone; i= 2 means did distinguish the dead zone) (Fig. 3)
$a_{4,n}$	relative proportion of fish remaining between the wingtips after excluding those in the deadzone (Fig. 3, Table 4)
$a_{5,n}$	relative proportion of fish in the herding zone after excluding those in the deadzone (Table 4)
$a_{6,n}$	proportion of the fish in front of the bridles and sweeps that would be herded into the path of the net
$a_{7,n,c}$	Proportion of fish that are captured of those that end up in front of the net
$a_{8,n}$	ratio of wingspread to doorspread used as a correction factor for q_{net} in instances where the swept area estimate has been computed based on the distance between the trawl net wingtips
$U_{n,c}$	Minimum threshold uncertainty factor (this factor could be made larger for net types with which a particular captain has had much less experience)
Model variables	
$\overline{I_{T,s}^{Sw.A.}}$	average empirical swept area biomass estimate for the trawlable substrate in area s from the years in which survey took place in that area.
$n_{yr,s}$	number of years for which an estimate of swept-area biomass is available for a given survey in the reference year set
$lr_{s,i-j}$	predicted natural logarithm of the ratio of net i to net j catchability
$r\_ob_{s,i-j}$	observed ratio of density values from net i and net j for survey area s
SE_s	standard error in the mean of the natural logarithms of the swept-area biomass estimates in area s

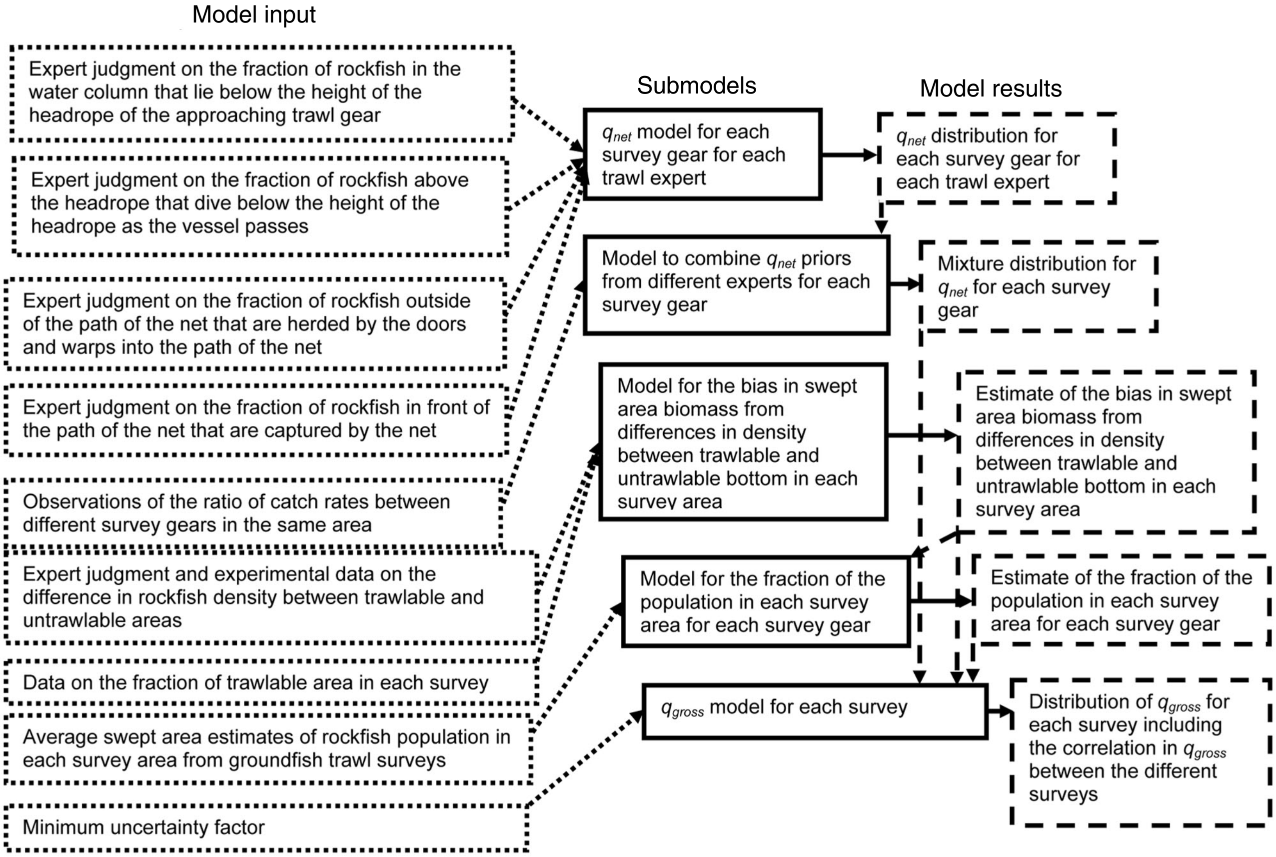

Figure 2

Outline of the structure of the trawl survey catchability model, showing the flow of information from model inputs to the model components (submodels) where the inputs are processed and integrated, to the final model results. See Table 1 for definitions of the variables.

$q_{available}$ = the proportion of B_y in the survey area; and

$q_{trawlable}$ = the average ratio of rockfish density between trawlable and untrawlable areas adjusted by the fraction of the seabed within the surveyed area that is trawlable.

We present conceptual models and equations for each of these components below.

Quantifying catchability with the trawl survey net (q_{net})

In most instances, results from experiments designed to estimate q_{net} for the survey gears and fish populations of interest are unavailable. Since the 1990s, some researchers have developed priors for q_{net} by integrating, within a Monte Carlo simulation model, expert judgment on the components of q_{net} and, in some instances, auxiliary data (Punt et al., 1993; McAllister and Ianelli, 1997; Boyer et al., 2001). Here we present a protocol for an approach that can be applied to estimates of biomass from trawl surveys when several experts provide key information, the population is surveyed by one or more types of trawl gears and, in one or more areas, records of catch rates from two or more types of trawl gears are available.

We first present a conceptual model for the components of q_{net}. It is assumed that a trawl net captures less than 100% of the fish that lie in its path, defined over the horizontal as the path between the trawl doors and over the vertical as the area from the surface to the bottom. Fish can escape for a variety of reasons including, but not limited to (Fig. 3), the following:

1 they are initially high up in the water column and do not "dive" to lie below the oncoming headrope of the trawl;
2 they are near bottom but are driven away horizontally by the influence of the warps near the doors as they spread outwards towards the doors;
3 they are initially in front of the paths of the sweeps and bridles but are not herded into the path of the net;
4 they escape over the headrope or under the footrope;

5 they are captured in the last few minutes of the tows and escape during retrieval (note that the DFO groundfish survey tows along the bottom last usually 19 minutes and in our application none of these fish were assumed to have escaped).

All of these potential sources of escape are factored into our catchability model.

We assumed that

1 q_{net} is constant among areas for the same type of trawl net;
2 q_{net} pertains to fishing during a bottom trawl survey, as opposed to commercial fishing. This assumption was emphasized to the trawl captains so that they would provide specifications based on standard trawl survey operations as opposed to commercial operating conditions; and
3 q_{net} does not vary with abundance.

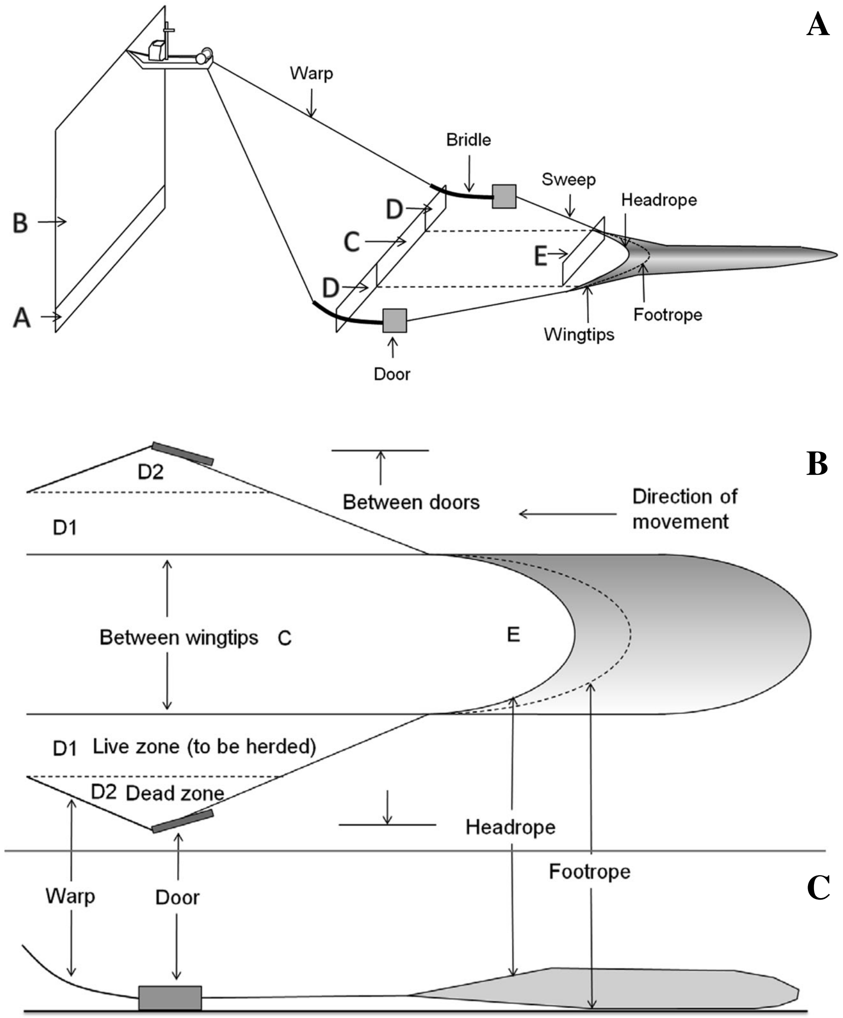

Figure 3

Diagram of fishing zones in the path of the bottom trawl. **(A)** Area A is the area below the boat between the doors and beneath the headrope. Area B is the area to the surface above area A. Area C is the area beneath the headrope to the footrope and between the net wingtips. Area D is the area beneath the headrope to the footrope and between the doors and the net wingtips. Area E is the area between the wingtips and beneath the headrope immediately in front of the trawl, i.e., the so called "kill zone," or capture zone. (**B**) Expanded top view and (**C**) side view showing the trawl warps, sweeps, and net configuration. D1, the "live zone" of the gear is the segment immediately outside of the wingtips in which rockfish are herded into the net path. D2, the "dead zone" of the gear, is the region just inside the trawl doors in which rockfish present escape from the pathway of the net. This conceptual scheme was used in interviews to enable trawl captains to express their views about the faction of rockfish in the water column that ended up in the trawl net.

$q_{trawlable}$-differences in fish density between untrawlable and trawlable areas

Trawl captains and groundfish researchers believe that the densities of rockfishes are higher over untrawlable bottom than over trawlable bottom. Note "untrawlable" is an operational distinction that reflects any type of bottom relief that trawl captains (research and commercial) judge as presenting too much risk for damage to the trawl gear. These opinions are based on the tendency for catch rates for virtually all rockfish species to be higher on, or nearer, rougher bottom, as well as the tendency for untrawlable bottom to be associated with a much stronger acoustic signal for rockfish, and on the basis of submersible studies, which indicate the tendency of rockfishes to be associated with rugged habitat (Krieger, 1993).

Estimates of biomass over swept areas are usually computed by assuming that the average catch rate of survey hauls in a given area (stratum) is a random sample of the entire survey area and, when multiplied by the total survey area, will provide the biomass index for the survey area. In this section, we present a bias correction factor to account for the average relative difference in fish density between trawlable and untrawlable areas in a surveyed area and the fraction of the surveyed area that is untrawlable.

It can be shown that the expected value for the survey biomass index when it is computed only from tows in trawlable habitat is

$$E(I_T) = \frac{q_{net}\, S\, B_{pop}}{\left(f_T + \alpha\left(1 - f_T\right)\right)}, \tag{3}$$

where f_T = the fraction of the total survey area that is trawlable;
α = the ratio of fish density in untrawlable to trawlable habitat; and
S = the fraction of the total population biomass potentially susceptible to capture by survey gear (B_{pop}) and that is on average present in the surveyed area.

To briefly explore the implications of this equation let

$$g_s = f_{T,s} + \alpha(1 - f_{T,s}), \tag{4}$$

where $f_{T,s}$ = the fraction of sea bottom in a surveyed area that is trawlable in survey area s; and
α = the ratio of target species density (t/km^2) in untrawlable to density in trawlable habitat.

Although α may vary with survey area, we typically do not have data that would allow us to estimate these separate factors and α therefore was assumed not to depend on s. In contrast, it is common to have data on the fraction of trawlable area within each survey area and therefore one can thus compute factor g for each survey area.

Should some experiment provide data on α, then the prior for α, $P(\alpha)$, could be statistically updated with the following equation:

$$P(\alpha \mid data) \propto P(\alpha) P(data \mid \alpha), \tag{5}$$

where $P(\alpha|data)$ = the posterior for α, given the data; and
$P(data \mid \alpha)$ = the probability of the data, given α.

Note that no such data were available for our case study application. $f_{T,s}$ can be treated as a beta random variable with binomial data on the number of trawlable sites for each area, or it can be fixed, if the number of trials in each area is very large.

$q_{availability}$-the fraction of total exploitable species abundance in each surveyed region

We developed a protocol to approximate the percentage of the coastwide target species exploitable biomass that is available to each of the surveys. This protocol computes and treats as a random variable the fraction of the total coastwide swept-area biomass in each survey area and accounts for potential differences between survey areas in the fraction of trawlable ground in each survey area. For this protocol, tow-by-tow data from the most extensive trawl survey (i.e., the "reference survey") were used. The protocol is illustrated with bocaccio as an example and includes the following assumptions:

1 The relative distribution of stock biomass among areas has been constant over a reference set of years and two or more groundfish trawl swept-area biomass estimates are available for all survey areas. For bocaccio this reference set covers the years from 2003 to 2007.
2 The proportion of untrawlable area to trawlable area within a surveyed region varies among regions and can be approximated from the observed frequencies of trawlable and untrawlable sites in the cumulative set of randomly allocated survey locations in each survey area. In fact, the locations found to be untrawlable are removed from the set of locations to be considered for research trawling in future years. However, in recent calculations we have found that the impact of this sequential removal of untrawlable locations on the estimated fraction of trawlable area is very small because the fraction of untrawlable areas is overall relatively small (less than about 20%).
3 The ratio of target species density in trawlable and untrawlable areas (α) is the same across areas and time.
4 The habitat for the target species is assumed to be the seabed area between a fixed depth range, e.g., 100–300 m in bottom depth for bocaccio.

Building on the above assumptions, we assume that the proportion of the coastwide target stock biomass available to each survey is the ratio of the swept-area biomass (adjusted for untrawlable area) estimated from trawl surveys during the reference-year period to coastwide stratified swept-area biomass of the target species (Table 2). For bocaccio, the coastwide swept-area biomass was the sum of the swept-area biomasses computed in each survey area from the DFO groundfish surveys plus a swept-area biomass estimate from the unsurveyed area not covered by the DFO groundfish surveys (Fig. 1B). This coastwide swept-area biomass includes regions over 100–300 m in bottom depth on the outer coast or in Hecate Strait (see, for example, in Fig. 1B the gap off the southwest coast of Haida Gwaii between the west coast of Haida Gwaii (WCHG) and QCS surveys). For the latter survey, a global estimate of species density was made across all trawl areas for the reference year period.

For surveys other than the reference survey (e.g., for bocaccio in the West coast of Vancouver Island (WCVI) shrimp survey, Queen Charlotte Sound (QCS) shrimp survey, and U.S. triennial surveys), the biomass of the target species present in the areas covered by the surveys was computed from densities observed in the ref-

Table 2

Estimates of bocaccio (*Sebastes paucispinis*) biomass with the swept-area method and based on Department of Fisheries and Oceans (DFO) groundfish surveys in each region in the years 2003–07. Percentage of coast-wide biomass refers to the fraction of coast-wide swept-area biomass (in regions 1–4, 8) that is on average found inside each region and is used in computing survey catchability. "SE ln(*bio*)" is the standard error for the mean of the natural logarithm of swept-area estimates of stock biomass in each region, with the mean determined from swept-area estimates in different years. "%Trawlable" is the estimate of the percentage of the region that was found to be trawlable based on random sampling of locations in each region for trawling and large sample sizes (>300 sites in each region). GFish=groundfish; WCVI=west coast of Vancouver Island; QCS=Queen Charlotte Sound; HS=Hecate Strait. WCHG=west coast of Haida Gwaii. The total is obtained only from the DFO groundfish survey because the other surveys are contained within it.

Survey number and region	Biomass (kg)[1]	Percentage of coast-wide biomass	Years of data	SE ln(bio)	% Trawable
1 WCVI Gfish	375,207	50	2004, 2006	0.0540	71.6
2 QCS Gfish	247,966	33	2003–05, 2007	0.2950	76.5
3 HS Gfish	35,340	5	2005, 2007	0.2670	78.3
4 WCHG Gfish	11,255	2	2006, 2007	0.0507	87.2
5 WCVI shrimp	20,787	3	2004, 2006	0.0262	100.0
6 QCS shrimp	27,767	4	2003–05	2.1010	100.0
7 U.S. triennial Gfish	180,599	24	2004, 2006	1.8590	82.0
8 Unsurveyed	76,664	10	2003–07	0.2020	0.0
Total	746,432				

[1] Computed from the product of the average density from the trawlable area and the total area of each survey area.

erence survey data set. Note that the regions covered by both shrimp surveys and the U.S. triennial survey lay within areas covered by the reference groundfish survey. For example, the biomass available in the WCVI shrimp trawl survey was based on the density observed in the tows conducted during the WCVI groundfish survey, within the area covered by the shrimp survey.

The fraction of total stock biomass, S_s in a given area s, can be obtained by

$$S_s = \frac{I_{T,s}\left(f_{T,s} + \alpha\left(1 - f_{T,s}\right)\right)}{\sum_{j=1}^{n_{areas}} I_{T,j}\left(f_{T,j} + \alpha\left(1 - f_{T,j}\right)\right)}, \tag{6}$$

where n_{areas} = number of regions for the reference survey plus 1 to account for the coastal habitat for the species that is outside of the surveyed area.

For the each region in the survey q prior model, $I_{T,s}$ can be considered a lognormal random variable:

$$I_{T,s} \sim \text{lognormal}\left(\ln\left(I_{T,s}^{med}\right), SE_s^2\right). \tag{7}$$

The cross-year median for the lognormal density function, $I_{T,s}^{med}$, in Equation 7 can be computed from the empirical mean swept-area biomass estimate ($I_{T,s}^{Sw.A.}$) in each area s and the standard error (SE):

$$I_{T,s}^{med} = \overline{I_{T,s}^{Sw.A.}} * \exp(-SE_s^2 / 2), \tag{8a}$$

where

$$\overline{I_{T,s}^{Sw.A.}} = \frac{1}{n_{yr,s}} \sum_{y=1}^{n_{yr,s}} I_{T,s,y}^{Sw.A}; \tag{8b}$$

$$SE_s^2 = \frac{1}{n_{yr,s}}\left(\frac{1}{n_{yr,s} - 1}\right) \times \sum_{y=1}^{n_{yr,s}} \left(\ln\left(I_{T,s,y}^{Sw.A}\right) - \overline{\ln\left(I_{T,s}^{Sw.A}\right)}\right)^2; \text{ and} \tag{8c}$$

$$\overline{\ln\left(I_{T,s}^{Sw.A}\right)} = \frac{1}{n_{yr,s}} \sum_{y=1}^{n_{yr,s}} \ln\left(I_{T,s,y}^{Sw.A}\right), \tag{8d}$$

where $n_{yr,s}$ = number of years in which a swept area biomass estimate is available for a given survey in the reference year set.

The reference swept-area estimate for unsurveyed regions was obtained from stratified estimates of species density from trawled areas and the estimated habitat area outside of surveyed areas. Because the average catch per tow is based on tows over trawlable bottom, the swept-area estimate was adjusted to account for the estimate of the fraction of trawlable area in the survey area and the average relative difference in bocaccio density between trawlable and untrawlable bocaccio habitat (see Eq. 3).

Approach to acquiring information from trawl experts

Our approach relies on a large number of experts being interviewed to seek their judgments on the credibility of hypothesized values for factors affecting trawl-net catchability (q_{net}). A sufficiently large number of experts is required to characterize the range of differences in opinion among experts (e.g., Martin et al., 2005; Uusitalo et al., 2005). This can be achieved by continuing to sample until the distribution of inputs stabilizes, e.g., the means and standard deviations in inputs change by less than 10% for each new expert interviewed. In the interviews each trawl captain was asked to specify the most likely, minimum plausible, and maximum plausible average values for a set of key factors conjectured to determine q_{net} and these values were then used to formulate a triangular distribution for each factor for each survey net specific to each captain. The component factors of q_{net} formulated below represent "average" effects. Thus the minimum and maximum input values for each key factor do not reflect a predicted response for one case (i.e., from the population of all tows), but the minimum and maximum values for the average value across all tows combined. The pdfs formulated thus represent density functions of the mean value for a given factor, not the population of values from all conceivable tows.

The probabilistic modeling approach that was applied to synthesize the captains' inputs was similar to that taken by Uusitalo et al. (2005) and Martin et al. (2005) to formulate priors based on interviews with several different experts. For each net type, the resulting q_{net} was modeled as a mixture of the distributions resulting from the specifications from each of the interviewed captains.

Answers to our questions allowed us to simplify the process of catching a bocaccio to six steps based on four questions:

Step 1 Resolve the relative distribution in the water column (a_1). Question 1) *What is your best estimate (and minimum and maximum) of the percentage of target species that would be near-bottom (within 3–4 m) as the vessel passed overhead?*

Rockfish, particularly bocaccio, are presumed to occupy the water column from surface to bottom, but their density increases with depth. The factor, a_1, for the relative distribution of the target species in the water column (zone A, Fig. 3) defines the proportion of fish below headrope height, as the vessel passes over the fish. For this step, three assumptions are made:

1 fish below the headrope, as the vessel passes over them, continue to stay below the height of the headrope until they arrive at the mouth of the net;
2 fish outside the doors (horizontally), continue to stay outside the doors; and
3 a_1 is the same for all nets (this is reasonable because most of the nets have headline heights of around 3 m and only the U.S. triennial net is higher).

Step 2 Resolve the proportion of off-bottom target species that "dive" into the "kill zone" (i.e., the area immediately in front of the opening of the trawl net), (i.e., zone E, Fig. 3) (a_2). Question 2) *What percentage of those fish initially off-bottom would dive into the kill zone?*

The factor a_2 is the proportion of fish in zone B that would dive into the kill zone from those initially above the head rope of a given type of net (zone B, Fig. 3). For factor a_2, the following assumptions are made:

1 all fish below the headrope, stay below the headrope until at the mouth of the net;
2 fish dive in response to vessel noise and warps; and
3 dive rate is equal for all net-warp-vessel combinations.

Step 3 Resolve the proportion of fish which lie in the "dead" zone, i.e., the zone between the doors but external to the trawl warps.

The answers to questions 1 and 2 provided the percentage of fish that were initially in the path of the trawl doors that would lie in the capture zone as the doors approached (between the doors and below the headrope) (zones C–D, Fig. 3). The disposition of the fish horizontally would then be partially determined by whether they lay directly in the path of the net between or outside the wingtips but still within the door path. Fish in zone C were assumed to stay there as the net approached (zone E). Fish in zone D would have to be herded inwards to area C by the sweeps and bridles (Fig. 3).

Discussions with some captains indicated that for fish that lie within 6 m of doors inside the door path there is zero catchability. As the trawl warps approach the doors near the bottom, they spread out towards the doors, possibly scaring near-bottom fish out of the kill zone. Therefore, as the doors approach the fish, the fish are assumed to be distributed across the path of the doors in one of three sectors, in proportion to the linear dimensions of that sector (Fig. 3), namely:

1 in the path of the net (i.e., between wingtips, zone C, Fig. 3, Tables 3 and 4);
2 in the path of the sweep and bridles but more than 6 m (for survey nets used for bocaccio) inside of the door path (herding zone, D1, Fig. 3B) (factor $a_{3,1,n}$); and
3 in the path of sweep and bridles but within 6 m of the doors (dead zone, i.e., horizontal area in which all fish are expected to escape capture) (D2, Fig. 3B).

Step 4 Resolve arithmetic correction for the relative proportions of fish remaining in front of the net (between wingtips) or in front of sweeps and bridles (inside of the dead zone).

After allowing fish in the dead zone to escape, we estimated the proportions of remaining fish that either lie in front of the net (zone C, Fig. 3) (factor $a_{4,n}$) or the "herdable" section of the sweeps and bridles

Table 3

Relative distribution of fish in different sectors and parts of the kill zone of the gear as the gear approaches a stationary fish. The factors, proportion of the linear distance between the trawl doors that is within wingtips ($a_{3,1}$) and proportion in the dead zone ($a_{3,2}$) are used in the trawl survey catchability model. Distances are in meters. See Figure 3 for a schematic diagram of a trawl net.

Net type	Nominal door spread	Nominal wing spread	Nominal distance between doors, outside of wings	Dead zone in herding area	Effective herding zone	Proportion remaining in herding zone ($a_{3,2}$)	Proportion within wingtips ($a_{3,1}$)	Proportion removed by dead zone
AWII trawl (groundfish)	63.3	14.4	48.9	6.0	36.9	0.583	0.227	0.190
Nor'Eastern trawl (U.S. triennial)	58.9	13.4	45.5	6.0	33.5	0.569	0.228	0.204
Shrimp trawl	26.5	10.6	15.9	6.0	3.9	0.147	0.400	0.453

Table 4

Relative proportions (P) of remaining fish in areas C and D1 (from columns 6 and 7 in Table 3, Fig. 3). Both of these factors (a_4 and a_5, respectively) are used in the trawl-survey catchability model.

Net	P between wingtips (a_4)	P in herding zone (a_5)
AWII trawl (groundfish)	0.281	0.719
Nor' Eastern trawl (U.S. triennial survey)	0.286	0.714
Shrimp trawl	0.731	0.269

(zone D1, Fig. 3B, Tables 3, 4) (factor $a_{5,n}$) (see Eq. 10 for captains who explicitly accounted for the dead zone and Eq. 11 for those who did not).

Step 5 Determine the proportion of fish that will be herded from the path of the sweeps and bridles (zone D1) into the path of net (inside the wingtips) (zone C). Question 3) *What percentage of the fish in front of the bridles and sweeps would be herded into the path of the net?*

The factor a_6 concerns the remaining fish in sweeps and bridles path and for this step the following assumptions are made:

1. fish initially in front of the net, stay in front of the net; and
2. factor a_6 is the same for all nets.

Step 6 Determine the proportions of fish that are captured of those that end up in front of the net ($a_{7,n,c}$). Question 4) W*hat percentage of the fish that make it to area E will be captured and retained by the net?*

Finally, of the fish that have ended up in front of the net (zone E in front of footrope, Fig. 3), what percentage will be captured and retained in the net?

Steps in the algorithm to compute a prior probability density function for estimates of catchability

WinBUGS 1.4 (Lunn et al., 2000) was applied to synthesize the inputs from the trawl captains and other technical settings and to produce output density functions for the q_{gross} values for each of the surveys. The steps of the algorithm applied are provided below.

Step 1 Draw a value for the ratio of fish density in untrawlable areas to fish density in trawlable areas, α, from the density function for it (see Eq. 3 and below for specifications).

Step 2 To generate a value for the fraction of total population biomass vulnerable to survey gear in each area, S_s, draw a value for swept-area biomass in each of the eight coastal areas, using the lognormal density function and the empirical swept-area value as the median and the variance in the natural logarithm of the estimate (Eqs. 6–8, Table 2).

Step 3 For each captain, draw a value for the proportion of fish below the headrope (a_1) using the parameters of the triangular distribution provided by each captain.

Step 4 For each captain, draw a value for the proportion of fish above the headrope that stay above the headrope as the net approaches (a_2), using the parameters of the triangular distribution provided for each captain.

For each captain, compute the proportion of fish entering the path of the net and doors from those in the water column that are in the path of the net and the doors ($a_{1,2}$), such that

$$a_{1,2} = 1 - (1 - a_1) * a_2. \tag{9}$$

Step 5 For each captain, draw a value for the proportion of fish that will successfully be herded from the path of sweeps and bridles to the path of the net (one captain) or herded from the path of the doors to the path of the net (the other captains) ($a_{6,n}$).

Step 6 For each captain, compute the fraction of fish between the doors that end up in front of the net, given the proportion of doorspread that is between the wingtips ($a_{3,1,n}$) (step 3 of previous section) for the following sections of the gear—the dead zone ($a_{3,2,n}$), between the dead zone and the wingtips (of the area not in the dead zone) ($a_{4,n}$), and between the wingtips (of the area not in the dead zone) ($a_{5,n}$)—and the fraction of fish herded into the path of the net ($a_{6,n}$).

For the captains that conditioned herding of fish into the front of the net on those fish that swim in the zone between the doors and the wingtips, the following formula applies:

$$a_{3.6,n,1} = (1 - a_{3,1,n}) \times a_{6,n} + a_{3,1,n}. \tag{10}$$

For the captain that conditioned herding of fish into the front of the net on those fish that swim in the area that does not include the dead zone, the following formula applies:

$$a_{3.6,n,2} = (1 - a_{3,2,n}) \times (a_{4,n} \times a_{6,n} + a_{5,n}). \tag{11}$$

Step 7 For each net type (n) and captain (c), draw a value for the proportion of fish that are captured of those that end up in front of the net ($a_{7,n,c}$). To do this, use the parameters of the triangular distribution provided for each captain for each net type.

Step 8 Compute q_{net} for each net type (n) and captain (c):

$$q_{net,n,c} = a_{1.2,c} \times a_{3.6,n,c} \times a_{7,n,c}. \tag{12}$$

Step 9 Compute the q_{gross} for each survey (s) for each captain (c):

$$q_{gross,s,c} = q_{net,n,c} \times U_{n,c} \times S_S / (g_s \times a_{8,n}), \tag{13}$$

where $U_{n,c}$ = the uncertainty random variable for each net type and captain;
S_s = the random variable for the fraction of exploitable stock biomass in the region s;
g_s = the random variable accounting for trawlable area in region s; and
$a_{8,n}$ = the fixed correction factor applied where the wingtip distance had been applied to compute the swept-area biomass.

$U_{n,c}$, is applied to each $q_{net,n,c}$ to ensure that the density functions are not overly precise (i.e., it applies a multiplicative uncertainty factor).

Such factors have been applied in other situations where it is presumed that the distributions offered by experts are far too certain (e.g., Boyer et al., 2001). In our application, an uncertainty factor was drawn from a lognormal density function with a coefficient of variation (CV) of 0.5 and a median of 1 for each captain and net type. See the discussion for further justifications for including this factor and for the choice of the value for the CV.

Step 10 Give each captain's q_{gross} equal prior weight in the final q_{gross} distribution such that the chance of including a given captain's input has equal prior probability.

We applied a C-dimensional Dirichlet density function where C is the number of captains. This was applied as the multivariate prior pdf for the relative weight given to each captain's q_{gross} distribution for a given survey. All C input parameters for this density function were set to 0.5, which gives a relatively uninformative prior for the weight placed on each captain. In each Monte Carlo iteration, one of the C captain's q_{gross} values was randomly chosen for the q_{gross} random variable for each of the seven research surveys. Thus, without any Bayesian updating with new data, each captain's inputs are given equal weight in the output probability distribution q_{gross} for each regional survey.

Step 11 Use observations of the ratio of average catch rates from the different survey gears, e.g., shrimp trawl and groundfish trawl, from comparative gear experiments in specific locations (intended or unintended) to update the $q_{net,c}$ density functions for these survey nets (see Eqs. 14–15 below).

The ratios of observed average catch rates for the different survey nets will give more weight to captain inputs that are more consistent with the observed ratios for these two net types.

Step 12 Apply WinBUGS (or other Bayesian integration software) to produce two or more sets of Markov chain results for the q_{net} parameters for each net type and q_{gross} parameters for each survey; apply diagnostics to remove the burn-in and summarize the posterior results.

Step 13 Evaluate the posterior correlations between the q_{gross} parameters for the different surveys and identify a suitable multivariate density function to summarize the results.

Because the q_{gross} distributions for the different survey regions in our application were computed with identical input values for q_{net} across survey regions, the q_{gross} variables tended to be highly correlated across survey regions. There is the potential for multimodality in the marginal density functions for q_{gross} for the different survey areas and thus a mixture distribution may be appropriate. Should the results for each survey be unimodal, then a multivariate lognormal density function should be a good candidate.

Implementation of the method for bocaccio

In the q prior model for British Columbia bocaccio, we treated the factor α as a random variable, having a triangular prior distribution with a minimum of 1, maximum of 10, and mode at 3. f_T is provided by survey area (Table 2) and treated as known because the number of sites sampled per survey area was high in all areas (300–1000 depending on the survey area). Shelf regions without trawl surveys (unshaded regions in Fig. 1B) were excluded from the original set of groundfish surveys because the fraction of trawlable seabed was known to be very low. Thus, f_T in areas where there are no surveys is presumed to be 0%

The average and standard error (SE) in the average of the natural logarithm of the available estimates of annual swept-area biomass for each survey region (Table 2) were computed and applied in the q prior model to generate from a lognormal density function samples of potential stock biomass in each region and the potential fraction of total stock biomass in each region. Some of these standard errors were very large and created large uncertainty in the fraction of stock biomass for each of the regions. Note that in instances in which the SE is less than 0.15, we recommend that this value be set to 0.15, because, in general, the minimum CV in a swept-area biomass, accounting for all sources of error variability (i.e., SE divided by the mean) for relative stock size, should be no less than 0.15 (the CV of a lognormal distribution is $\sqrt{\exp(\sigma^2)-1}$, where σ is the SD in the natural logarithm of the random variable). The empirical values for SE may be low because of small sample sizes (e.g., n=2 years) and chance. We believe that because of the highly clumped spatial distribution of bocaccio, longer time series would yield higher values for SE than were obtained when the empirical values happened to be less than 0.15.

The U.S. triennial survey and the two shrimp surveys are contained within the WCVI and QCS groundfish surveys (Fig. 1B). These larger surveys that contain the smaller, more localized ones are called here “containing surveys.” For the smaller or “contained” surveys, the random variable (RV) for $I_{T,s}$ was limited to the product of the fraction of area occupied by the contained survey and the RV for $I_{T,s}$ for the containing survey. This computation presumes that bocaccio density in the contained survey is no larger than that in the containing survey and limits the biomass for the contained survey to no more than that expected if the density was the same between the contained and containing survey.

In our application, we consulted with 12 commercial trawl captains—each with at least 10 years of experience in trawling for rockfish. All captains had experience (11–22 years) with types of trawls used in the DFO groundfish and U.S. triennial surveys, i.e., both groundfish and shrimp trawl nets, and with total groundfish landings ranging from 6800 to 275,000 t. Captains 1–4 were interviewed in groups of two and the remaining captains were interviewed separately. An attempt was made in each interview to provide the same explanation for the requested information, although the interview was conducted in an informal conversational manner. The format undoubtedly varied in subtle ways over the course of the 12 interviews. During our interviews with trawl captains, we characterized “typical survey fishing” as occurring on average at 150 m depth from June to July from 1 h after sunrise to 1 h before sunset. This fixed interval of time was necessary because trawl captains preferred to answer the questions while considering specific fishing conditions (i.e., time, depth, season, etc.)

For bocaccio, only one of the captains presumed that the a_6 proportion reflected the proportion of fish between the dead zone and the path of the net that are herded into the path of the net. The rest of the captains presumed that this proportion reflected the fraction of fish between the doors and the path of the net that are herded into the path of the net. The doorspread of the U.S. triennial survey Nor’ Eastern trawl net was not measured. We assumed it had the same ratio of wingtip to doorspread as that of the Atlantic western (WII) trawl net used in the DFO groundfish survey.

For the q_{net} interview questions, each captain was asked for catch estimates for each of the three nets. The nets are towed at different speeds, have different vertical openings and, perhaps most importantly, the mouth opening of the shrimp trawl is not configured, so that the headrope overhangs the footrope (known as a “cape”). The net parameters are as follows:

1 DFO Atlantic Western trawl: towed at ~3 knots, and having a 3.7-m vertical opening;
2 U.S. Nor’ Eastern trawl: towed at ~3 knots and having a 7.1-m vertical opening; and
2 DFO shrimp trawl: towed at ~2 knots and having a 2.7-m vertical opening.

Most groundfish trawls have a shorter headrope than footrope so that the headrope precedes the footrope through the water providing a “cape” or “hood.” As a fish encounters the footrope, it cannot escape by swimming directly up. On the shrimp trawl, however, the headrope and footrope are virtually in line. Presumably, when the bocaccio detect the proximity of the mouth opening of the shrimp trawl, the net front is already effectively a 2.7-m vertical “wall” of footrope, disturbed sediment, and headrope. It is reasonable to assume that some bocaccio would escape vertically. When a bocaccio encounters the groundfish footrope, however, it is surrounded on four sides (wings, cape, and the bottom). We assumed that the relatively large bocaccio did not escape through the net and that the probability of retention was 1. The value for this factor, $a_{7,n}$, depends on the net ($a_{7,1}$ for the AWII trawl, $a_{7,2}$ for the triennial Nor’Eastern, $a_{7,3}$ for the DFO shrimp trawl). Our approach derives catchability based on doorspread, and therefore the U.S. triennial and the WCVI shrimp trawl estimates first had to be altered by the ratio of wingspread to doorspread ($a_{8,n}$).

Table 5

Biomass estimates of bocaccio (*Sebastes paucispinis*) based on survey tows using the shrimp trawl survey net and the Atlantic western (WII) groundfish trawl survey net, Estimates were based on survey positions shown in Figures 4 and 5. Results are shown for Queen Charlotte Sound (2003–07 for shrimp trawl and 2004–05 for AWII groundfish) and west coast of Vancouver Island (2004, 2006). The ratio of catch rates between these two survey gears was used to screen the plausibility of values for trawl-net catchability for these two nets that was determined from the interviews of the trawl captains.

	Shrimp trawl		AWII groundfish trawl	
Region	Number of tows	Biomass (kg)	Number of tows	Biomass (kg)
Queen Charlotte Sound	212	4993	52	39,746
West coast of Vancouver Island	141	5258	66	20,787

The shrimp and groundfish survey gears were applied in the same years in the survey area of the WCVI shrimp survey and the QCS shrimp survey. The observed mean ratio of bocaccio density between the trawl and shrimp survey nets for QCS for the years 2003, 2004, 2005, and 2007 was 8.76, with a SE in the natural logarithms of the estimates of 0.59 (Table 5, Fig. 4). The observed mean ratio for density estimates for the WCVI shrimp survey region between the groundfish and shrimp nets for the years 2004 and 2006 was 3.95, with a SE of 0.116 (Fig. 5). This latter SE was increased to 0.3 for the statistical estimation, because it was judged unlikely that the precision could be so high and there were only two years of survey data to provide this estimate. In each Monte Carlo iteration, the natural logarithms of the computed q_{net} values chosen for the shrimp and groundfish surveys were taken and the logarithm of the q_{net} for the shrimp survey was subtracted from the logarithm of the q_{net} for the groundfish survey. This difference was used as the expected log ratio for these survey catch rates for these two types of trawl nets. A lognormal density function was then applied to compute the probability of the observed ratio, given the model predicted ratio of q_{net} for these two nets:

$$lr_{s,i-j} = \log(q_{n=i,s}) - \log(q_{n=j,s}) \text{ and } i \neq j, \tag{14}$$

$$r\_ob_{s,i-j} \sim \log normal(lr_{s,i-j,}\sigma_{s,i-j}{}^{2}), \tag{15}$$

where the subscripts i and j denote the DFO groundfish survey and shrimp survey nets; respectively, and

$r\_ob_{s,i-j}$ = the observed ratio of density values from groundfish and shrimp nets for survey area s.

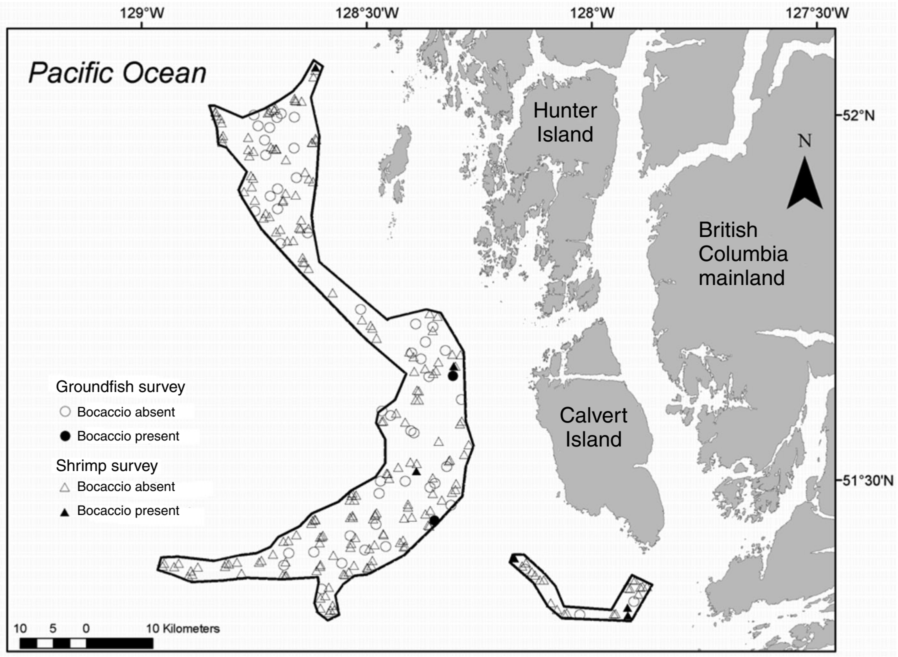

Figure 4

Mapped zones and trawl tow positions (symbols) of the Queen Charlotte Sound groundfish and shrimp trawl surveys where the two surveys overlapped. These two surveys provided an unintended reference source of the catch-rate ratio data for these two survey gears that were then used to update the groundfish-to-shrimp trawl-net catchability ratios for each of the experts. Polygons surrounding the overlapped survey areas were connected by hand to delimit the outer boundaries. Open and closed circles indicate the absence and presence, respectively, of bocaccio (*Sebastes paucispinis*) in the groundfish surveys. Open and closed triangles indicate the absence and presence, respectively, of bocaccio in the shrimp surveys.

As indicated above, there are two observed ratios for bocaccio; one for the WCVI and one for QCS. For WCVI, $\sigma_{s,i-j}$ was 0.3, and for QCS, $\sigma_{s,i-j}$ was 0.59.

The WinBUGS results for bocaccio were numerically stable after rapid burn-in and rapid mixing. The Gelman-Rubin (Brooks and Gelman, 1998) statistic was applied to assess the burn-in period, which was judged to be about 500 iterations. A total of 40,000 iterations with two chains were judged to be sufficient to provide precise approximations of the target density function. Using the results after the burn-in, we found that the ratio of Monte Carlo error (analogous to standard error in the sampled posterior mean) to the posterior standard deviations (SDs) for all outputted variables was far less than the minimum standard of 5% (Best and Thomas, 2000).

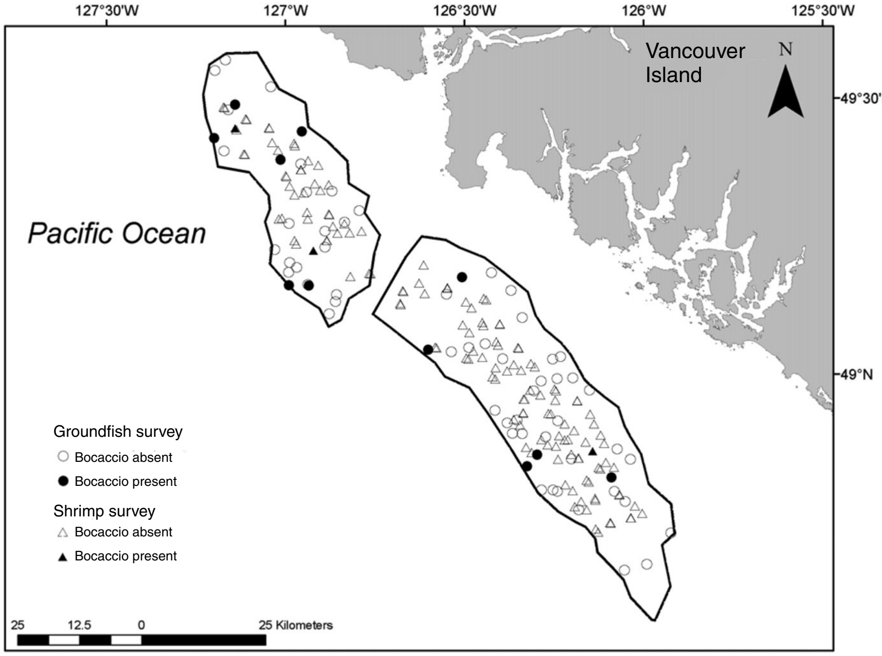

Figure 5

Mapped zones and trawl tow positions (symbols) of the west coast Vancouver Island groundfish and shrimp trawl surveys where the two surveys overlapped. These two surveys provided the catch-rate ratio data for these two survey gears that were then used to update the groundfish-to-shrimp trawl-net catchability ratios for each of the experts. Polygons surrounding the overlapped survey areas were connected by hand and delimit the outer boundaries. Open and closed circles indicate the absence and presence, respectively, of bocaccio (*Sebastes paucispinis*) in the groundfish surveys. Open and closed triangles indicate the absence and presence, respectively, of bocaccio in the shrimp surveys.

Results

We first considered the individual distributions computed from each captain's inputs for the catchability of each of the three net types (q_{net}). For each of the three net types, a wide range of plausible values for q_{net} were obtained from the 12 interviewed captains and there was considerable variability between the captains and some of the distributions were nonoverlapping (Fig. 6). The CVs in the q_{net} distributions by captain for each net varied from about 0.1 to 0.6, reflecting considerable variability in individual levels of uncertainty in the q_{net} inputs.

The q_{gross} values obtained for each captain and for each net type with no updating and no uncertainty factor showed considerably wider distributions and more overlap in all cases between the captains than the q_{net} distributions for each captain (Figs. 6 and 7). The q_{gross} distributions for the different surveys showed varying amounts of overlap between the captains with the WCVI shrimp survey showing the least amount of overlap and the U.S. triennial survey showing the most overlap because of very low precision in q_{gross} among captains. The low precision was primarily due to the high uncertainty in the fraction of stock biomass in the U.S. triennial survey area (Table 2). The CVs in the q_{gross} distributions by captain ranged from about 0.3 to 0.7 for the DFO groundfish surveys and the WCVI shrimp survey (Fig. 7). However, the QCS shrimp survey showed high CVs of about 1.5–1.8 because of the added uncertainty in accounting for the fraction of the stock in each survey area and the ratio of bocaccio density in untrawlable and trawlable areas. The q_{gross} distributions for the shrimp trawl surveys (e.g., for WCVI) were centered considerably lower than those provided for the groundfish surveys partly because of low values for q_{net} and because a small fraction of the stock falling in these areas. Also for the shrimp trawl survey areas, the fraction trawlable was 100%, whereas the groundfish trawl survey areas this was closer to 70–80% (Table 2).

We next consider different approaches to combining the q_{net} distributions from the different experts into a single q_{net} distribution for each net type. When equal weighting was applied to the inputs from the different captains without Bayesian updating and without the uncertainty factor, the q_{net} distributions for each net were multimodal (Fig. 8). Under these same conditions, the combined distributions for q_{gross} for each net showed varying amounts of departure from unimodality; the q_{gross} distribution for the WCVI shrimp survey showed the most pronounced bimodality (Fig. 9). When the uncertainty factor was applied without Bayesian updating, the q_{net} distributions showed less pronounced multimodality (Fig. 8); multimodality was no longer seen in any of the q_{gross} distributions and the distributions became slightly wider (Fig. 9, Table 6).

We compared the ratios in values of q_{net} for the groundfish survey to q_{net} for the shrimp survey (provided by the captains) with the observed ratios in values of q_{net} for the groundfish survey to q_{net} for the shrimp survey in the WCVI and QCS surveys

(Fig. 10). s/b10Although the observed ratios for WCVI and QCS were about 4 and 9, the ratios obtained from the captains' inputs ranged from about 1 to 32 (Table 7). The CVs in the expertly determined ratios ranged from about 0.1 to 0.5, conveying a range of degrees of uncertainty between captains (Table 7). Where the captains' ratios deviated most from the observed ratios and had the smallest CVs, the posterior probability for the captain was effectively zero or very low. This situation occurred for six of the captains (Table 7). In contrast, ratios that deviated considerably from the observed ones but had high uncertainty, e.g., for a captain whose mean ratio was 0.7 and CV was 0.4, still retained some posterior weight whereas captains with mean ratios of 1.3 and 1.5 but much smaller CVs had effectively zero posterior weight. The posteriors for the six captains that retained most of the weight ranged from about 0.06 to 0.38. These posteriors showed, if anything, a negative correlation (about −0.10 to −0.30) with the three measures of trawling experience (years of experience, and tons of groundfish and bocaccio landed) (Table 8). Therefore, although an expert's amount of experience may be a reliable indicator of his or her technical proficiency (i.e., the estimates of total groundfish landings and total bocaccio catch are strongly positively correlated with years of experience), experience does not indicate the reliability of the information that he or she may provide.

When Bayesian updating was applied without the uncertainty factor, most of the weight shifted from three modes for q_{net} to predominantly two modes for each net type (Fig. 8). For example, the third mode over the highest values in the shrimp q_{net} posterior was eliminated. The central tendencies for the shrimp q_{net} and q_{gross} values decreased by about 40%, whereas that for the DFO AWII nets increased by no more than about 5% with the Bayesian update. Under these same conditions, precision in the q_{gross} distribution for each survey increased only for the shrimp surveys (Table 6). Bimodality was no longer present in the q_{gross} distributions (Fig. 9). In contrast to the instance with no uncertainty factor and no Bayesian updating, when Bayesian updating and the uncertainty factor were applied, the q_{net} distributions by captain all overlapped for each of the three nets (Fig. 10). The mean value for q_{net} for the shrimp trawl was lower and more uncertain than for the two groundfish nets (Fig. 8). None of the q_{net} and q_{gross} composite distributions showed bimodality and results were not quite as precise as with the analogous case without the uncertainty factor (Figs. 8 and 9, Table 6). The CVs in the groundfish survey q_{gross} values ranged from about 0.77 to 0.83; and 95% probability intervals (PIs) ranged between 22- and 25-fold between the bounds (Table 9). The CVs for the shrimp survey q_{gross} values were considerably higher at about 1.5 and 2.7 (95% PIs of about 84- and 3100-fold). This high uncertainty was largely due to large differences between the inputs provided by captains but also due to higher uncertainty in the fraction of stock in these surveys (Table 2). The U.S. triennial survey q_{gross} had a high CV (1.7) and an 800-fold 95% probability interval (PI). This high uncertainty is also due mainly to the high uncertainty in the fraction of the stock in this survey (Table 2).

One key factor is the ratio of fish density in untrawlable areas to that in trawlable areas, α. When this factor was set to 1 and the Bayesian update and uncertainty factor were applied, the central tendencies of the posterior distributions for all of the surveys approximately doubled, indicating that the effect of this parameter is to decrease q_{gross} for all surveys and to lead to increased population biomass estimates (Table 6). Doubling the mode and maximum value for α from 3 and 10 to 6 and 20 caused the mean for q_{gross} to decrease

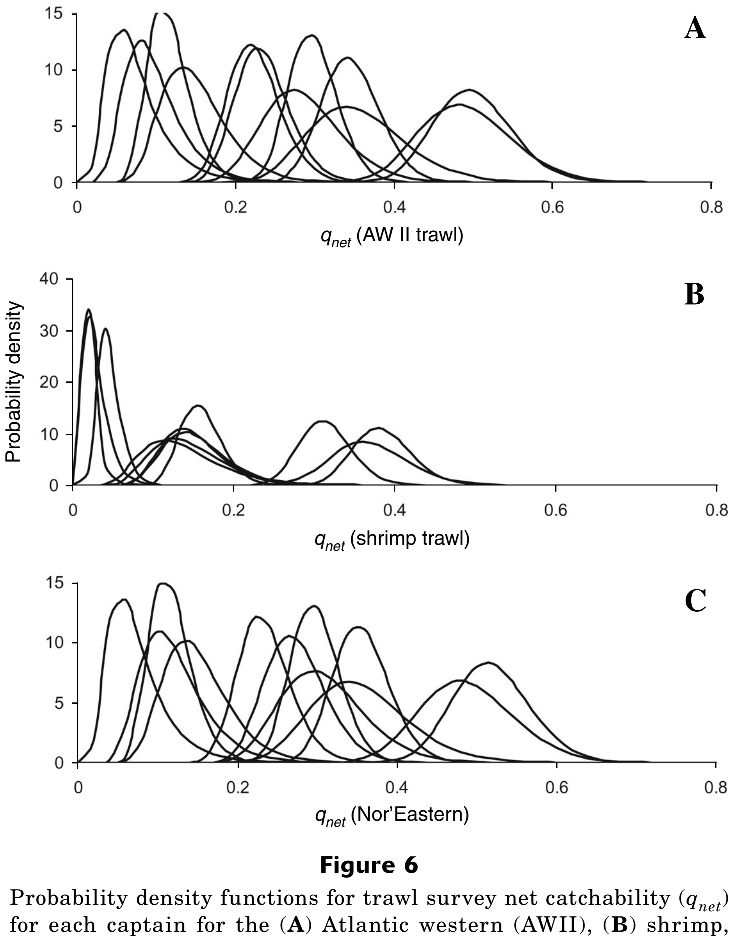

Figure 6

Probability density functions for trawl survey net catchability (q_{net}) for each captain for the (**A**) Atlantic western (AWII), (**B**) shrimp, and (**C**) Nor'Eastern trawl nets, based on inputs provided for each captain without any Bayesian updating and without the uncertainty factor applied.

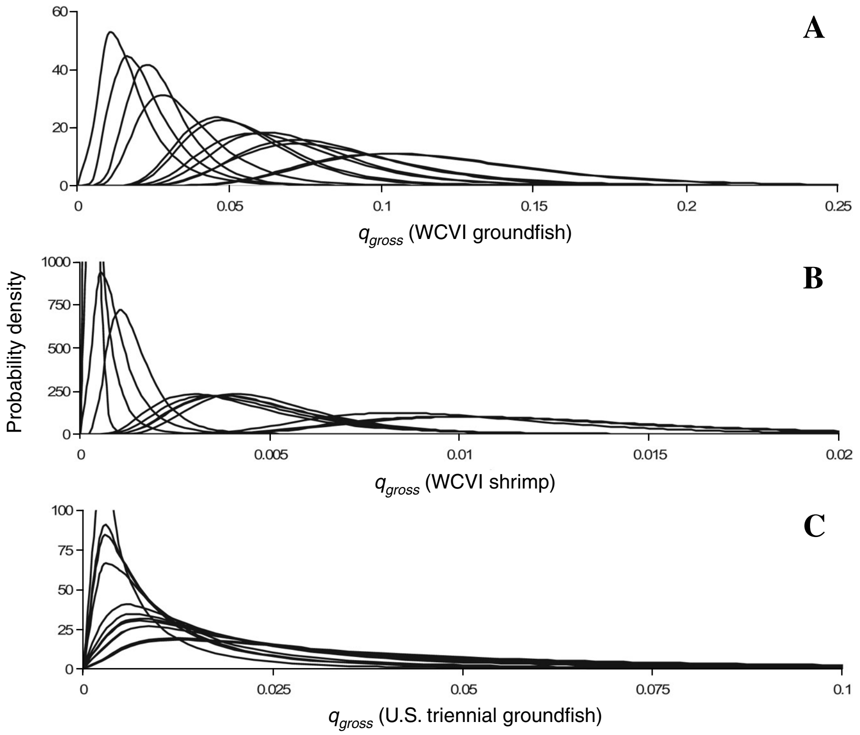

Figure 7

Probability density functions for trawl survey catchability (q_{gross}) obtained for each captain for the (**A**) west coast Vancouver Island (WCVI) groundfish, (**B**) WCVI shrimp, and (**C**) U.S. triennial groundfish surveys, based on inputs provided for each captain without any Bayesian updating and without the uncertainty factor applied.

to between 63% and 81% of the reference case values. The CVs for q_{gross} for the different surveys decreased slightly when α was set to 1 and increased slightly when its input distribution mode and maximum were doubled (Table 6).

The q_{gross} values for the different surveys showed varying amounts of positive correlation, which resulted from the use of the same or very similar nets in all of these surveys and the captains prescribing highly correlated prior inputs as in the case of the AWII and Nor'Eastern nets (Table 10, Fig. 8 shows a high degree of similarity in the q_{net} outputs for these two nets). The q_{gross} values for the DFO groundfish survey nets showed the highest correlations with values up to about 0.96. The q_{gross} for the U.S. triennial survey showed the lowest correlations with the other nets because of the high amount of uncertainty in the fraction of the population in this survey (correlations between 0.14 and 0.35). The QCS shrimp q_{gross} also showed low correlations with the other surveys also because of the high uncertainty in the fraction of the population in this survey area.

In our application, density functions for q_{gross} were unimodal and in all instances positively skewed. Thus, a multivariate lognormal density function was formulated to summarize the joint prior density function for q_{gross} for the six survey time series used in the stock assessment. This multivariate density function was formulated using the posterior median and covariance outputs from the WinBUGS (Tables 10 and 11). The prior results for q_{gross} for six of the surveys were compared with posterior results for q_{gross} from a stock assessment of Bristish Columbia bocaccio for which a noninformative prior for q_{gross} was used (Table 11). All posterior medians for q_{gross} obtained from the stock assessment with noninformative priors for q_{gross} (Table 11) were inside of the 95% PIs for the informative q_{gross} prior (Table 11). However, in most instances the posterior medians were larger than the prior medians, indicating that the stock assessment data tend to produce stock biomass values lower than those indicated by the q_{gross} density function obtained in this study.

Some key stock assessment quantities are also shown that were obtained with a noninformative prior and the informative q_{gross} prior (Table 12). The posterior mean values for stock biomass at maximum sustainable yield, stock biomass in 2008, and replacement yield changed slightly with the use of the informative q_{gross} prior. In contrast, the posterior CVs for the current stock biomass and replacement yield decreased substantially with the use of the informative prior for q_{gross}.

Discussion and conclusions

We provide an approach to formulating a Bayesian prior for trawl survey catchability for rockfish that can integrate subjective judgment from several experts on factors affecting net catchability with data obtained from field experiments and trawl research surveys. The approach is useful for situations where a stock assessment model is to be fitted to one or more survey indices and although directed at rockfish surveys, it could be extended to other groundfish species. For this approach, data are used from a series of related trawl surveys covering most of the British Columbia continental shelf, all based on the same trawl gear, to provide estimates of the fraction of the population in each survey area. Bias correction factors are formulated and can be updated with experimental data that allow us to evaluate hypothesized average differences in target fish species density between trawlable and untrawlable areas and the fraction of area in the survey that is treated as untrawlable. The current approach presumes that experts all have experience with all of the types of nets that are used in the surveys or with nets that are very similar. The approach updates each captain's inputs on the basis of the consistency with observations from experiments where the ratios of catch rates between different types of survey nets were evaluated. This updating process reduced the degree of uncertainty in the prior by considerably modifying the posterior distributions, particularly for the most poorly understood gear—the shrimp trawl.

A few different procedures were applied to counteract the adverse effects on stock assessment results that may result from the tendency of individual experts to provide distributions that are too certain. One procedure was to apply an uncertainty factor (Boyer et al., 2001); this is discussed further below. The second was to apply a mixture distribution approach to incorporate judgment from different experts. However, this procedure may cause the resulting posterior distributions to be multimodal—a feature that may arise when the narrow distributions offered by the various experts fall into different modes. Such a result is less likely when there is a large number of contributing experts.

Attempts to directly estimate catchability with trawl nets (q_{net}) have met with limited success, particularly for rockfish. The principal difficulty lies in measuring the abundance of fish that is positioned in front of the net. Krieger and Sigler (1996) attempted to estimate catchability of Pacific ocean perch (*S. alutus*) for a bottom trawl on the basis of observations from a submersible vessel. They reported estimates for q_{net} of 0.97–1.27 for trawl catchability based on wingtip spread. Using the AWII to calculate an approximate ratio of doorspread to wingspread of about 4.4 (AWII, Table 3), they determined a doorspread catchability of 0.22–0.29 for Pacific ocean

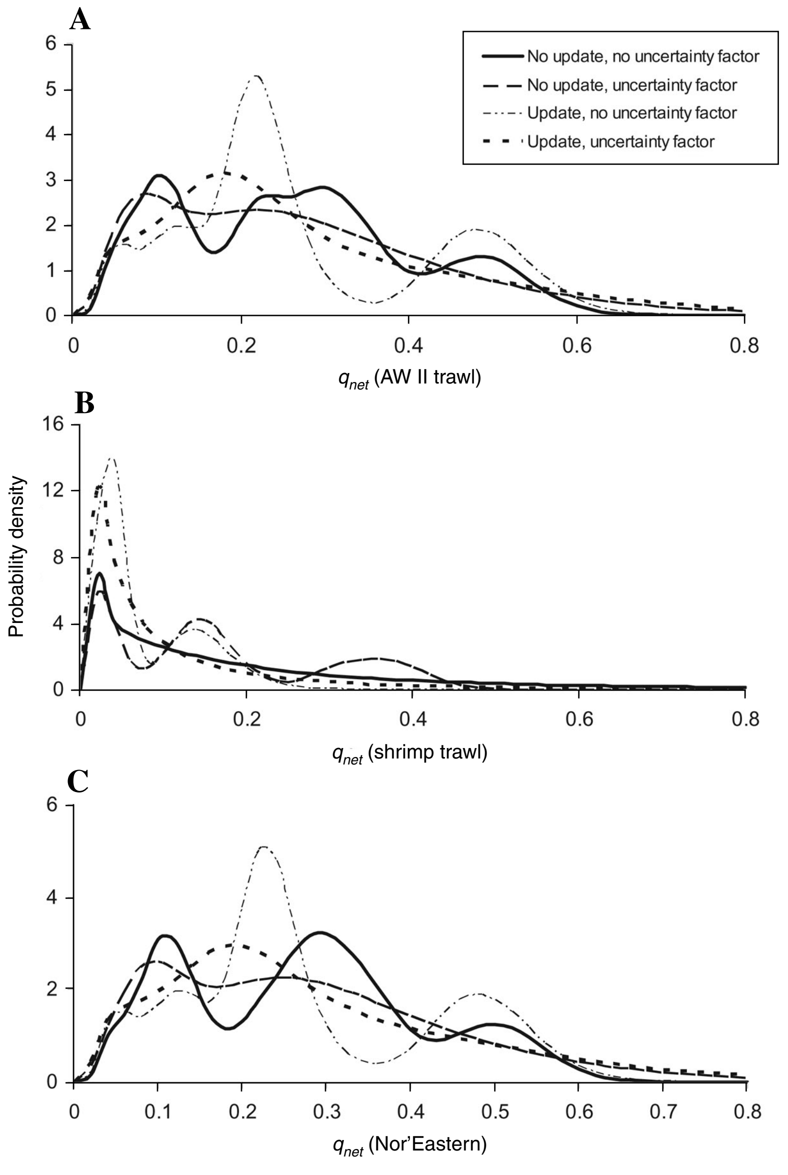

Figure 8

Probability density functions for trawl survey net catchability (q_{net}) for the (**A**) Atlantic western (AWII), (**B**) shrimp, and (**C**) Nor'Eastern trawl nets, based on inputs provided for each captain with and without any Bayesian updating, and with and without the uncertainty factor applied.

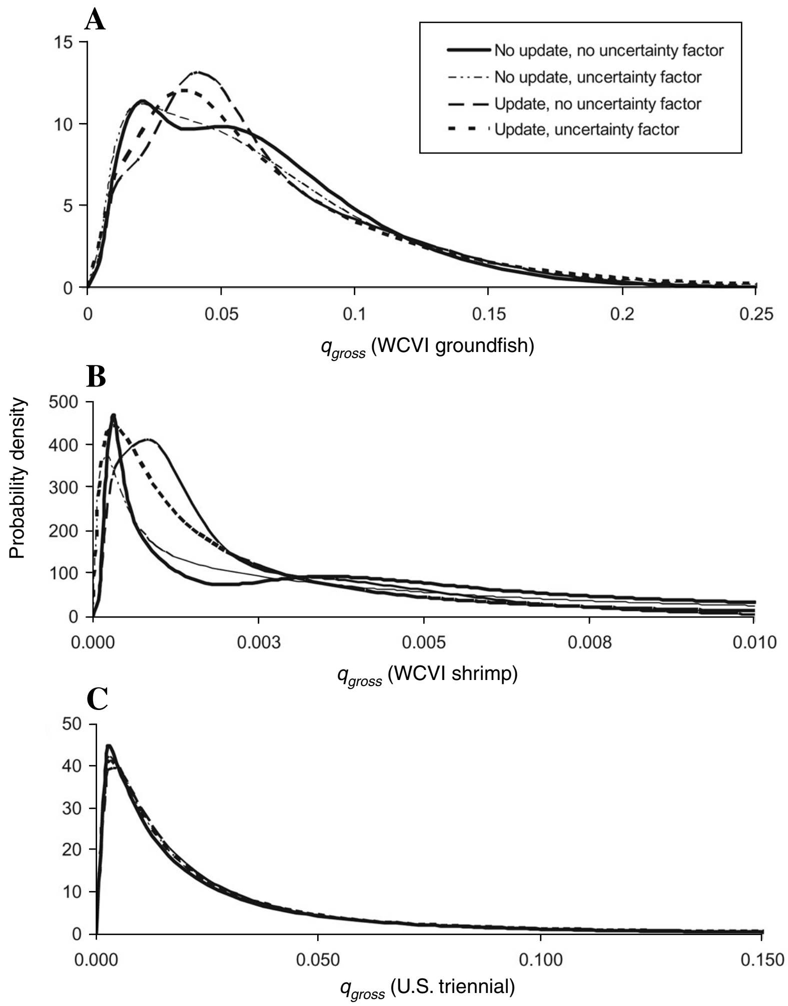

Figure 9

Probability density functions for trawl survey catchability (q_{gross}) for the (**A**) west coast Vancouver Island (WCVI) groundfish, (**B**) WCVI shrimp, and (**C**) U.S. triennial groundfish surveys, based on inputs provided for each captain with and without any Bayesian updating, and with and without the uncertainty factor applied.

perch. Korotkov[1] used an underwater camera-mounted sled towed in front of the trawl to provide a ground-truth of actual fish density. He estimated a doorspread catchability of 0.1–0.4 for unspecified species of groundfish. Our estimates of q_{net} for bocaccio for three different trawl net types ranging from about 0.1 to 0.3 are similar to his estimates. Scientists at the Alaska Fisheries Science Center (NMFS) have spent many years attempting to estimate catchability of the trawl used in their west coast groundfish surveys. Their most successful work was with flatfish for which they observed maximum door-spread catchability for large arrowtooth flounder (*Atheresthes stomias*) of 0.47 (Somerton et al., 2007). The catchability for a flatfish such as arrowtooth flounder could be expected to be higher than that for rockfishes because bottom trawl nets are generally designed to capture flatfishes, which tend to stay very close to the bottom as opposed to many rockfishes, such as bocaccio, which tend to distribute themselves higher in the water column.

Previous efforts at indirectly forming a prior for q_{gross} involved seeking expert judgment and, in some instances, adding auxiliary data to the components of q_{gross}, and then integrating these components within a Monte Carlo framework to formulate a pdf for q_{gross} (McAllister and Ianelli, 1997; Boyer et al., 2001). Different approaches were used to elicit information from experts. In some instances, the experts were interviewed separately to gain information on key factors determining q_{gross} (e.g., Punt et al. 1993, McAllister and Ianelli, 1997; Mosqueira, 2005). Another approach was to put several experts in the same room so that they could form a consensus on these factors (Boyer et al., 2001). An important limitation to these approaches has been that the posterior distributions often tend to be very narrow as a result that too few experts were consulted or that divergent opinions were forced into a consensus.

That experts often hold divergent views while each being certain about his or her knowledge has long been recognized as a problem when forming priors based on expert input. In the last decade, a number of analysts have suggested that it is important to retain this diversity as an output of the analysis and that it is unwise to eliminate the diversity by averaging across experts (Burgman et al., 1993; Chrome et al., 1996; Uusitalo et al., 2005). Some researchers have advocated assigning weights to experts according to their level of expertise (Burgman et al., 1993); others have assigned equal weighting to expert input, providing that all of these experts initially qualify to provide expert judgment (Martin et al., 2005; Uusitalo et al., 2005). It may not be desirable to assign different weights when the number of available experts is relatively few, because it is possible that a single expert may end up with all of the weight, thus defeating the purpose of the exercise.

We recommend applying an uncertainty factor to the for q_{net} variable obtained from each expert's inputs to

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[1] Korotkov, V.K. 1984. Fish behaviour in a catching zone and influence of bottom trawl rig elements on selectivity. Int. Council. Explor. Sea, Council Meeting 1984. B:15.

Table 6

Posterior means and coefficients of variation (CV) in the natural logarithm for bulk catchability (q_{gross}) under four different runs of the trawl survey catchability model with and without the Bayesian update and with and without the uncertainty factor applied. The values in the first column give the prior mean and CV for q_{gross} that could be used in a stock assessment. WCVI =west coast of Vancouver Island; QCS=Queen Charlotte Sound; HS=Hecate Strait. WCHG=west coast of Haida Gwaii.

Survey number and region	Bayesian update, uncertainty factor		Bayesian update, no uncertainty factor		No Bayesian update, uncertainty factor		No Bayesian update, no uncertainty factor		Bayesian update, uncertainty factor, same density in trawable and untrawable areas		Bayesian update, uncertainty factor, very high densities in untrawable areas	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV	Mean	CV
1 WCVI groundfish	0.070	0.77	0.067	0.67	0.068	0.76	0.065	0.66	0.145	0.68	0.046	0.85
2 QCS groundfish	0.046	0.80	0.044	0.71	0.044	0.79	0.042	0.70	0.094	0.71	0.030	0.89
3 HS groundfish	0.0067	0.83	0.0064	0.74	0.0064	0.82	0.0061	0.73	0.0137	0.75	0.0043	0.91
4 WCHG groundfish	0.0021	0.79	0.0020	0.69	0.0021	0.78	0.0020	0.68	0.0044	0.70	0.0014	0.87
5 WCVI shrimp	0.0030	1.46	0.0022	0.81	0.0072	1.63	0.0052	0.94	0.0062	1.36	0.0019	1.51
6 QCS shrimp	0.00036	2.74	0.00026	1.89	0.00086	2.92	0.00063	2.05	0.00054	2.52	0.00029	3.01
7 U.S. triennial groundfish	0.047	1.73	0.045	1.62	0.047	1.70	0.045	1.61	0.069	1.50	0.037	1.87

Table 7

The posterior mean ratio and posterior coefficient of variation (CV) for the ratios for trawl-net catchability (q_{net}) for the groundfish and shrimp trawl nets obtained from inputs provided by each of the captains. The posterior probability assigned to each captain's inputs is given in the last column.

Captain	Mean ratio	Mean CV	Posterior probability assigned to each captain's inputs
1	2.30	0.52	0.110
2	9.18	0.45	0.165
3	0.96	0.15	0.000
4	1.30	0.10	0.000
5	0.70	0.38	0.007
6	3.02	0.19	0.277
7	0.95	0.10	0.000
8	0.77	0.25	0.000
9	1.91	0.25	0.060
10	1.47	0.15	0.000
11	31.86	0.11	0.000
12	5.26	0.26	0.380

counteract the problem of experts being overly certain (Chrome et al., 1996; Martin et al., 2005; Uusitalo et al., 2005). The use of highly precise prior distributions for q has at least two adverse consequences for fish stock assessment. First, when a highly precise prior for q is applied (e.g., CV<0.4), the estimates of quantities of interest (e.g., virgin biomass, B_0) can be highly precise and exclude values consistent with stock assessment data (Boyer et al., 2001). Second, simulation evaluations have shown that when highly precise priors for q (e.g., with prior CV<0.5) that are centered over values as little as 50% higher or lower than the actual value, it takes many more years for stock assessment data to update precise priors than less precise priors centered over the same incorrect values (McAllister and Kirkwood, 1998). Application of a multiplicative uncertainty factor with a median of 1 and a CV of no less than about 0.5 maintains

Table 8

The correlation between measures of expertise and the posterior placed on each trawl captain's input. These correlations are presented to evaluate the presumption that the reliability of a trawl captain's judgment on trawl-net catchability increases with experience (i.e., the posterior probability on the captain should be positively correlated with years of experience). See *Results* section for further details.

	Years of experience	Total landings (t)	Total bocaccio catch (t)	Posterior probability obtained on a captain
Years of experience	1			
Total landings (t)	0.66	1		
Total bocaccio catch (t)	0.70	0.85	1	
Posterior probability obtained on a captain	−0.09	−0.29	−0.24	1

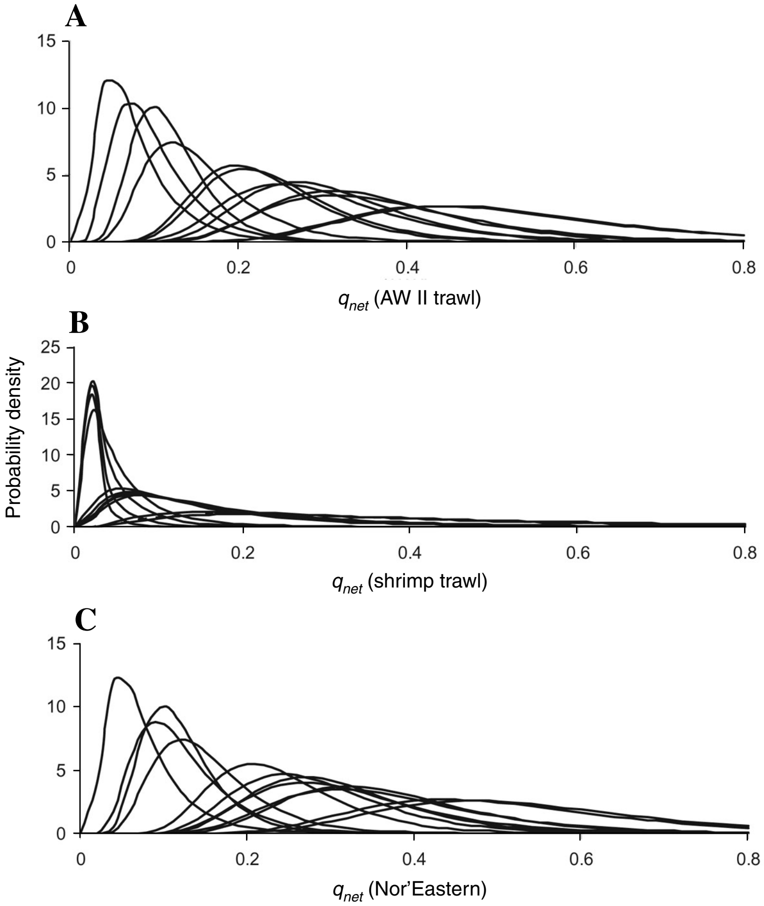

Figure 10

Probability density functions for trawl survey net catchability (q_{net}) for each captain for the (**A**) Atlantic western (AWII), (**B**) shrimp, and (**C**) Nor'Eastern trawl nets, based on inputs provided for each captain with Bayesian updating and with the uncertainty factor applied.

the central tendency of the experts' distributions and gives a prior CV in q_{net} for each expert that is no less than 0.5. Simulation evaluation has shown that prior CVs for $q \geq 0.5$ enable stock assessment data to override a biased prior for q within relatively few (e.g., 5–10) years (McAllister and Kirkwood, 1998). The choice of a CV of 0.5 is somewhat arbitrary but in our view necessary.

A hierarchical meta-analysis of stock assessment data from different populations of the same species group was applied to quantify the cross-stock central tendency and variability in q_{gross} for rockfish in the U.S. triennial survey (Millar and Methot, 2002). This approach has the advantage of avoiding expert judgment altogether and is tractable providing there is uniformity in the survey gear used in the different surveys. However, differences in behavioral responses to trawl gear among species could limit the validity of the assumption of exchangeability, which must be made in hierarchical modeling, and thus limit the applicability of the results as a prior distribution to an unsampled population. The log-transformed mode in the posterior pdf of "bulk" catchability equated to about 1.27 between the wingtips. The ratio of doorspread to wingspread ratio for this survey is not available but is probably similar to the approximately 4.4:1 ratio of the AWII configuration used in the DFO groundfish surveys and translates to a doorspread catchability estimate of about 0.29.

The priors provided in this study have higher CVs (0.8–2.7) than previous priors on survey q obtained from different experts (ranging from about 0.4–0.7, e.g., Punt et al. 1993; Boyer et al., 2001). This difference is partly due to the high uncertainty in the fraction of the population falling within each survey area which did not apply to the other studies because

Table 9

Output statistics for q_{gross} for the run with the Bayesian update and with the uncertainty factor applied. Posterior means (mean), standard deviations (SD), and coefficients of variation (CV) are given. The last three columns show the 2.5th, 50th, and 97.5th percentiles. WCV=west coast of Vancouver Island; QCS=Queen Charlotte Sound; HS=Hecate Strait. WCHG =west coast of Haida Gwaii.

		Mean	SD	CV	2.5th	50th	97.5th
1	WCVI groundfish	0.070	0.054	0.77	0.010	0.055	0.212
2	QCS groundfish	0.046	0.037	0.80	0.006	0.036	0.143
3	HS groundfish	0.0067	0.0055	0.83	0.0008	0.0051	0.0215
4	WCHG groundfish	0.0021	0.0017	0.79	0.0003	0.0017	0.0067
5	WCVI shrimp	0.0030	0.0044	1.46	0.0002	0.0016	0.0143
6	QCS shrimp	0.00036	0.00098	2.74	0.0000008	0.0000730	0.00263
7	U.S. triennial groundfish	0.047	0.08225	1.73	0.0004	0.0161	0.287

Table 10

Posterior correlation matrix for the natural logarithm of the q_{gross} values for the seven surveys off British Columbia, during bocaccio (*Sebastes paucispinis*) were captured. The index number in the first column and first row indicates the survey for which the correlations apply. See Table 9 for a key to the survey indices.

	1	2	3	4	5	6	7
1	1.000						
2	0.912	1.000					
3	0.928	0.879	1.000				
4	0.963	0.912	0.929	1.000			
5	0.601	0.568	0.581	0.604	1.000		
6	0.312	0.311	0.305	0.315	0.526	1.000	
7	0.346	0.323	0.331	0.343	0.259	0.140	1.000

Table 11

Comparison of prior and posterior medians and standard deviations in the natural log of q_{gross} SD(ln$q$) before and after a stock assessment with noninformative priors for q_{gross}. See Tables 6 and 9 for the prior 95% probability intervals for q_{gross}. NA means not available. WCVI=west coast of Vancouver Island; QCS=Queen Charlotte Sound; HS=Hecate Strait. WCHG=west coast of Haida Gwaii.

		Prior for q_{gross}		Posterior for q_{gross}	
		Uncertainty factor, Bayesian update		After fitting assessment model to data with the noninformative survey q prior	
		median q	SD(lnq)	median q	SD(lnq)
1	WCVI groundfish	0.0534	0.78	0.1040	0.50
2	QCS groundfish	0.0343	0.80	0.0566	0.49
3	HS groundfish	0.00492	0.82	0.0030	0.52
4	WCHG groundfish	0.00160	0.79	NA	NA
5	WCVI shrimp	0.00161	1.14	0.0091	0.35
6	QCS shrimp	0.000065	2.08	0.0023	0.46
7	U.S. triennial groundfish	0.0144	1.75	0.0924	0.35

Table 12

Posterior means and coefficients of variation (CVs) of key stock assessment quantities for bocaccio (*Sebastes paucispinis*) obtained with a noninformative and informative prior for q_{gross} (see Tables 6 and 9 for the inputs for the informative prior). See Stanley et al. (2009) for the stock assessment method applied. B_{msy} (t) refers to the population biomass that provides the maximum sustainable yield in tons. B_{2008} (t) refers to the estimated population biomass in the year 2008 in tons.

	B_{msy} (t)	CV	B_{2008} (t)	CV	Replacement yield (t)	CV
Non-informative q_{gross} prior	24,146	0.68	4697	2.27	310	1.24
Informative q_{gross} prior	27,021	0.66	3022	0.83	236	0.65

it was felt that these other surveys covered most of the population's range. Also, in contrast to the present study, in these other studies it was effectively assumed that inputs were obtained from only one expert and did not formally account for cross-expert uncertainty.

All other studies so far have developed priors for q that have zero prior correlation (i.e., independence was assumed). In contrast, we developed a mixed-model structure for survey q that produces strong nonzero correlation in q_{gross} values between different surveys—a necessary consequence because the information sources used to produce the q_{gross} values for different surveys are not independent. The prior correlation between q_{gross} values for different surveys was very high in some instances (up to 0.96) because different surveys were using the same gear. This high correlation resulted in the same inputs for a given gear type feeding into the formulation of the q_{net} factor across different surveys. It is important to include this correlation in the prior for q_{gross} in a stock assessment because it accounts for the dependencies between the q_{gross} values for different surveys. Use of the marginal prior variances and assuming independence, i.e., applying zero correlation, would overstate the amount of prior information available about q_{gross}.

In contrast to the norm, of which experts tend to be overly certain, all captains in this study expressed concern about their estimates. They commented that there had been few opportunities in their careers to compare actual catches with acoustic signals for bocaccio. Three captains said that they could not provide an estimate for at least one question. All captains expressed that they would have been more comfortable estimating these values for other schooling rockfish, particularly yellowtail rockfish and widow rockfish (*S. entomelas*) because of the greater opportunity to correlate acoustic observations with observed catches. Furthermore, they commented that for bocaccio, as well as other species, catchability would be influenced by factors such as location and bottom type, time of day, state of the tide, and whether the fish were present in large schools or were solitary.

The Bayesian computations in our approach that vet the expert-specified inputs against survey-observed values for the same quantities had the result of excluding the inputs from about half of the captains. This situation is undesirable from the point of view of an attempt to include different viewpoints. However, it provides an empirical basis for screening the inputs provided by different experts. More conventional measures of experience (e.g., years of experience, total groundfish landings, and total bocaccio catch) showed either no correlation or a negative correlation with the amount of posterior weight placed on the captains. This finding indicates that practitioners should avoid applying apparently sensible criteria to formulate weights to inputs from different experts. Comparison of empirical data with the expert advice within the context of a model appears to provide a reasonably objective way of screening such advice and should be considered instead.

One of the most poorly understood parameters is the ratio of rockfish density in untrawlable to that in trawlable areas. In this analysis, a subjective prior was applied which ranged between 1 and 10, with a mode at 3. This application had the effect of reducing the central tendency of the q_{gross} by half for all surveys which would give larger estimates of population biomass. Doubling the width and mode of the input distribution for α further decreased the mean value for q_{gross}, although by no more than about 37%. We have suggested a simple Bayesian approach to updating this prior, using estimates of α from experiments. Possible approaches to estimating α could include experiments designed to estimate relative density in trawlable and untrawlable locations with gillnets, hook-and-line sampling gear, or submersible vessels (Kreiger and Sigler, 1993).

The q_{gross} prior developed for British Columbia bocaccio was applied in a recent stock assessment of this population. The availability of these priors was crucial because most of the survey index series were quite short and all had low precision. Although the prior CV was very high, i.e., no less than about 0.8, this mildly informative prior still helped to bound the range of plausible hypotheses about current stock size and replacement yield. The posterior medians for q_{gross} were also within the prior 95% PIs when a noninformative prior for it was applied, indicating that the uncertainty obtained in the priors was reasonable and that the priors were consistent with values indicated by the fit of the assessment model to the data. Thus, in this application, the method provided useful inputs for a stock assessment by bounding the range of values for estimated parameters and reducing uncertainty in key management quantities. The higher precision obtainable in stock assessment results when a noninformative prior for q is replaced with an informative prior will reduce uncertainty concerning the status of the population and allow fisheries managers to apply harvest-control measures with less uncertain consequences. With our application, less pessimistic and less imprecise assessment results could lower the risk of implementing stock rebuilding policies that would cause unnecessary hardship on the fishing industry, and larger harvests could be taken with greater confidence that they would be sustainable.

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