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### Estimation of research trawl survey catchability for biomass reconstruction of the eastern Scotian Shelf

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## Abstract

This report summarizes results and methods of estimating the catchability of trawl surveys, from a meta-analytic perspective. We have attempted to compile all quantitative data in the world on the subject to allow reconstruction of fishing community structure on the eastern Scotian Shelf of Canada.

We consider two types of analysis. “Bulk” catchabilities in which the survey swept-area biomass is converted into an estimate of absolute biomass using a single estimate catchability for all individuals. These were generally obtained directly from the literature or from assessment models where length-specific results could not be obtained. The other type of analysis estimates the length-specific catchability from quantitative assessments, i.e., various types of sequential population analysis. The length-specific data were analysed using maximum likelihood and hierarchical Bayesian models.

We collated 80 estimates of bulk and length specific catchability for 23 species from stock assessments conducted in North America, Europe, and New Zealand. Using hierarchical Bayesian methods, we combined estimates of catchability within species (and across similar species) to derive *synthetic* estimates of length-specific catchability that can be applied in the calculation of absolute abundance from swept-area biomass estimates from trawl survey time series. After ecological and morphological features of various species found on the Scotian Shelf, we provide recommendations as to the values of catchability to be applied for species for which we could not obtain direct estimates.

## Résumé

Le présent rapport résume, dans le cadre d’une méta-analyse, les méthodes et résultats d’estimation du potentiel de capture atteint par des relevés au chalut. Nous avons tenté de compiler toute les données quantitatives au monde sur ce sujet afin de pouvoir reconstituer la structure de la communauté ichthyologiques sur l’est de la plate-forme Scotian, au Canada.

Nous nous penchons sur deux types d’analyses. D’abord, les analyses du potentiel de capture « global » qui transforment la biomasse obtenue par des relevés utilisant la méthode des aires balayées en une estimation de la biomasse absolue à l’aide d’une seule estimation du potentiel de capture pour tous les individus. Ces valeurs du potentiel de capture sont généralement tirées directement de la littérature ou, lorsque des résultats par longueur n’étaient pas disponibles, de modèles d’évaluation. L’autre type d’analyse estime le potentiel de capture par longueur à partir d’évaluations quantitatives, à savoir divers types d’analyses de population séquentielles. Les données par longueur ont été analysées à l’aide du modèle de probabilité maximale et de modèles bayésiens hiérarchiques.

Nous avons rassemblé 80 estimations du potentiel de capture « global » ou par longueur de 23 espèces provenant d’évaluations de stocks effectuées en Amérique du Nord, en Europe et en Nouvelle-Zélande. Nous avons utilisé des méthodes bayésiennes hiérarchiques pour combiner des estimations du potentiel de capture d’une même espèce (ou d’espèces semblables) afin d’obtenir des estimations du potentiel de capture par longueur, qui peuvent servir à calculer des abondances absolues à partir des biomasses estimées par la méthode des aires balayées dans le cadre de séries chronologiques de relevés au chalut. Nous présentons des caractéristiques écologiques et morphologiques de diverses espèces qui fréquentent la plate-forme Scotian, puis nous recommandons les valeurs de potentiel de capture à appliquer aux espèces pour lesquelles nous n’avons pas pu obtenir des estimations directes.

## Introduction

Since the 1960s there have been dramatic changes, both physical and biological, in the ocean environment from Labrador to George's Bank. These changes have been particularly pronounced on the eastern Scotian Shelf. Physical changes include a decrease, to a 50 year low, in bottom temperatures during the mid 1980s to the mid 1990s. Biological changes include dramatic declines in many groundfish stocks in recent years, while there has been an increase in the abundance of other species, such as grey seals, shrimp, snow crab and small pelagic fishes. A fishing moratorium was implemented on the eastern Scotian Shelf in the early 1990s, yet the groundfish stocks have failed to recover. Multispecies models of the eastern Scotian Shelf are being developed to explore the possible causes of these changes in abundance and productivity.

Reliable estimates of biomass are required for ecosystem modeling and are an integral part of describing ecosystems. Biomass is estimated using analytical methods such as sequential population analysis for a few exploited species, such as cod. For most species however, biomass is estimated from scientific trawl research surveys as trawlable biomass. This is not an absolute estimate of biomass since fish are sampled disproportionately by the survey gear. Thus biomass estimates from a research survey are some unknown proportion of their true biomass. In order to obtain more realistic estimates of species biomass, conversion of the survey data based on the "catchability" of species to the gear is required.

## Catchability and biomass reconstruction

Catchability, as used here, describes how the abundance and size composition of a species differs between the population and the survey catch. The estimate for catchability ( $q$ ) is the value required to scale swept-area abundance to population abundance. The catchability process can be described by three components as suggested by Edwards (1968): (1) availability to the gear (the vertical distribution of the species), (2) vulnerability (including herding effects, net avoidance, and mesh selectivity), and (3) spatial/seasonal factors (the spatial distribution of the fish in the trawlable and untrawlable regions). Catchability less than 1 indicates that less fish were caught than predicted to be found in the path of the trawl, conversely  $q > 1$  implies that more fish were caught than occupied the area trawled. Catchability could be greater than 1 if the trawl gear was able to herd fish into the net or if the calculation of swept-area biomass involves extrapolating abundance to untrawlable regions where the fish are less abundant. Understanding these processes has important consequences for the interpretation of survey indices and subsequent management decisions (Godø and Walsh 1992).

A variety of factors are known to affect catchability, i.e., fish behaviour (Wardle 1983), catch size and mesh size (Suuronen and Millar 1992; Walsh 1992; Godø et al. 1999), small gear modifications (Lauth et al. 1998), time of day (Casey and Myers 1998; Korsbrekke and Nakken 1999), and swimming endurance (Winger et al. 1999).

A variety of theoretical models have been proposed (Dickson 1993a; Ramm and Xiao 1995). Although these models have been subject of limited tests (Dickson 1993b), these models are not now accurate enough to be used in practice.

Intercalibration experiments are one approach that have been used to compare changes in catchability between different trawl gears (Pelletier 1998). Although such experiments are very useful,

they seldom have enough paired tows to accurately estimate length-specific intercalibration. For example, over 200 paired tows may not be adequate (Warren 1996). Furthermore, such experiments will only provide estimates of the *relative* catchability of the survey gears.

Estimates of catchability allow the reconstruction of biomass in an ecosystem (Edwards 1968; Clark and Brown 1977; Yang 1982; Sparholt 1990). Such reconstruction allows one to examine temporal changes in community structure (Casey 2000).

## **Why meta-analysis is needed for this problem**

Traditionally, most fisheries biologists have relied upon data only from the population of interest to assess the impact of fishing, pollution, or climate variability. However, the need for a synthetic approach has long been seen as crucial in fisheries research (Beverton and Holt 1959; Pauly 1980; Brander 1994).

The first approach is to carry out very intensive studies with minimum estimation error. In medical studies, this would typically involve the design and implementation of a very large controlled clinical trial on a homogeneous group. In fisheries, the equivalent approach is to perform detailed observational and experimental studies of fish distribution and reactions to trawl survey gear (D. Somerton, National Marine Fisheries Service (NMFS), 7600 Sand Point Way NE, Seattle, WA, pers. comm.).

The second approach is to use quantitative methods of research synthesis known as meta-analysis. One definition of meta-analysis is “the statistical analysis of a collection of analysis results from individual studies for the purpose of integrating the findings” (Cooper and Hedges 1994, p.537). This approach has been well developed in several fields, e.g., medicine, and is now regularly used to help make crucial decisions on the treatment of diseases and the implementation of social policies. Note, however, that we are using the term in a broader sense in that we do not restrict meta-analysis to the combination of *summary statistics* (“analysis results”) from individual studies, instead allowing for a combined analysis of the complete data sets from all of the studies.

An additional important motivation is that meta-analysis can help avoid biases caused by imperfect methods that may mislead the researcher about one population, or several populations assessed using the same method. However, it is critical that appropriate statistical methods be used to combine data from many studies. There are many subtle pitfalls if multiple studies are combined in a naive fashion.

## **Experimental versus observational data**

The use of meta-analytic approaches in population ecology is typically much different than those used in combining experimental data. With experiments, the goal is to combine results on the “size” of an experimental effect, which is similar among experiments. When estimating population parameters, the goal is to estimate the mean and variability of a parameter that is important for the dynamics of the population. In the ecological case, the data are usually observational, i.e., typically a multivariate time series of abundances, from which the reviewer can make inferences about the parameter. The biological assumptions are different. When analyzing experimental data, the prime assumption is that the experiments are comparable. In studies of population dynamics, the assumption is that the different populations that are being examined share some characteristics

that are “similar” among populations. This assumption implicitly helps the biologist, but is usually not formally implemented into analyses of population dynamics. That is, biologists believe that a common biological characteristic unifies a particular species, while they also realize that variability always exists within and among populations.

### **Random effects versus fixed effects models**

One argument in favor of random effects models is that they better represent the heterogeneity that is likely. A fixed effects model assumes that there is a single effect (e.g., of a particular drug) whereas a random effects model makes the more realistic assumption that there is likely to be effect-size heterogeneity (e.g., the drug may have different effects depending on the makeup of the patient population as well as protocol differences and other hard-to-quantify differences).

Random effects analyses can be seen to incorporate the inherent variability (e.g., genetic variability) and effect of covariates that have not measured (Hardy and Thompson 1996). This variability among populations is included in the estimate of the random effect variance.

In this analysis we will use random effect models, i.e., we will always assume that the parameters of the catchability curve are similar across species surveyed at a similar time of the year.

### **Objectives**

The catchability and biomass estimates resulting from our work will add to our basic understanding of the relative species composition of the eastern Scotian Shelf ecosystem. They will also be used as inputs to ecosystem models allowing the reconstruction of absolute biomass of the fish community.

The objectives of our work here are to

1. Construct a global database of catchability estimates from stock assessments and other methods.
2. Provide meta-analytical estimates of catchability (by length where possible) for fish species found on the Scotian Shelf.
3. Enable the description of the eastern Scotian Shelf ecosystem based on relative species composition.
4. Provide the methodology for deriving biomass estimates for other systems.

## **Methodology**

### **Data used for meta-analysis**

We attempted to compile all the data on research trawl catchability in the world. Due to the short time available we restricted ourselves to four regions: New Zealand, the North Sea, and the east and west coasts of North America. We compiled 80 datasets with age/length specific catchability estimates from 23 species (Tables 1 and 2).

Data were collected that met the following criteria:

- An age-structured (or length-structured) stock assessment was performed using trawl survey data.
- The survey covered all, or most, of the stock assumed for modeling purposes.

Estimates of catchability were obtained from published and unpublished stock assessment reports produced by the relevant fisheries management bodies. We attempted to obtain estimates from the most recent assessment, however, in cases where there had been significant changes in survey gear, older assessments were used. If the catchability estimates were not presented, or were presented in a form that was not suitable for our purposes, we contacted the scientists directly to obtain the catchability estimates or other information that was required. Where it was necessary to scale the estimates of catchability from the model units to absolute swept-area units, we checked our calculations with the scientists involved in the assessment.

It was important that the survey cover the stock otherwise estimates of catchability were likely to be negatively biased. For all data sets we collected the catchability estimates at age (or size), estimates of uncertainty (when available), biological parameters to allow the transformation of age to length, and details of the survey used. This data was stored in a text-based database (details in Appendix 1).

A very important consideration was the method used to calculate the swept-area of a trawl. Most surveys in North America and Europe use wing-spread or horizontal net opening as the unit of width. However, in New Zealand all swept-area calculations use door spread as the measure of width. Thus, to ensure compatibility between the New Zealand data and the rest, estimates of catchability were divided by the ratio of door spread to wing spread. This ratio is likely to vary with depth, so the value used was the mean ratio observed over the depths inhabited by the species of interest. Currently this information is not available for the *Shinkai Maru* and *Amatal Explorer* surveys so estimates of catchability for these surveys were not used in the meta-analysis.

In addition to the estimates of age/length specific catchability, we also compiled estimates of “bulk catchability” from two studies, Sparholt (1990) and Casey (2000). The bulk estimates were in the form of a single species-specific catchability estimate.

The methods relating to the bulk and age/length catchability estimates are described in detail below.

## **Bulk analyses**

In this approach a proportion is estimated, that is assumed to be characteristic of a species and a given survey gear. This proportion is

$$p = \frac{\text{biomass estimated from the survey}}{\text{actual biomass}}.$$

This proportion can be estimated from visual and acoustic surveys (Edwards 1968) or from the ratio of the total biomass of a species estimated from a research survey to the biomass estimated from a catch-at-age analysis (Yang 1982; Sparholt 1990).

Such an approach has clear disadvantages, catchability is usually size-specific, and thus would be expected to change as the size composition of the population changed over time. However, for

some species, e.g., sandlance, this may make very little difference. Another concern of the bulk method is that the catchability from visual surveys may be estimated only during the day, while the catchability of the survey gear may change over a 24 hour period (Casey and Myers 1998). Trawl surveys conducted on the Scotian Shelf during both day and night (W. MacEachern Department of Fisheries and Oceans (DFO), *pers. comm.*). Casey (2000) discusses a method to convert this type of estimate into corrected survey catchability.

Here we obtain 3 different estimates of the bulk catchability: those derived from Edwards estimates, from the International Young Fish Survey (IYFS) from the North Sea and from the English Groundfish Survey (EGFS) from the North Sea (Sparholt 1990).

## **Diel correction**

The estimates of catchability by Edwards', the North Sea English Groundfish Survey, and the IYFS are based upon catch rates obtained during the day. The EGFS is carried out only during daylight hours, and the bottom trawl section of the IYFS are carried out during the day. The methods are less clear for Edwards, but it appears that he is concerned with daytime catchability because of his methods, e.g., video and submarine observations. This may cause estimates of abundance to be either underestimated, due to the increased visibility of the trawl during the day (Glass and Wardle 1989), or overestimated, if species exhibit diel vertical migrations that take them out of the vertical range of the trawl at night (Michalsen et al. 1996).

There are several approaches to this conversion. Casey (2000) multiplied the night hauls by a conversion factor to make them equivalent to the daytime hauls, and then applied the catchability correction derived from Edwards. An alternative approach, if one wishes to avoid this step, is to apply a correction factor to the yearly average, based upon the proportion of tows that are at night. If  $p$  is the fraction of tows at night, and  $c_n$  is the ratio of catch rates during the day to the catch rates at night, then the biomass estimate obtained from the average catch rate would be multiplied by  $(pc_n + (1 - p))$  to convert it into daytime units (the conversion for  $p = 0.5$  are given in Table 4).

In our analysis we made the diel conversion only if the overall estimate for the species was statistically significant. In most cases, this correction was relatively small; however, for some species the correction is important. Sandlance has a much higher catchability during the day, the ratio of day to night catch rates  $c_n$  is 4.90.

## **Bulk catchability from Edwards' analysis**

For the estimates based upon Edwards' analysis, we took Edwards estimates for the most closely related species, and multiplied by a diurnal correction factor derived from (Casey and Myers 1998).

The estimates of catchability from Edwards (1968) are for research surveys carried out in the day. When compared with catchability expected over a 24 hour period, this may cause abundance to be either underestimated, due to the increased visibility of the trawl during the day (Glass and Wardle 1989), or overestimated, if species exhibit diel vertical migrations that take them out of the vertical range of the trawl at night (Michalsen et al. 1996). Conversion factors for the variation in diel catchability were calculated for over 50 species in the northwest Atlantic (Casey and Myers 1998). These will be used to correct the survey estimates from Edwards, and other estimates of catchability carried out during daylight only.



## Bulk catchability from the North Sea

Our approach to the IYFS and the EGFS was to convert estimates of kg per hour trawled (the index of abundance used in both surveys), to an absolute estimate of biomass for the North Sea, and then compare these results to the MSVPA estimates of biomass. Both the IYFS and EGFS use a stratified random design, so the average catch per tow should be an index of absolute abundance. We divided this index by the swept-area of the trawl per hour of the survey (the speed times the net opening) and multiplied by the area of the North Sea (we used the area above the 300 meter isobath in ICES region IV; this number was estimated from the CIA database of ocean depth). Sparholt (1990) provides the basis for our analysis of these surveys, but does not provide the estimate of absolute catchability, which we calculate as above. Using Sparholt, we can estimate catchability directly for 10 species, which provide the basis for the analysis to extend these estimates to the other species.

## Length-specific catchabilities

Length-specific catchabilities were derived from catch-at-age analyses. There are two approaches to catch-at-age analyses: (1) traditional virtual population analysis (VPA) methods that assume catch-at-age is known exactly and estimate catchability-at-age for each year, and (2) methods that assume error in the catch-at-age data and estimate a single age-specific selectivity curve for each gear/research vessel type. Estimates derived from both modeling approaches were used here.

The traditional VPA (and its extensions) assumes that the catch-at-age is known without error, and uses research survey data to “tune” the analysis to estimate the number of survivors in the last year and the fishing mortality. In order to carry out these estimates it is also necessary to estimate catchability-at-age. It is usually assumed that estimation errors are lognormal, i.e.,

$$S_{ta} = q_a N_{ta} e^{\epsilon_{ta}},$$

where  $\epsilon_{ta} \sim N(0, \sigma^2)$ ,  $N_{ta}$  is the estimated number of fish at age  $a$  in year  $t$  from the VPA,  $q_a$  is the catchability at age  $a$  for the survey,  $S_{ta}$  is the survey estimate of the numbers, and  $\epsilon_{ta}$  is the estimation error. The log catchability  $Q_a$  is estimated using a simple average

$$\hat{Q}_a = \sum_{t=1}^T (\log(N_{ta}) - \log(S_{ta})) / T,$$

with the usual standard error.

An alternative approach is to estimate a single age or length-specific selectivity curve for each survey series. In this case, a more complex objective function is minimized. Here we need to consider two parts of the relationship. First, the total biomass for a species is estimated from the survey in each year,  $B_t$ , and this is compared to the biomass predicted by the model, again usually assuming a lognormal error term. That is,

$$B_t = \left( \sum_a N_{ta} q w_a s_a \right) e^{\epsilon_t},$$

where  $\epsilon_t \sim N(0, \sigma^2)$ ,  $w_a$  is average weight-at-age, and the survey catchability,  $q$ , is assumed to be constant for each survey.

In a separate likelihood, the proportion of fish caught in a survey of age  $a$  in a given year is used to estimate the selectivity at age  $s_a$  (often standardized to a maximum of 1), typically by assuming the proportion at age follows a multinomial, or related distribution. In this case the estimate of catchability-at-age is

$$\hat{q}_a = \hat{q}\hat{s}_a.$$

### **Converting from age to length based catchabilities**

In both cases, we will need to convert the catchabilities from age-specific to estimates based on fish length. We used the von Bertalanffy growth function (VBGF) for this conversion. Where possible, we used estimates for these parameters reported in stock assessment reports. If these were not available, we used raw length-at-age, or mean length-at-age data to estimate the parameters of the VBGF. Parameter estimates of the VBGF parameters were taken from Fishbase (Froese et al. 1997) for that particular stock if available, or the nearest stock if local estimates weren't available. Combined sex estimates were used preferentially, with female estimates used if the former were not available.

### **Species groupings**

It was only possible to collect catchability estimates for a small number of species (23). Estimates are generally only available for commercially important species that are formally assessed. While the east coast provided that largest number of datasets (33) this was only for five species. To enable the reconstruction of biomass for the rest of the species in community we needed to make assumptions about likely similarities in catchability across species. The length-specific catchability estimates have a distinct advantage in this regard. Rather than assume that the catchability of a red hake (size  $\approx 50\text{cm}$ ) is the same as cod (size  $\approx 100\text{cm}$ ), we can assume that it has the same catchability as a 50cm cod.

### **Bulk catchabilities**

Sparholt (1990) classifies the species in the North Sea into 7 groups that he believes are caught similarly by the survey gear; he uses the catchability estimates from the above 11 species to infer the catchability for these 7 groups. We will use similar groups as all the species either occur, or have congeneric species, across the North Atlantic.

For two New Zealand species (red gurnard and John dory), very few age classes were modeled so there were insufficient data to fit length-specific catchability curves. However, the estimates for these species may be useful as bulk estimates for some species.

New Zealand red gurnard (*Chelidonichthys kumu*) are demersal fish with a hard rigid head which reach a maximum size of about 55cm (Annala et al. 1999). In commercial trawl gears with 125mm codend mesh it is possible to catch large numbers of small (10cm) gurnard. Catchability estimates for this species may be appropriate for some of the sculpin species. The New Zealand John dory (*Zeus faber*) appears very similar to the American John dory so it is reasonable to apply the New Zealand estimates. The maximum size of the American John dory (up to 60cm, Scott and Scott

(1988)) is larger than observed for the New Zealand species (female  $L_{\infty} = 41\text{cm}$ , Annala et al. (1999)), however, it is unlikely that there would be any differences in catchability at the larger sizes.

### **Length specific catchabilities**

For the purpose of hierarchical modeling the data were divided into seven groups (Table 3). The two gadoid groups include species from the order gadiforms.

### **Cod**

Data for two species of cod were available, Atlantic cod and Pacific cod. Only one dataset was available for Pacific cod and the catchability curve was considerably different from the Atlantic cod datasets (see Figure 1), so this data was excluded from the analysis.

### **Haddock**

We only had data for one species of haddock. Of the eight datasets, four were from Georges Bank, two were from the North Sea, and two were from waters north of Nova Scotia.

### **Demersal gadoids**

This group contained all of the gadoid species that were generally demersal in their lifestyle. In addition to cod and haddock, this group included whiting.

### **Pelagic gadoids**

This group included two New Zealand species, hoki and hake, and saithe from the North Sea, walleye pollock from the Bering Sea, and silver hake from the Scotian Shelf. Four of the hoki datasets were excluded as no estimates for the door-spread to wing-spread ratio were available for these trawl surveys.

### **Ling**

Ling (*Genypterus blacodes*) is elongated eel-shaped fish which generally feeds on the bottom on crustaceans and fish (Annala et al. 1999). It lives to about 30 years with females obtaining lengths of 160cm. The Chatham Rise trawl survey catches ling of all ages (SJH personal observation). It was decided to model this species by itself as it could provide estimates for the wolffish and eelpout species.

### **Flatfish**

It was difficult to decide which species to include in this group. Sparholt (1990) reported that the catchability of plaice (*Pleuronectes platessa*) species was much higher than that of sole (*Solea vulgaris*) species.

We excluded the rock sole and yellowfin sole assessments from the Bering Sea from the analysis because the maximum length based catchability appeared to be set at one in the assessment. We

have discussed this in detail with David Somerton (Alaska Fisheries Science Center, Seattle, WA). It appears that the catchabilities close to one may be realistic for the Bering Sea, but this is because the gear is designed to take advantage of the extremely flat and easily trawlable bottom. The catchability estimates for other regions, which have more rocks, are much less. Given these factors, we excluded all Bering Sea datasets from the analysis.

The American plaice data from 3LNO and 4T were excluded because of the extremely high estimates (Figure 1). We have discussed this issue with some of the assessment biologists who carried out the assessments (J. Morgan, NF DFO) but were unable to arrive at any explanation.

### **Redfish (genus *Sebastes*)**

It was very difficult to find stock assessments for redfish type species that had survey estimates of catchability. From the west coast we compiled six datasets from two species. We discussed the Pacific Ocean Perch and shortspine thornyhead assessments in great detail with the Jim Ianelli (Alaska Fisheries Science Center) as well as the head of the Alaska assessment division (A. B. Hollowed). The research surveys and stock definition for these assessments are undergoing revisions.

As redfish and related species (*Sebastes* and *Sebastolobus*) generally inhabit deeper water, often the surveys did not cover all of the stock. This is very clearly shown in the two plots for the shortspine thornyhead (*Sebastolobus alaskanus*) (Figure 1). The shelf survey did not cover the larger individuals while the special slope survey did. Due to concerns over the appropriate catchability model to use and issues relating to survey coverage, no meta-analysis of this data was attempted. Detailed examination of the distribution of redfish on the Scotian Shelf is required before estimates of catchability can be derived.

### **Meta-analytic models**

The purpose of the meta-analysis is to provide a quantitative summary of all information known about catchability at length that is relevant to the particular population. This is the knowledge we have *prior* to observing direct data on a new population. That is, we will attempt to estimate the “prior” distribution of catchability at length.

All models that attempt to analyze more than one population at once are inherently hierarchical. That is, they assume that there is something in common about members of a taxonomic group, and attempt to model that similarity in some way. Once that assumption is made, the differences between the empirical Bayes and fully Bayes approaches should be small. The goal in each case is to learn about the parameters of the prior distribution, often called the *hyper-parameters*.

### **Approaches to inference**

Nonlinear mixed effects models belong to the general class of hierarchical models. Recently, the hierarchical Bayes approach has enjoyed considerable popularity, because it permits estimation of a very broad class of models and may produce more realistic assessments of the uncertainty of parameter estimates. However it requires specification of a joint prior distribution for the fixed effects and variance components. Even if the joint prior is assumed to decompose into a product of marginal priors, the task may be challenging. Furthermore estimation, typically using Markov

Chain Monte-Carlo (MCMC) methods, can be time consuming and determination of convergence may be difficult.

A traditional mixed model approach is an alternative, and software currently exists for both linear and non-linear models of this type if Gaussian observational errors and random effects are assumed. Here we choose to focus on hierarchical Bayesian methods as it is easy to provide useful predictive distributions (described later) using this approach.

The hierarchical Bayes approach puts priors on the parameters of the random effects distributions (the so-called *hyper-parameters*), which are often called *hyper-priors*. We sometimes refer to the hierarchical Bayes approach as “fully Bayes” to distinguish it from the empirical Bayes approach and hybrid approaches involving specification of prior distributions for some but not all parameters (e.g., Liermann and Hilborn (1997)). Hierarchical Bayes approaches are commonly implemented today using Markov Chain Monte Carlo (MCMC) algorithms. If the hyper-priors are uninformative and the marginal likelihood of the hyperparameters is relatively peaked, the empirical Bayes and fully Bayes approaches should give similar results (Smith 1983). Appendix 2 provides a self-contained discussion of the connection between Bayes and empirical Bayes inference for hierarchical models using a generalized notation.

The fully Bayes approach was implemented using BUGS (Bayesian Inference Using Gibbs Sampling) (Gilks et al. 1994). This is freely available software that uses either the Gibbs sampler or the Metropolis Hastings algorithm to sample of the joint posterior distribution for the parameters of interest. It is then possible to obtain estimates of the marginal posterior distributions for any function of the estimated parameters. This makes it possible to obtain estimates of uncertainty in the estimated parameters as well as construct predictive distributions as functions of these estimated parameters, i.e., prediction of catchability at length as a function of the parameters of the scaled logistic.

## Catchability models

### Notation and basic ideas

Studies of gear selectivity form the basis of models of length-specific catchability. Millar (1995) described seven different functional forms for modeling hook and gillnet selectivity that provide a starting point for our analysis. Two of the models are described below.

As part of our initial exploratory analysis of the data, we fitted three types of curves, a gamma density curve, and normal curve, and a logistic. For each of these curves a scaling parameter was required as the density under the gamma and normal curves was not required to be one, and the logistic curve was not necessarily asymptotic at one. On no occasion did the normal curve fit better than the gamma curve so the normal curve was not considered further. The formal model structure is described below.

Assuming lognormal observational errors, the three parameter logistic model for catchability-at-length  $q(l)$ , from data set  $i$ , has the form

$$q_i(l) = \gamma_i' \frac{\exp(\alpha_i + \beta_i l)}{1 + \exp(\alpha_i + \beta_i l)} \exp(\varepsilon_{i,l}), \quad (1)$$

where  $\gamma_i$  is the logarithm of maximum catchability,  $\alpha_i$  and  $\beta_i$  are the traditional parameters describing the two parameter logistic model, and  $\varepsilon_{i,l} \sim N(0, \sigma_i^2)$ . To constrain the estimates of  $\gamma_i'$  to be

positive we estimate  $\gamma_i = \log(\gamma'_i)$ . This was also found to increase the speed of convergence and improve the mixing of the Bayesian model.

The gamma probability density function with unit scale and shape parameter ( $\alpha$ ) and including a location parameter ( $m$ ) and a vertical scaling parameter ( $\gamma$ ), leads to the gamma model:

$$q_i(l) = \gamma_i \frac{(l - m)^{\alpha-1} e^{-(l-m)}}{\Gamma(\alpha)} e^{\varepsilon_l}. \quad (2)$$

Both models were used in the individual dataset fitting (Figure 1) but only the scaled logistic model was used in the hierarchical modeling.

## Modeling approaches

We used two distinct approaches in the modeling of catchability-at-length. Standard non-hierarchical modeling methods only utilize information from the data set in question, while hierarchical models have the ability to combine information from the data set with extra information from other independent data sets (Liermann and Hilborn 1997). Both approaches and their implementation will be discussed below.

### Non-hierarchical models

#### Model I (Individual data sets model):

In this case, we treat the parameters as fixed and survey-specific for each data set. It is based on the unreasonable assumption that there is no relationship among estimates of catchability for the different surveys. This is the model shown in Equation 1. This model was fit using maximum likelihood rather than within a Bayesian framework. However, a Bayesian analysis with uninformative or reference priors should give the same results. Model I was run using the NLMINB function in S-Plus for each data set individually. The output from this model is the joint maximum likelihood estimates for the parameters of the logistic curve for each data set. These estimates were used to generate a logistic curve of catchability-at-length for each data set.

### Hierarchical models

Hierarchical Bayesian modeling is one technique that allows the combination of data from independent sources (Gilks et al. 1994; Carlin and Louis 1996). When different data sets represent individual populations, such models assume that there is something in common about members of a taxonomic group, and attempt to model that similarity in some way (Myers and Mertz 1998). Recently, the hierarchical Bayesian approach has enjoyed considerable popularity, because it permits estimation of a very broad class of models and may produce more realistic assessments of the uncertainty of parameter estimates (Carlin and Louis 1996).

## Model II (Random $\gamma$ 's, single $\alpha$ and $\beta$ model):

This hierarchical model assumes a single  $\alpha$  and  $\beta$  for all of the data sets within each meta-analysis groups but allows variation in the height parameter,  $\gamma_i$ . Thus, it is assumed that there is one single general shape for the logistic curve for catchability across the group but the height of the curve varies across surveys. The estimates of the  $\gamma_i$  are assumed to come from a common distribution,

$$q_i(l) = \gamma_i' \frac{\exp(\alpha + \beta l)}{1 + \exp(\alpha + \beta l)} \exp(\varepsilon_{i,l}). \quad (3)$$

The hierarchical structure for  $\gamma_i$  is shown in Figure 3. The  $\gamma_i$ 's come from a normal prior distribution which is parameterized with a mean  $\mu$ , and variance  $\sigma^2$  (the  $\gamma_i$ 's were lognormally distributed),

$$\gamma_i \sim N(\mu, \sigma^2).$$

The parameters of these distributions are the hyper-parameters, which are also selected from their own prior (hyper-prior) distributions. A diffuse normal prior is used for the mean,  $\mu$  (Figure 3), this suggests that there is little prior information to suggest that any estimate of  $\mu$  is *a priori* considered more probable than any other (note that this does imply that  $\gamma_i'$  is non-negative). The conjugate prior for the variance of a normal distribution is the inverse gamma (Carlin and Louis 1996), here we assume that the inverse of the variance, or precision, has prior probability given by a gamma distribution. Here we parameterized the gamma distribution with two parameters, ( $r, \omega$ ), such that

$$f(1/\sigma^2 | r, \omega) = \omega^r (1/\sigma^2)^{r-1} e^{-\omega(1/\sigma^2)} / \Gamma(r), \quad x > 0$$

where  $r$  is the “shape” parameter,  $\omega$  is the inverse of the “scale” parameter, and  $\Gamma(r)$  is the complete gamma function of  $r$  (Spiegelhalter et al. 1995). In the base case models it was assumed that  $1/\sigma^2 \sim \text{gamma}(0.001, 0.001)$ .

As opposed to the hierarchical structure of the estimates of  $\gamma_i$ , the parameters of the prior distributions for  $\alpha$  and  $\beta$  were fixed rather than estimated. Very broad (almost flat) normal priors were assumed for  $\alpha$  and  $\beta$  and the prior distributions were constrained using the upper and lower bounds (I(lower, upper)). These bounds are used to both constrain the parameters within very broad range of reasonable estimates and to assist the Metropolis-Hastings algorithm. Another important consideration was the relative reliability of the different data sets. Here we assumed that each data set had its own estimation error variance,  $\sigma_i^2$ , which was sampled from a known gamma distribution. Priors for these other parameters are given below:

$$\begin{aligned} \beta_g &\sim N(0.13, 10000) I_{(0,0.5)}, & \alpha_g &\sim N(-5, 10000) I_{(-20,-2.5)}, \\ \sigma_i^2 &\sim \text{gamma}(1 \times 10^{-6}, 1 \times 10^{-6}). \end{aligned}$$

Any possible influence of these constraints, and the hyper-priors, were assessed using alternative bounds and priors.

More complex models are possible in which all three parameters are assumed to come from their own common distribution. Such a model was not considered here due to the small numbers of data sets in each group.

For all groups except for ling, a seasonal categorical variable (summer/fall versus spring/winter) was added to help better model the difference in the mean maximum catchability  $\mu$  within each group. In this case we estimated a separate  $\mu$  for each season ( $\mu_s$ ) but assumed that  $\sigma^2$  was the same for each season. Thus we allowed the mean of the distribution from which the  $\gamma_i$ 's was drawn from to vary with season

$$\gamma_{i,s} \sim N(\mu_s, \sigma^2). \quad (4)$$

A Bayesian approach can be used to obtain estimates of individual parameters, e.g., mean or median of the marginal posterior distribution. It is the parameters derived from the marginal distributions that we will compare to the maximum likelihood estimates. In the process of calculating the joint posterior distribution, it is possible to calculate a value that is a function of the unknown parameters. This has the advantage of conserving any correlation structure that may exist between the unknown parameters. We used this approach to generate “predictive distributions” for catchability-at-length. If  $q_{n+1}(\cdot)$  represents a new data set of observations of catchability-at-length, independent of the data used in the analysis,  $\mathbf{q}(\cdot)$ , given the underlying unknown parameters,  $\theta$ , then the predictive distribution for  $q_{n+1}(\cdot)$  is given by (after Carlin and Louis (1996))

$$p(q_{n+1}(\cdot) | \mathbf{q}(\cdot)) = \int f(q_{n+1}(\cdot) | \theta) p(\theta | \mathbf{q}(\cdot)) d\theta, \quad (5)$$

where  $\theta = (\sigma_i^2, \dots, \sigma_n^2, \mu_s, \sigma^2, \alpha, \beta)$ . This distribution summarizes all information concerning the new observations of catchability-at-length, given the likelihood, priors, and data observed (Carlin and Louis 1996).

The hierarchical Bayesian approach was implemented using BUGS (Bayesian Inference Using Gibbs Sampling) (Gilks et al. 1994). This is freely available software that can use both the Gibbs sampler and the Metropolis-Hastings algorithm to sample the joint posterior distribution for the parameters of interest. It is then possible to obtain estimates of the marginal posterior distributions for any function of the estimated parameters. This makes it possible to obtain estimates of uncertainty in the estimated parameters as well as to derive predictive distributions as functions of these estimated parameters, i.e., prediction of catchability-at-length as a function of the parameters of the scaled logistic.

## Model runs

A hierarchical Bayesian analysis was conducted for each group and predictive intervals for length-specific catchability were determined. Model I was run using the nlminb function in S-Plus for each data set individually and Model II was run for each of the meta-analysis groups described in Table 3 using BUGS. A “burn-in” of 5000 iterations was allowed and following this the Metropolis-Hastings algorithm was run for 200 000 iterations with every 100th sample retained. This reduced the autocorrelation in the chains. We retained 2000 samples of each parameter of interest (and functions thereof). Full BUGS model code for the models is available from the first author.



# Results

## Bulk analyses

Bulk estimates of catchability from Edwards (1968) (corrected for diel variability) and from Sparholt (1990) were calculated (Table 4). Those derived from Sparholt (1990) are from the English Groundfish Survey (EGFS) and the International Young Fish Survey (IYFS). The IYFS are of limited value for traditional groundfish surveys because a portion of the survey was in mid water. We thus do not recommend their use, but they do serve as a useful crosscheck on the other analyses. Sparholt only had estimates for 11 species, (sprat, cod, haddock, saithe (pollock in North America), whiting, plaice, sole, herring, Norway pout, sandeel (also known as sandlance), and mackerel. To obtain estimates for other species, he grouped them into categories derived from the above species. We have used his categories where appropriate.

Sparholt based his analysis on a multispecies VPA. This model uses more realistic estimates of juvenile natural mortality than most alternatives. We believe his estimates to be particularly useful for species such as sandlance.

The most important differences between Edwards and Sparholt is for the flatfish. These estimates will make a very large difference in practice. Based upon the length-based analyses (see below) we believe that the survey gear used in the EGFS is inefficient at catching flatfish. The EGFS is not used in the quantitative assessment of flatfish in the North Sea.

Both red gurnard and John dory had very few age classes and were not included in the hierarchical modeling. However, bulk estimates were derived and are given in Table 5. Estimates for red gurnard were divided into large (25–35cm) and small ( $\approx$  15cm) fish.

## Single model fits

The scaled logistic and gamma density curves were fit to all datasets that had more than two data points (Figure 1). These represent **Model 0**, described earlier. Model fitting was performed using the S-Plus `nlminb` function for non-linear estimation. In many cases both models gave near identical fits to the observed catchability estimates (e.g., the hoki datasets). In some cases, one or both of the models had difficulty converging (e.g., `hadgbnefscfall`). Overall the models did not appear to be inappropriate for describing the relationship between catchability and length.

Some of the individual estimates were very extreme (e.g., `aplai3lnospr`, `rcod3ecsisumm`, and `jdory2f8wcnl`) and were not included in the estimation of bulk catchability or length-specific catchability.

Harley and Myers (2001) provide further details of the analysis of length-specific catchability including a comparison of the individual maximum likelihood fits for the scaled logistic and the hierarchical Bayesian estimates.

## Hierarchical modeling results

A fully Bayes approach was primarily used in this analysis as it provided the best environment for the construction of predictive intervals for catchability at length. The traces for the fixed effects in each model run were plotted to assess whether or not the MCMC had converged to stationary

distribution of the joint posterior. Initial runs performed without the inclusion of any explanatory variables showed very slow mixing of the Metropolis Hastings algorithm as indicated by very high autocorrelation in the fixed effects.

A “burn-in” of 5000 iterations was allowed then the MCMC algorithm was run for 200 000 iterations with every 100th sample retained. This reduced the autocorrelation in the chains and allowed the MCMC algorithm to adequately sample the joint posterior. It was only practical to retain 2000 samples of each parameter of interest as the large number of parameters (and functions of parameters) monitored led to extremely large files that were difficult to analyze using S-Plus.

A fully Bayesian analysis was conducted for each group and predictive intervals for length-specific catchability derived (Figure 2) and Table 7).

## **Cod**

Two models were run for cod, one using gear type as an explanatory variable and the other using split-season. Median catchability for summer-fall surveys was higher than that of spring-winter surveys (0.88 versus 0.72 at a length of 100cm).

The trawl model indicated that the Engel high rise trawl had the highest catchability of cod followed by the Western IIa and the Yankee trawl gears. The maximum catchability for the Western IIa was 0.78 which is slightly less than half way between the two seasonal estimates.

A simple model with no factors was run for cod using both empirical and fully Bayes techniques and the two gave almost identical results.

## **Haddock**

Catchability increased in an almost linear fashion with size. There was considerable difference between catchability in summer-fall surveys compared to spring winter surveys (1.30 versus 0.81 at a length of 70cm). Catchability was higher for haddock than for cod.

## **Demersal gadoids**

This group contained mostly cod and haddock so the results are essentially a weighted average of the individual results. As with cod, catchability was higher in summer-fall surveys than spring-winter surveys (0.98 versus 0.79 at a length of 100cm). The summer-fall estimates were more uncertain than the spring-winter estimates.

## **Pelagic gadoids**

There was only one observation of catchability from a spring-winter survey, so it is not recommended that this be used. Predictably, catchability for the summer-fall surveys was lower for the pelagic gadoids than the demersal gadoids (0.56 versus 0.98 at a length of 100cm). Catchability at a length of 70cm was still slightly lower for pelagic gadoids than haddock.

## **Ling**

As only four datasets were available for this group, no explanatory variables were included. Catchability was very low for fish between 10cm and 50cm, but rose steeply to reach 0.8 for fish 100cm and above. Catchability for large ling was similar to that predicted for large demersal gadoids.

## **Flatfish**

The length-specific catchability curve the flatfish species was very steep. Catchability of flatfish was estimated to be slightly higher during summer-fall surveys compared to spring-winter surveys (0.6 versus 0.5 at a length of 50cm).

## **Recommended catchability estimates**

In this section we examine all data and arrive at recommendations for the assignment of catchability estimates to species found on the eastern Scotian Shelf (Table 6).

## **Cod and haddock**

The results for these species are considered in detail above.

## **Redfish**

Redfish requires more analysis for reasons discussed above. We recommend Edwards' catchability estimates corrected for diel variability, until an analysis of the spatial distribution of redfish on the Scotian Shelf has been undertaken.

## **Atlantic mackerel**

Atlantic mackerel migrate through the Scotian Shelf region, thus it is impossible to estimate from a survey without additional information. The estimates from the EGFS probably represent the most accurate estimates.

## **Hakes**

The best estimates for catchability for white hake are probably from the length based demersal gadoid meta-analysis. This gives a catchability similar to that estimated by Edwards (0.51).

The estimate for silver hake is critical because of its large biomass in the region. Edwards believed it had a very low catchability (0.04), and the EGFS estimates a similar low value if we consider it in the same class as Norway Pout (0.049). These low estimates are consistent with those obtained from the length based pelagic gadoid meta-analysis, given the relatively low mean size of silver hake.

We recommend the length based pelagic gadoid meta-analysis for the other hake species.

## **Other demersal gadoids**

Other demersal gadoids (cusk, monkfish) were also in the demersal gadoid length based assessment. Note that this results in a slightly lower estimate for monkfish than Edwards' estimates.

## **Flatfish**

The estimates for the flatfish were very variable among regions. The results ranged from catchabilities above 5, i.e. American plaice from Newfoundland, to very small (less than 0.1 for ICES assessments (Table 4)). We recommend using the length-based meta-analysis for all flatfish in the region.

## **Skates**

Skates represent a particular challenge to evaluate because no age-structured assessments exist for these species. We suggest in general using the meta-analytic results for flatfish for these species. This would result in relatively low catchabilities for small species, such as little skate, and relatively high catchabilities for larger species such as thorny skate. We suggest that the barndoor skate be evaluated using Edwards' estimate of catchability because he makes a point of saying it has a very low catchability because of strong net avoidance. Although we view the estimates of skate catchability as uncertain, the alternative approaches used in the North Sea for starry ray (*Raja radiata*) suggest the estimates will be reasonable (Sparholt and Vinther 1991).

## **Wolfish and eelpout**

These species most closely resemble the behaviour and morphology of the ling than any other group, therefore we recommend using the ling length-specific meta-analysis for this group.

The other alternative approach would be to use the demersal gadoid meta-analysis (Figure 2); however, this would result in much higher catchability for lengths less than 80 cm. Given the unusual shape for these species, this would not appear to be reasonable.

The use of the ling meta-analysis results gives similar, relatively low catchability as estimated by Edwards.

## **Grenadiers**

The grenadiers are gadoids, but they have a shape close to the ling. It is therefore uncertain which group they belong in: demersal gadoid or ling. We tentatively recommend the demersal gadoid group, but suggest that the ling group be considered as well.

The major uncertainty for the reconstruction of biomass of grenadiers is that the majority of the species range lies deeper than the surveys.

## **Sculpins**

The sculpins should be considered in the demersal gadoid group. This choice gives lower selectivities than Edwards direct estimates for smaller sculpins (the longhorn) and for relatively larger

sculpins (the sea raven). It may not be unreasonable to increase the “effective” length of the sculpins to account for this increased catchability because of morphology and behaviour. This factor for increased effective length should be on the order of 1.5. Further analysis would be required to obtain quantitative estimates of this factor. The higher catchabilities for sculpins for a given length is supported by the bulk analysis of the red gurnard. The catchability of the larger red gurnard (length 25–35 cm.) is 0.9, which is much higher than the gadoid estimate for this length.

## **Spiny dogfish**

The large migrations undertaken by this species, i.e., from Newfoundland to south of Georges Bank, make the estimation of biomass of this species difficult. It most closely resembles a demersal gadoid in its habits, so we suggest using the meta-analysis results for this group. This is consistent with Edwards and Sparholts conclusions.

## **Herring**

The EGFS estimate of bulk catchability is 0.025, while Edwards’ estimate is 0.0153. We have no reason to prefer either estimate without more detailed analysis.

## **Sandlance**

The direct estimates of bulk catchability from the North Sea will probably be the most reliable estimates. These estimates will depend strongly on season, because of the behaviour of this species.

## **Capelin**

Capelin is closest to the sandlance of any species that we have direct estimates for catchability. The direct estimates of bulk catchabilities for North Sea sandlance (EGFS) will probably be the most reliable estimates for capelin.

## **Alewife**

Edwards estimate for alewife is much higher than his estimate for herring, even though the behaviour of these two species at sea are similar. It is unclear what the basis for this difference is, we therefore recommend using the same value as herring.

## **Other small pelagics**

Small pelagic fish we have not previously discussed, e.g., shad, should be treated the same as herring.

## **Lumpfish**

Lumpfish are often pelagic when they are not in spawning condition during the summer (Scott and Scott 1988), we thus suggest treating them as pelagic gadoids. Note, that they migrate inshore to spawn during the summer, so that summer surveys will greatly underestimate the biomass. The Newfoundland spring surveys on the Southern Grand Banks showed extreme seasonal trends in abundance.

## **Alligatorfish**

The alligatorfish, and relatives, are placed in the ling group because of their morphology.

## **Greeneyes**

These bottom-living fish (Scott and Scott 1988) are placed with the gadoids; however, most of their range is outside of the survey area, i.e., they live to a depth of 6000 meters. Also they may undergo vertical migration.

## **Argentine**

Edwards is the only direct estimate of catchability of this species. Sparholt infers the catchability estimates for argentine by assuming they are the same as Norway pout. The estimates derived from the Sparholt's analysis of the English groundfish survey are much higher than Edwards (Table 4). For robustness both estimates should be investigated in inferring total biomass from research surveys.

# **Conclusions and research recommendations**

## **Data augmentation**

We have tried to obtain all assessments in which it was possible to estimate absolute catchability. In some regions, e.g., New Zealand, we believe we have obtained all useful data. In many regions, there are few surveys that cover the entire stock, e.g., this is true for most of the ICES assessments.

There are two extensions where more data could be obtained.

## **Data not used in assessments**

Quantitative assessments often do not use research survey estimates unless they have a relatively low variance. For example, trawl survey estimates for herring are rarely used to “tune” herring SPAs. However, it would be possible to estimate catchability by directly comparing the research survey estimates with the SPA results. We have done this with our analysis of the English Groundfish Survey bulk catchabilities, but it could be extended to many other species.

## **Use of surveys that cover a portion of the stock**

In this analysis we have only considered surveys that covered most or all of the stock area. This has greatly limited our use of surveys in some region, particularly in the ICES area, where different countries cover different portions of the stock area.

We could greatly augment the database by using surveys that covered only a portion of the stock region. For example, if we had independent data on the stock distribution, we could infer the abundance over the unsurveyed region. We have done this to a limited extent with North Sea cod, which includes the Skagerrak in the SPA but not the survey.

## **Calibration of different surveys**

One of the most difficult problems in fisheries is the intercalibration of research surveys when the survey gear and vessel changes. It is rarely possible to estimate them with great precision based upon paired tow experiments. For example, on the Scotian Shelf one of the greatest uncertainties in the analysis is this change in survey gear. In 1996, it was decided, based upon model fits using the assumption that the catch-at-age data were known without error, that new conversions were required, and that the estimates after 1981 were too high by a factor of around 2. However, the data shows clear evidence for increase discards over time (Myers et al. 1997).

Our analysis points the way for an improved approach. This would require that SPA be carried out separately for each survey time series. A sustained research effort to optimally estimate these calibration coefficients would greatly improve assessments.

## **Alternative approaches using experiments**

The primary approach used in this analysis is the comparison of research surveys from estimates derived from catch-at-age models that assume removals from the fishery are known with little or no error. An alternative approach is a detailed experimental analysis of the actual catchability of the survey gear directly. David Somerton of the Alaska Fisheries Science Center has used this approach with great success in the Bering Sea surveys.

## **Enhanced meta-analysis**

Several extensions to our approach are possible that would probably give improved results. We could model morphology and behaviour simultaneously in a meta-analysis, i.e., include species like ling with the demersal gadoids but include a parameter that described the effects of morphology on catchability.

It may also be possible to estimate gear effects in more detail; however, we are primarily limited by data.

## **The importance of estimating absolute catchability in assessments**

In many assessments survey indices are modeled as a mean catch rate rather than as area-swept abundance. In these circumstances, model estimates of “relative” catchability have no simple interpretation. We recommend that area-swept estimates of catchability be derived as a part of any

stock assessment as these values can be more easily interpreted and used as a diagnostic. In cases where catchability is either very high, or low, this may suggest a problem with the assessment.

## **Priors for catchability in stock assessment models**

Hilborn and Liermann (1998) discuss the importance of the synthesis of existing information for the improved assessment of exploited fish populations. The results from a meta-analysis such as the one undertaken here could be incorporated into stock assessments in the form of auxiliary information. This could be done through Bayesian prior distributions (e.g., Punt and Hilborn (1997)) or as a penalty function. For a stock assessment that estimates both survey selectivity and survey catchability (e.g., a common West Coast USA assessment) it might be appropriate to set the maximum selectivity at 1 and then construct a prior distribution for catchability based on  $\mu_s$ . This approach was used in the assessment of the Pacific ocean perch off the coast of Washington and Oregon (Ianneli et al. 2000).

It is not clear how the results of a meta-analysis could be incorporated into a traditional VPA framework other than diagnostic check on the VPA estimates. A less powerful way to use these results would be by informally comparing stock assessment results with those from a meta-analysis. Another approach would be to conduct fully Bayesian assessments within a hierarchical framework. This would involve the simultaneous modeling of all the populations and would involve some parameters (e.g., catchability or spawner-recruitment parameters) being estimated in a hierarchical manner. At present, this represents a daunting prospect in terms of both programming complexities and computational demands. However, if stock assessment science is to move forward it is important that auxiliary information be able to be incorporated into stock assessment procedures.

## **Alternative function forms for length-specific catchability**

Thompson (1994) used a four-parameter logistic curve that allowed for a descending right-hand limb which in some cases may provide a better fit to the data than the three-parameter model assumed here. While there may be behavioural factors responsible for a descending right-hand limb in some cases, this descending limb is confounded (in estimation) with increased mortality at older ages (Thompson 1994). We believe that the logistic curve used here provides a good starting point but that curves allowing a descending right-hand limb should be considered in cases where observational studies support decreased catchability at larger sizes. It is possible to extend future analysis to include other models such as the four-parameter logistic curve used by Thompson (1994) but estimates from more complex models may be less reliable as many data sets had only 5–8 length/catchability observations.

## **Seasonal differences**

A seasonal variable was used to account for differences in catchability within groups. Surveys were grouped into those conducted in summer or fall and those conducted in spring or winter. In all groups, catchability was estimated to be higher in summer and fall surveys. Due to the small numbers of datasets available, it is possible that season may be confounded with other factors or



that the results are simply due to one or two extreme datasets. It is recommended that seasonal differences be investigated in more detail.

## **Diel variability**

Most research vessel surveys outside of the Northeast Atlantic, take place only during the daylight hours. While this appears to matter relatively little for some species it makes a great deal of difference for others, e.g., sandlance Casey and Myers (1998). Although Casey and Myers (1998) provide diel corrections for many species on the Scotian shelf, there are several important species, e.g., silver hake and pollock, that are not well estimated from this study. Reliable estimates of diel variations in catchability would improve estimates for these species.

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Table 1: Catchability data used in the meta-analysis.

Species/Code	Stock	Survey	Source
<i>Atheresthes stomias</i>			
afounberafsc	Bering Sea	AFSC survey	Wilderbuer and Sample (1999)
<i>Chelidonichthys kumu</i>			
rgurn1ebop	New Zealand GUR1e	Bay of Plenty survey	Hanchet et al. (prep)
rgurn1ehg	New Zealand GUR1e	Hauraki Gulf survey	Hanchet et al. (prep)
rgurn1wvnci	New Zealand GUR1w	West coast survey	Hanchet et al. (prep)
rgurn2eecni	New Zealand GUR2e	East coast North Island survey	Hanchet et al. (prep)
<i>Gadus macrocephalus</i>			
pcodgoaafsc	Gulf of Alaska		G Thompson (NMFS <i>pers. comm.</i> )
<i>Gadus morhua</i>			
cod2j3klfall	NAFO Divisions 2J+3KL	Fall survey	Shelton et al. (1996)
cod3nofall	NAFO Divisions 3NO	Fall survey	Davis et al. (1996)
cod3nospr	NAFO Divisions 3NO	Fall survey	Davis et al. (1996)
cod3noussr	NAFO Divisions 3NO	Fall survey	Davis et al. (1996)
cod3pcanspr	NAFO Division 3P	Spring survey	Bratney et al. (1999)
cod3pfrenwint	NAFO Division 3P	French winter survey	Bratney et al. (1999)
cod4tfall	NAFO Division 4T	Fall survey	Chouinard et al. (1999)
cod4vnjul	NAFO Division 4Vn	Summer survey	Mohn et al. (1998)
cod4vswspr	NAFO Division 4VsW	Spring survey	Mohn et al. (1998)
cod4vswsum	NAFO Division 4VsW	Summer survey	Mohn et al. (1998)
codgbnefscfall	Georges Bank	NEFSC fall survey	O'Brien and Cadrin (1999)
codgbnefscspr36	Georges Bank	NEFSC spring Yankee 36 survey	O'Brien and Cadrin (1999)
codgbnefscspr41	Georges Bank	NEFSC spring Yankee 41 survey	O'Brien and Cadrin (1999)
codgomnefscfall	Gulf of Maine	NEFSC fall survey	Mayo (1998)
codgomnefscspr	Gulf of Maine	NEFSC spring survey	Mayo (1998)
codnsskegfs	North Sea and Skaggearak	English GFS	International Council for the Exploration of the Sea (1999)
codnsskibtsql	North Sea and Skaggearak	IBTS 1st quarter	International Council for the Exploration of the Sea (1999)



Table 1: Catchability data, cont'd.

Species/Code	Stock	Survey	Source
<i>Genypterus blacodes</i>			
lin34crtbayes	New Zealand LIN3&4	Summer survey	Horn et al. (2000)
lin34crtmiael	New Zealand LIN3&4	Summer survey	Horn et al. (2000)
lin5and6aut	New Zealand LIN5&6	Fall survey	Horn et al. (2000)
lin5and6spr	New Zealand LIN5&6	Spring survey	Horn et al. (2000)
<i>Hippoglossoides elassodon</i>			
fsoleberafsc	Bering Sea	AFSC survey	Spencer et al. (1999a)
<i>Hippoglossoides platessoides</i>			
aplai3lnospr	NAFO Divisions 3LNO	Spring survey	Morgan et al. (1999)
aplai4tfall	NAFO Division 4T	Fall survey	Marin et al. (1998)
aplaigomfall	Gulf of Maine	Fall survey	O'Brien et al. (1999)
aplaigomspr	Gulf of Maine	Spring survey	O'Brien et al. (1999)
<i>Lepidopsetta bilineata</i>			
rsoleberafsc	Bering Sea	AFSC survey	Wilderbuer and Walters (1999)
<i>Limanda aspersa</i>			
ysoleberafsc	Bering Sea	AFSC survey	Wilderbuer and Nichol (1999)
<i>Limanda ferruginea</i>			
yflouccodfall	Cape Cod	Fall survey	Cadrin (2000a)
yflouccodspr	Cape Cod	Spring survey	Cadrin (2000a)
yflougeobfall	Georges Bank	Fall survey	Cadrin (2000b)
yflougeobspr	Georges Bank	Fall survey	Cadrin (2000b)
yflousnengfall	Southern New England	Fall survey	Cadrin (2000c)
yflousnengspr	Southern New England	Spring survey	Cadrin (2000c)
yflousnengwin	Southern New England	Winter survey	Cadrin (2000c)
<i>Macruronus novaezelandiae</i>			
hok1criseae	New Zealand HOK1	Chatham Rise - <i>Amatal Explorer</i>	Cordue (2000)
hok1crisesm	New Zealand HOK1	Chatham Rise - <i>Shinkai Maru</i>	Cordue (2000)
hok1criset	New Zealand HOK1	Chatham Rise - <i>Tangaroa</i>	Cordue (2000)
hok1subae	New Zealand HOK1	Sub Antarctic - <i>Amatal Explorer</i>	Cordue (2000)
hok1subsm	New Zealand HOK1	Sub Antarctic - <i>Shinkai Maru</i>	Cordue (2000)

Table 1: Catchability data, cont'd.

Species/Code	Stock	Survey	Source
hok1subt	New Zealand HOK1	Sub Antarctic - <i>Tangaroa</i>	Cordue (2000)
hoki1southt	New Zealand HOK1	Southland - <i>Tangaroa</i>	Cordue (2000)
<i>Melanogrammus aeglefinus</i>			
had4tvwjul	NAFO Division 4TVW	Summer survey	Frank et al. (1997)
had4xjul	NAFO Division 4Vn	Summer survey	Hurley et al. (1999)
haddnsskegfs	North Sea and Skagerrak	English GFS	International Council for the Exploration of the Sea (1999)
haddnsskibtsq1	North Sea and Skagerrak	IBTS 1st quarter	International Council for the Exploration of the Sea (1999)
hadgbnefscfall	Georges Bank	NEFSC fall survey	Gavaris and Van Eeckhaute (1998)
hadgbnefscspr36	Georges Bank	NEFSC spring Yankee 36 survey	Gavaris and Van Eeckhaute (1998)
hadgbnefscspr41	Georges Bank	NEFSC spring Yankee 41 survey	Gavaris and Van Eeckhaute (1998)
hadgeobcanspr	Georges Bank	Canadian spring survey	Gavaris and Van Eeckhaute (1998)
<i>Merlangius merlangus</i>			
whitivviidegfs	ICES areas IV and VIIId	English GFS	International Council for the Exploration of the Sea (1999)
whitivviidibtsq1	ICES areas IV and VIIId	IBTS 1st quarter	International Council for the Exploration of the Sea (1999)
<i>Merluccius australis</i>			
hak1autm	New Zealand HAK1	Fall survey	Dunn et al. (2000)
hak1spr	New Zealand HAK1	Spring survey	Dunn et al. (2000)
hak4crise	New Zealand HAK4	Summer survey	Dunn et al. (2000)
<i>Merluccius bilinearis</i>			
shakssjuly	Scotian Shelf	Summer survey	Showell (1998)

Table 1: Catchability data, cont'd.

Species/Code	Stock	Survey	Source
<i>Pleurogrammus monopterygius</i>			
amacberafsc	Bering Sea	AFSC survey	Lowe and Fritz (1999)
<i>Pleuronectes quadrituberculatus</i>			
aplaiafsc	Bering Sea/Aleutian Islands	AFSC survey	Spencer et al. (1999b)
<i>Pollachius virens</i>			
saitnsskegfs	North Sea and Skagerrak	English GFS	International Council for the Exploration of the Sea (1999)
<i>Pseudophycis bachus</i>			
rcod3ecsisum	New Zealand RCO3	Summer survey	Bentjees (prep)
rcod3ecsiwin	New Zealand RCO3	Winter survey	Bentjees (prep)
rcod7wcsifall	New Zealand RCO7	Fall survey	Bentjees (prep)
<i>Sebastes alutus</i>			
pperaluafsc	Aleutian Islands	AFSC survey	Ito et al. (1999)
pperberafsc	Bering Sea	AFSC survey	Ito et al. (1999)
pperchwashafsc	Washington and Oregon	AFSC survey	Ianelli and Zimmerman (1998)
ppergaafsc	Gulf of Alaska	AFSC survey	Heifetz et al. (1999)
<i>Sebastolobus alascanus</i>			
sspinpacshelf	Pacific coast	AFSC shelf survey	Rogers et al. (1998)
sspinpacslope	Pacific coast	Slope survey	Rogers et al. (1998)
<i>Theragra chalcogramma</i>			
wpollberafsc	Bering Sea	AFSC survey	J Ianelli (NMFS pers. comm.)
<i>Zeus faber</i>			
jdory1ebop	New Zealand JDO1e	Bay of Plenty survey	Horn et al. (1999)
jdory1ehg	New Zealand JDO1e	Hauraki Gulf survey	Horn et al. (1999)
jdory2eecni	New Zealand JDO2e	East coast North Island survey	Horn et al. (1999)
jdory2f8wcnl	New Zealand JDO2w	West coast FMA8 survey	Horn et al. (1999)
jdory2f9wcnl	New Zealand JDO2w	West coast FMA9 survey	Horn et al. (1999)

Table 2: Summary of data collected for each region.

<b>Region</b>	<b>Species</b>	<b>Datasets</b>
East coast North America	5	33
New Zealand	6	26
North Sea	4	7
West coast North America	10	14
TOTAL	23	80

Table 3: Groupings and numbers of data sets used for the hierarchical meta-analysis.

<b>Group/Species</b>	<b>Included</b>	<b>Excluded</b>
<b>Cod</b>		
<i>Gadus macrocephalus</i>	0	1
<i>Gadus morhua</i>	17	0
<b>Total</b>	<b>17</b>	<b>1</b>
<b>Haddock</b>		
<i>Melanogrammus aeglefinus</i>	8	0
<b>Total</b>	<b>8</b>	<b>0</b>
<b>Demersal gadoids</b>		
<i>Gadus macrocephalus</i>	0	1
<i>Gadus morhua</i>	17	0
<i>Melanogrammus aeglefinus</i>	8	0
<i>Merlangius merlangus</i>	2	0
<b>Total</b>	<b>27</b>	<b>0</b>
<b>Pelagic gadoids</b>		
<i>Macruronus novaezelandiae</i>	3	4
<i>Merluccius australis</i>	3	0
<i>Merluccius bilinearis</i>	1	0
<i>Pollachius virens</i>	1	0
<i>Theragra chalcogramma</i>	1	0
<b>Total</b>	<b>9</b>	<b>4</b>
<b>Ling</b>		
<i>Genypterus blacodes</i>	4	0
<b>Total</b>	<b>4</b>	<b>0</b>
<b>Flatfish</b>		
<i>Atheresthes stomias</i>	0	1
<i>Hippoglossoides elassodon</i>	0	1
<i>Hippoglossoides platessoides</i>	2	2
<i>Lepidopsetta bilineata</i>	0	1
<i>Limanda aspersa</i>	0	1
<i>Limanda ferruginea</i>	6	1
<i>Pleuronectes quadrituberculatus</i>	0	1
<b>Total</b>	<b>8</b>	<b>5</b>
<b>Redfish</b>		
<i>Sebastes alutus</i>	0	4
<i>Sebastolobus alascanus</i>	0	2
<b>Total</b>	<b>0</b>	<b>6</b>

Table 4: Conversion factors for diel catchability and the relative catchability of species. Two factors are given for the diel conversions. To convert the night hauls to make them equivalent to the daytime hauls, multiply the night hauls by  $c_n$ . If there is an approximately equal number of night and day hauls used, the average biomass can be multiplied by  $c_a$  to convert into equivalent daytime units. After these conversions are made, divide the resulting number by one of the catchabilities to obtain an estimate of absolute biomass.

Species	Diel		Catchability		
	$c_n$	$c_a$	Edwards	EGFS	IYFS
Alewife	1.00	1.00	0.37	0.0248	0.257
American plaice	1.22	1.22	0.28	0.096	0.0438
Argentine	1.00	1.00	0.018	0.0493	0.13
Atlantic cod	1.00	1.00	0.28	0.499	0.561
Atlantic halibut	1.40	1.2	0.38	0.096	0.0438
Atlantic herring	1.00	1.00	0.0153	0.0248	0.257
Barndoor skate	0.379	0.6895	0.10	0.096	0.0438
Capelin	1.00	1.00		0.00087	0.000241
Haddock	1.66	1.33	0.48	0.595	1.13
Longfin hake	0.56	0.78	0.42	0.303	0.186
Longhorn sculpin	0.24	0.62	0.42	0.499	0.561
Monkfish	1.00	1.00	0.16	0.499	0.561
Pollock	1.00	1.00	0.08	0.303	0.186
Redfish	2.23	1.615	0.27	0.499	0.561
Sandlance	4.90	2.95		0.00087	0.000241
Sea raven	0.57	0.785	0.90	0.499	0.561
Shorthorn sculpin	1.00	1.00	0.42	0.499	0.561
Silver hake	1.00	1.00	0.04	0.049	0.13
Smooth skate	0.54	0.57	0.10	0.096	0.0438
Spiny dogfish	1.00	1.00	0.36	0.499	0.561
Spotted wolffish	0.91	0.96	0.16	0.499	0.561
Striped wolffish	0.75	0.85	0.16	0.499	0.561
Thorny skate	0.379	0.6895	0.10	0.096	0.0438
White hake	1.00	1.00	0.51	0.303	0.186
Witch flounder	0.90	0.95	0.49	0.096	0.0438

Table 5: Bulk catchability estimates for small and large red gurnard and John dory

Group	mean	minimum	maximum
Red gurnard (small)	0.108	0.085	0.127
Red gurnard (large)	0.925	0.401	1.272
John dory	0.022	0.018	0.043

Table 6: Assignment of Scotian Shelf species to catchability groups for meta-analytical and bulk catchability estimates. For each species we make a best estimate of the method to obtain estimates of catchability. In some cases, we recommend a length-based catchability from one of the meta-analyses. In other we recommend the bulk catchability from Edwards analysis (Edwards) or our analysis of the English Ground Fish Surveys that estimated a bulk catchability from the MSVPA (listed as EGFS). If any uncertainty exists, we mark the preferred method with an \*.

<b>Common name</b>	<b>Scientific name</b>	<b>Meta-group</b>	<b>Bulk-group</b>
Redfish	<i>Sebastes</i> spp.	Redfish	Edwards*
Atlantic mackerel	<i>Scomber scombrus</i>		ENGS
Short-fin squid	<i>Illex illecebrosus</i>		
White hake	<i>Urophycis tenuis</i>	Demersal gadoids	
Red hake	<i>Urophycis chuss</i>	Demersal gadoids	
Cusk	<i>Brosme brosme</i>	Demersal gadoids	
Witch flounder	<i>Glyptocephalus cynoglossus</i>	Flatfish	
Yellowtail flounder	<i>Limanda ferruginea</i>	Flatfish	
Winter flounder	<i>Pseudopleuronectes americanus</i>	Flatfish	
Gulf stream flounder	<i>Citharichthys arctifrons</i>	Flatfish	
Fourspot flounder	<i>Paralichthys oblongus</i>	Flatfish	
Brill	<i>Scophthalmus aquosus</i>	Flatfish	
Lefteye flounder		Flatfish	
Atlantic halibut	<i>Hippoglossus hippoglossus</i>	Flatfish	
Greenland halibut	<i>Reinhardtius hippoglossoides</i>	Flatfish	
Barndoor skate	<i>Raja laevis</i>		Edwards
Thorny skate	<i>Raja radiata</i>	Flatfish	
Smooth skate	<i>Raja senta</i>	Flatfish	
Little skate	<i>Raja erinacea</i>	Flatfish	
Winter skate	<i>Raja ocellata</i>	Flatfish	
Northern sand lance	<i>Ammodytes dubius</i>		EGFS
Sand lance (American)	<i>Ammodytes americanus</i>		EGFS
Capelin	<i>Mallotus villosus</i>		EGFS for sandlance
Striped Atlantic wolffish	<i>Anarhichas lupus</i>	Ling	
Spotted wolffish	<i>Anarhichas minor</i>	Ling	
Northern wolffish	<i>Anarhichas denticulatus</i>	Ling	
Wolf eelpout	<i>Lycenchelys verrilli</i>	Ling	
NFLD eelpout	<i>Lycodes lavalaei</i>	Ling	
Laval's eelpout	same as above	Ling	
Ocean pout	<i>Macrozoarces americanus</i>	Ling	
Arctic eelpout	<i>Lycodes reticulatus</i>	Ling	
Eelpouts (NS) Atlantic	<i>Lycodes atlanticus</i>	Ling	

Table 6: Assignment of Scotian Shelf species to catchability groups, cont'd.

Common name	Scientific name	Meta-group	Bulk-group
Vachon's eelpout		Ling	
Short-tailed eelpout		Ling	
Gray's cutthroat eel (Slatjaw)	<i>Synaphobranchus kaupi</i>	Ling	
Marlin-spike grenadier	<i>Nezumia bairdi</i>	Demersal gadoids	
Roughnose grenadier	<i>Trachyrhynchus murrayi</i>	Demersal gadoids	
Rock grenadier	<i>Coryphaenoides rupestris</i>	Demersal gadoids	
Longhorn sculpin	<i>Myoxocephalus octodecemspinosus</i>	Demersal gadoids	
Northern searobin	<i>Prionotus carolinus</i>	Demersal gadoids	
Sea raven	<i>Hemitripterus americanus</i>	Demersal gadoids	
Grubby (little)	<i>Myoxocephalus aeneus</i>	Demersal gadoids	
Mailed sculpin	<i>Triglops murrayi</i>	Demersal gadoids	
Arctic hookear sculpin	<i>Arctediellus uncinatus</i>	Demersal gadoids	
Polar sculpin	<i>Cottunculus microps</i>	Demersal gadoids	
Twohorn sculpin	<i>Icelus bicornis</i>	Demersal gadoids	
Atlantic hookear sculpin	<i>Arctediellus atlanticus</i>	Demersal gadoids	
Spiny dogfish	<i>Squalus acanthias</i>	Demersal gadoids	
Monkfish	<i>Lophius americanus</i>	Demersal gadoids	
Silver hake	<i>Merluccius bilinearis</i>	Pelagic gadoids	
Longfin hake	<i>Urophycis chesteri</i>	Pelagic gadoids	
Off-shore hake	<i>Merluccius albidus</i>	Pelagic gadoids	
Herring (Atlantic)	<i>Clupea harengus harengus</i>		Edwards or EGFS
American shad	<i>Alosa sapidissima</i>		herring
Alewife	<i>Alosa pseudoharengus</i>		herring
Atlantic Argentine	<i>Argentina silus</i>		Edwards or EGFS
Butterfish	<i>Peprilus triacanthus</i>		herring
American john dory	<i>Zenopsis conchifera</i>		John dory
Alligatorfish	<i>Aspidophoroides monoptyerygius</i>	Ling	
Atlantic sea poacher	<i>Agonus decagonus</i>	Ling	
Snake blenny	<i>Lumpenus lumpretaeformis</i>	Ling	
Daubed shanny	<i>Lumpenus maculatus</i>	Ling	
Radiated shanny	<i>Ulvaria subbifurcata</i>	Ling	
Wrymouth	<i>Cryptacanthodes maculatus</i>	Ling	
Slender eelblenny	<i>Lumpenus fabricii</i>	Ling	
Northern hagfish	<i>Myxine glutinosa</i>	Ling	
Longnose greeneye	<i>Parasudis truculenta</i>	Demersal gadoids	



Table 6: Assignment of Scotian Shelf species to catchability groups, cont'd.

<b>Common name</b>	<b>Scientific name</b>	<b>Meta-group</b>	<b>Bulk-group</b>
Short-nose greeneye	<i>Chlorophthalmus agassizi</i>	Demersal gadoids	
Cod Atlantic	<i>Gadus morhua</i>	Cod	
Haddock	<i>Melanogrammus aeglefinas</i>	Haddock	
American plaice	<i>Hippoglossoides platessoides</i>	Flatfish	
Pollock	<i>Pollachius virens</i>	Pelagic gadoids	
Fourbeard rockling	<i>Enchelyopus cimbrius</i>	Demersal gadoids	
Threebeard rockling	<i>Gaidropsarus ensis</i>	Demersal gadoids	
Cunner	<i>Tautoglabrus adspersus</i>	Demersal gadoids	
Rosefish (black belly)	<i>Helicolenus dactylopterus</i>	Demersal gadoids	
Lumpfish	<i>Cyclopterus lumpus</i>	Pelagic gadoid	
Atlantic spiny lumpsucker	<i>Eumicrotermus spinosus</i>	Pelagic gadoid	

Table 7: Parameters of the scaled logistic curve used to approximate the predictive distributions of catchability at length from Figure 2 (while the same  $\alpha$  and  $\beta$  was assumed for each season, there are slight differences in the values below as these values are estimated by fitting to the quantiles of the samples from the predictive distributions).

Atlantic cod						
	summer/fall			spring/winter		
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$
mean	-5.06	0.139	0.949	-5.02	0.137	0.769
$P_{0.05}$	-5.31	0.1490	0.422	-5.39	0.1470	0.396
$P_{0.25}$	-5.21	0.1440	0.651	-5.17	0.1410	0.562
$P_{0.5}$	-5.14	0.1410	0.870	-5.05	0.1380	0.719
$P_{0.75}$	-5.03	0.1380	1.150	-4.98	0.1360	0.917
$P_{0.95}$	-4.85	0.1310	1.760	-4.87	0.1330	1.310
Haddock						
	summer/fall			spring/winter		
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$
mean	-2.77	0.0646	1.590	-2.78	0.0650	1.020
$P_{0.05}$	-2.92	0.0707	0.679	-2.90	0.0688	0.507
$P_{0.25}$	-2.84	0.0694	1.080	-2.86	0.0684	0.736
$P_{0.5}$	-2.80	0.0661	1.500	-2.81	0.0663	0.931
$P_{0.75}$	-2.76	0.0628	1.990	-2.76	0.0645	1.180
$P_{0.95}$	-2.68	0.0588	2.860	-2.70	0.0633	1.740
Demersal gadoids						
	summer/fall			spring/winter		
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$
mean	-3.47	0.0914	1.040	-3.47	0.0917	0.843
$P_{0.05}$	-3.65	0.0969	0.522	-3.65	0.0981	0.484
$P_{0.25}$	-3.58	0.0943	0.758	-3.55	0.0950	0.650
$P_{0.5}$	-3.50	0.0925	0.968	-3.52	0.0938	0.797
$P_{0.75}$	-3.43	0.0908	1.240	-3.44	0.0908	0.988
$P_{0.95}$	-3.37	0.0871	1.830	-3.35	0.0868	1.350
Pelagic gadoids						
	summer/fall			spring/winter		
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$
mean	-4.58	0.0785	0.640	-4.57	0.0781	0.7330
$P_{0.05}$	-4.70	0.0814	0.276	-4.67	0.0806	0.045
$P_{0.25}$	-4.63	0.0798	0.431	-4.62	0.0795	0.153
$P_{0.5}$	-4.61	0.0789	0.580	-4.58	0.0788	0.335
$P_{0.75}$	-4.57	0.0780	0.769	-4.59	0.0778	0.707
$P_{0.95}$	-4.53	0.0775	1.190	-4.60	0.0798	2.300

Table 7: Parameters of the scaled logistic curve, cont'd

Flatfish						
	summer/fall			spring/winter		
	$\alpha$	$\beta$	$\gamma$	$\alpha$	$\beta$	$\gamma$
mean	-4.43	0.109	0.986	-4.39	0.109	0.856
$P_{0.05}$	-4.43	0.1240	0.398	-4.36	0.1190	0.275
$P_{0.25}$	-4.35	0.1160	0.609	-4.4	0.1170	0.485
$P_{0.5}$	-4.35	0.1110	0.831	-4.4	0.1120	0.716
$P_{0.75}$	-4.4	0.1060	1.190	-4.39	0.1070	1.060
$P_{0.95}$	-4.65	0.1020	2.220	-4.44	0.1010	2.010
Ling						
	$\alpha$	$\beta$	$\gamma$			
mean	-13.70	0.191	1.840			
$P_{0.05}$	-13.80	0.1920	0.996			
$P_{0.25}$	-13.90	0.1930	1.360			
$P_{0.5}$	-13.90	0.1930	1.660			
$P_{0.75}$	-13.70	0.1900	2.010			
$P_{0.95}$	-13.60	0.1890	2.720			

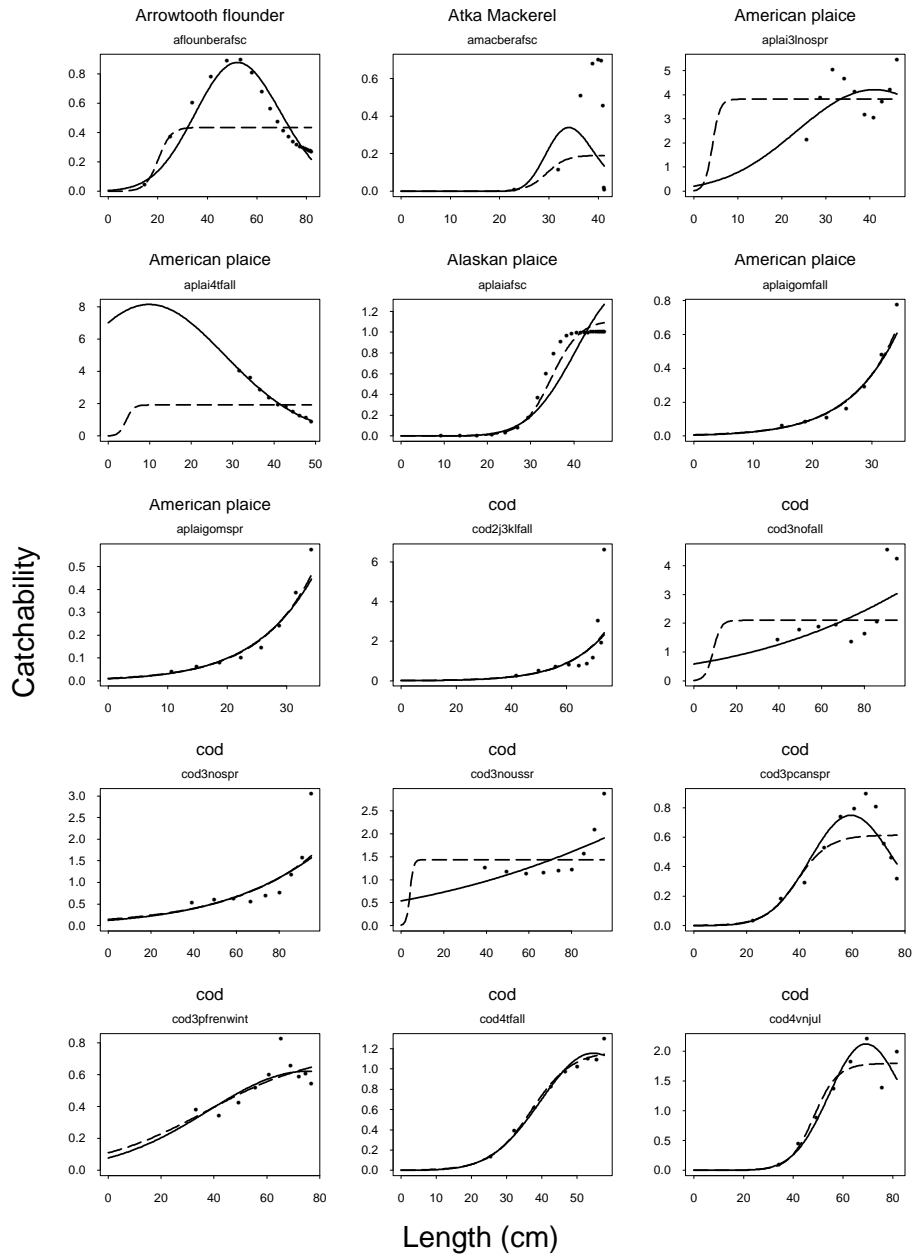


Figure 1: Individual fits of the scaled logistic (dashed line) and gamma density (solid line) curves. The code for each plot corresponds to that in Table 1.

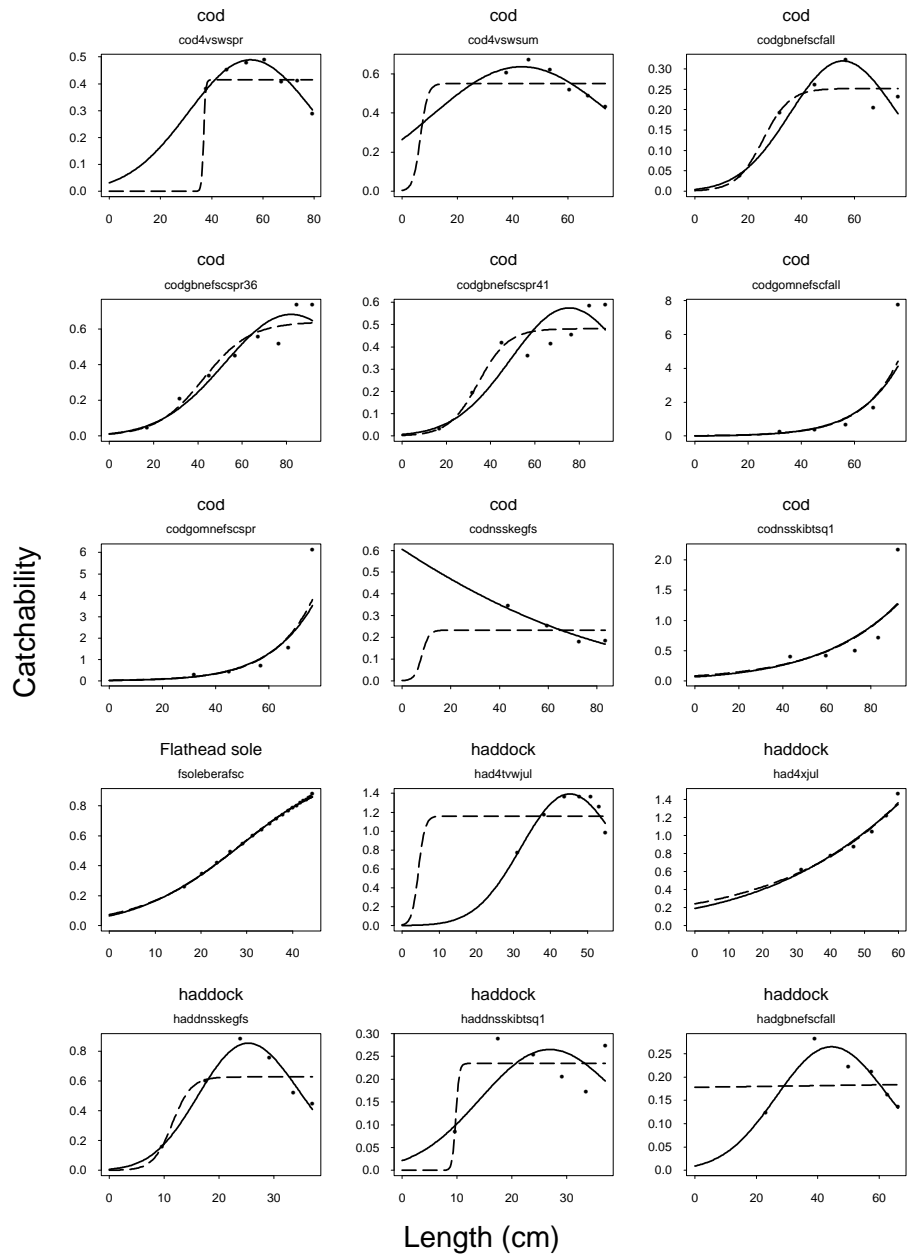


Figure 1: continued

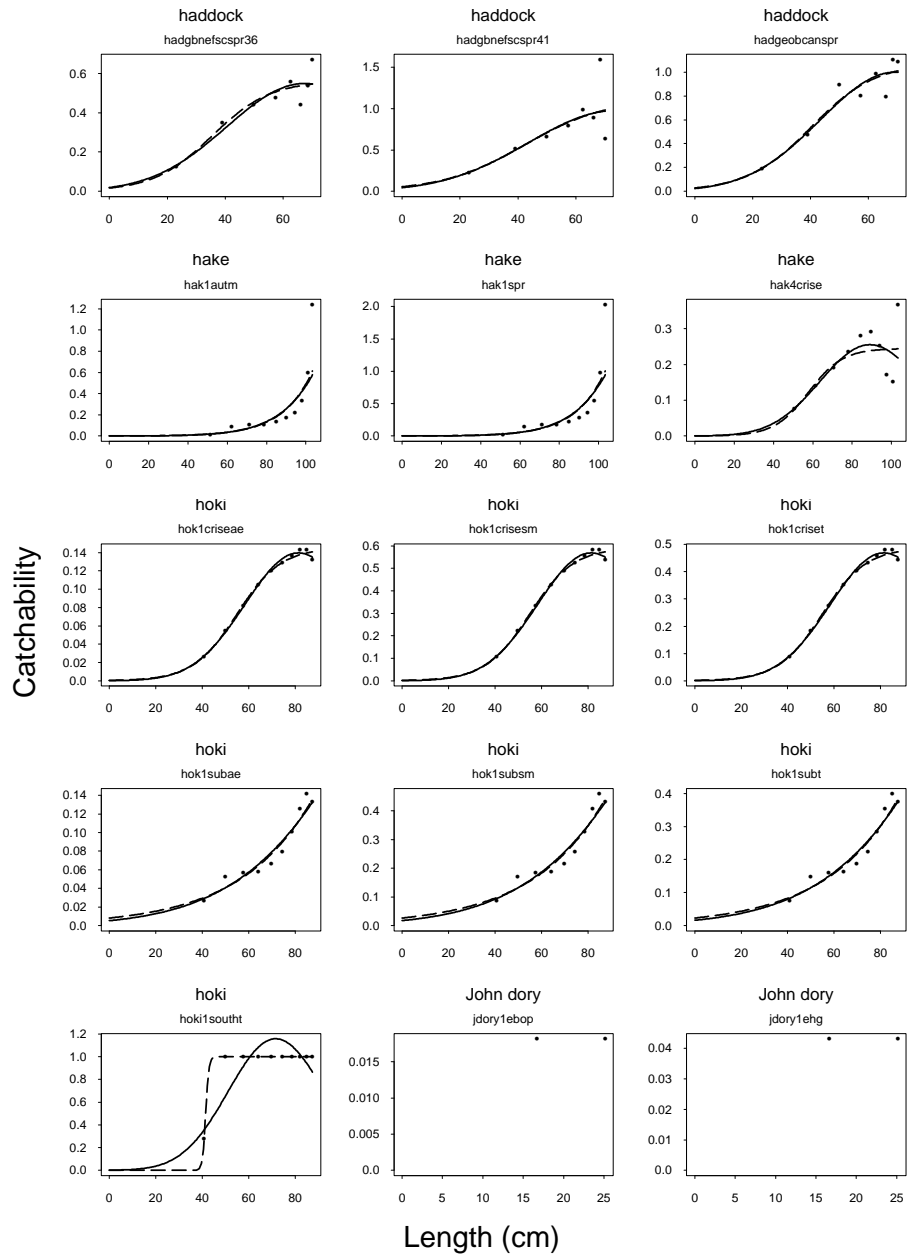


Figure 1: continued

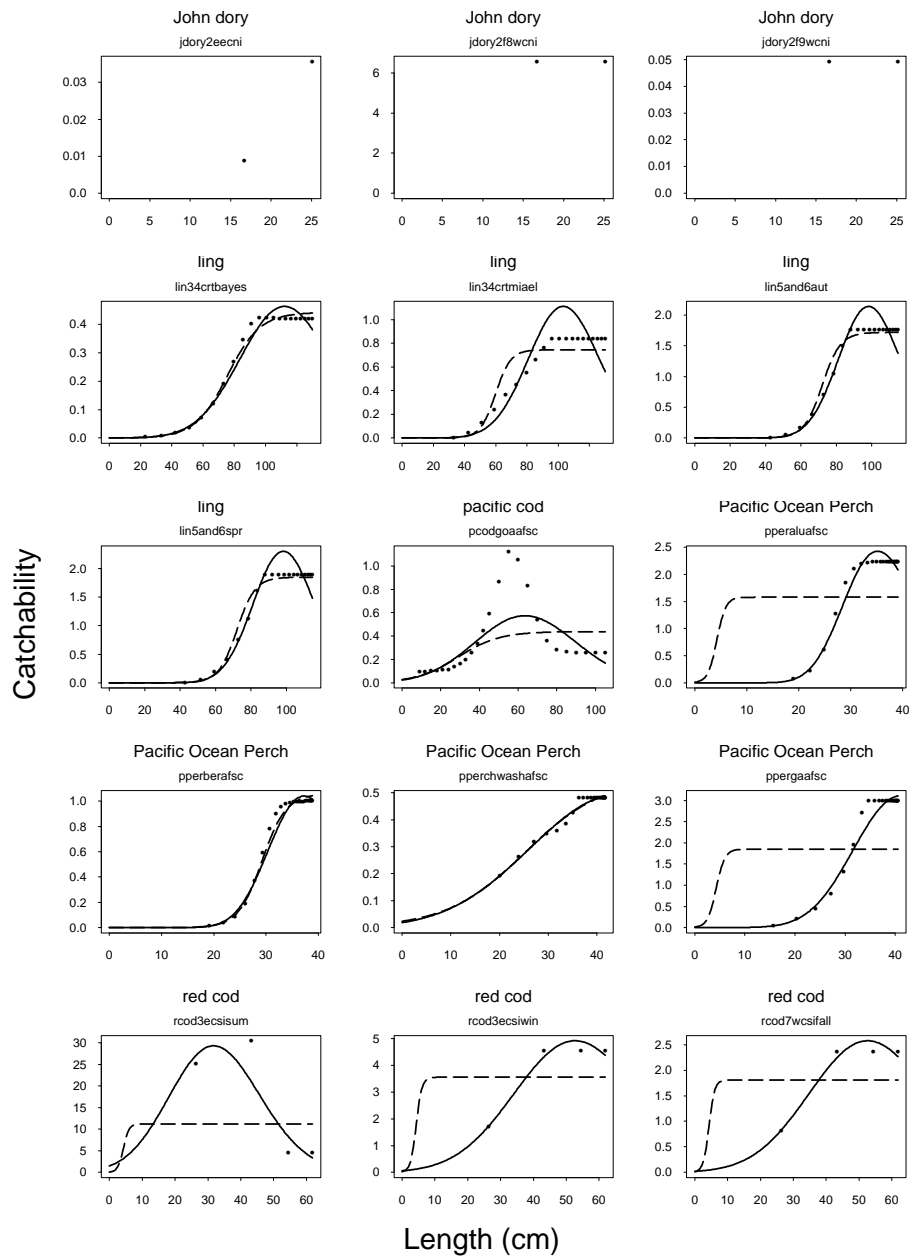


Figure 1: continued

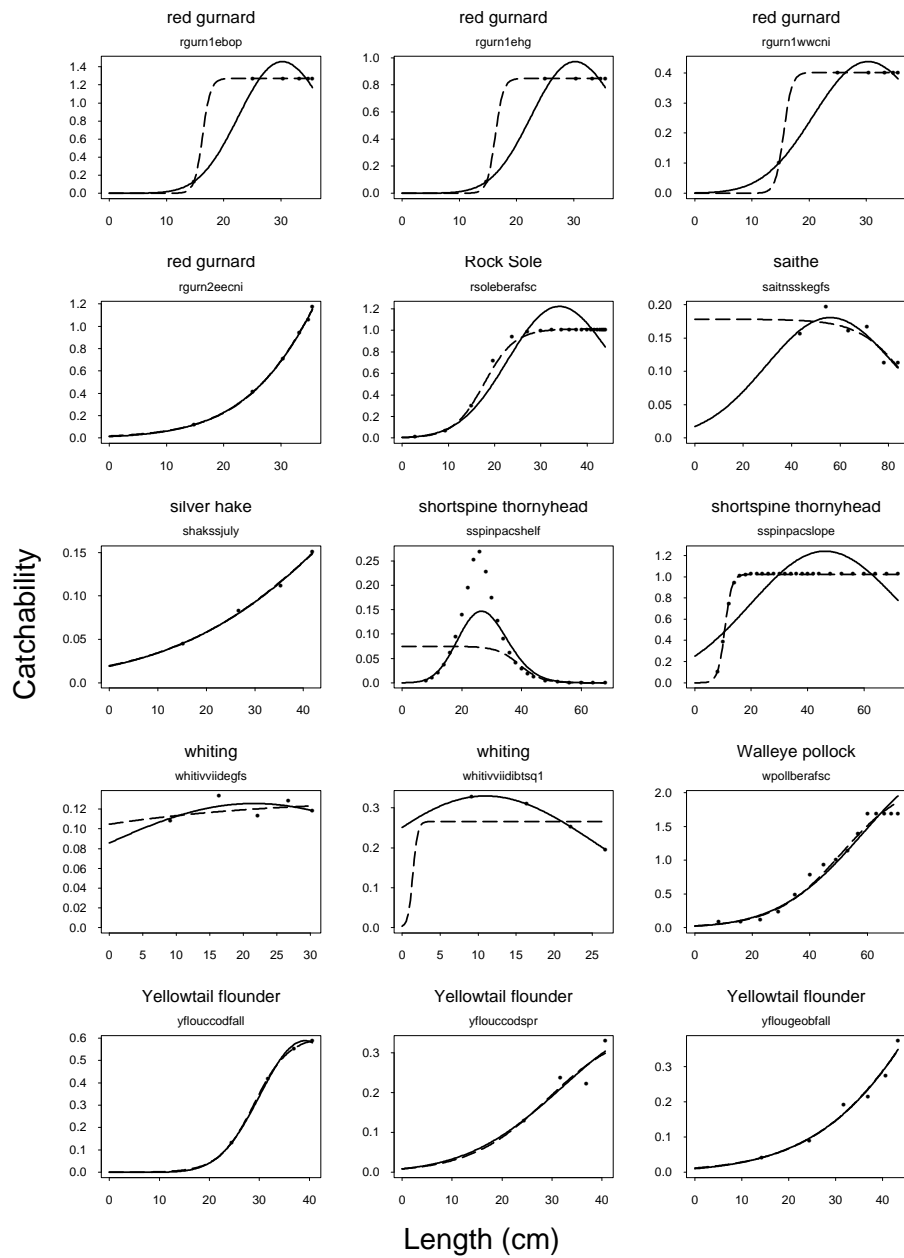
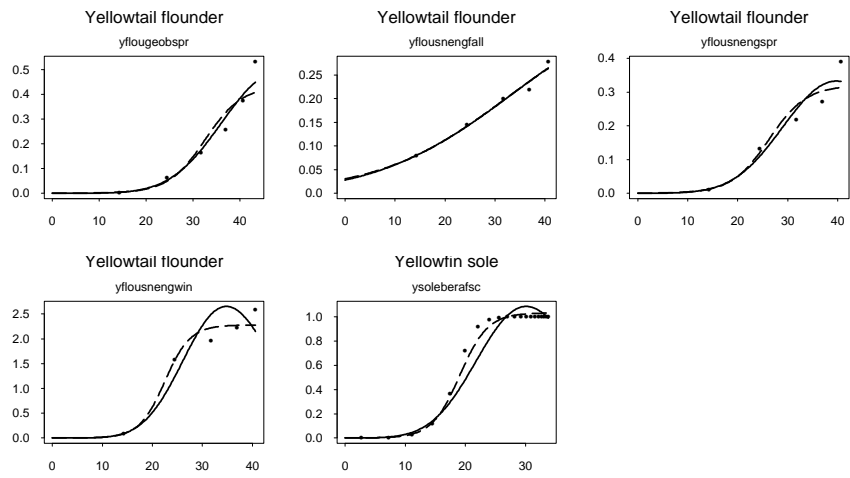


Figure 1: continued



Catchability



Length (cm)

Figure 1: continued.

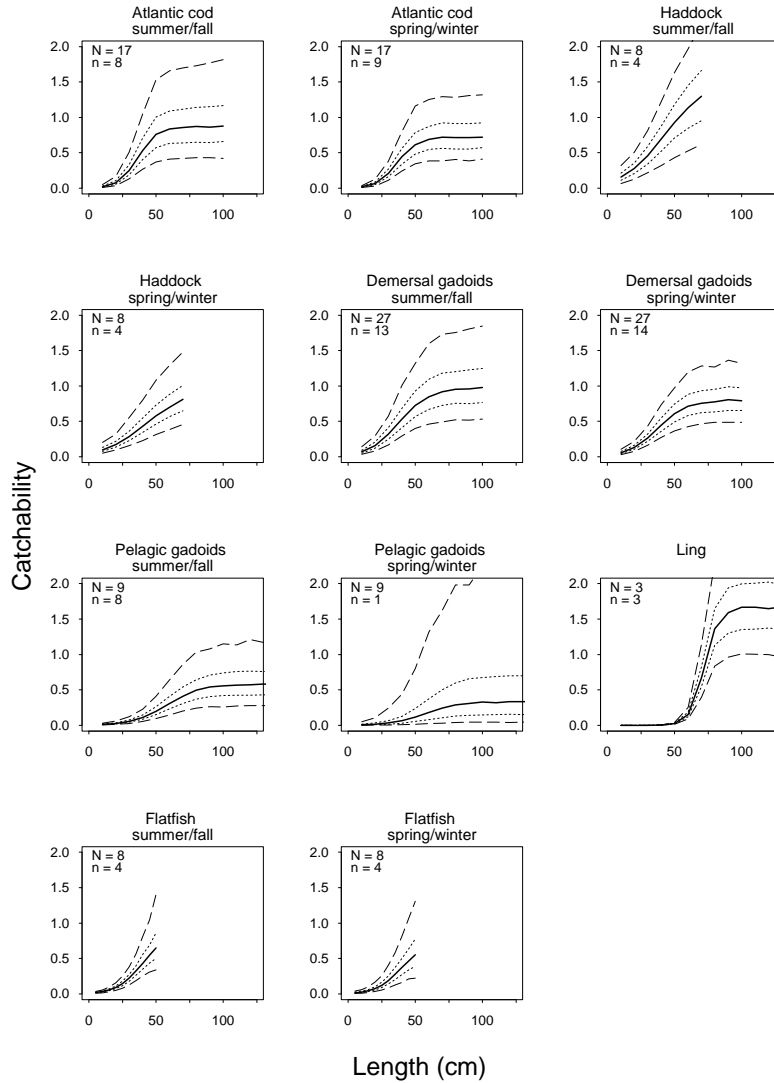


Figure 2: Predicted length-specific catchability for the different meta-analytical groups. Where a seasonal variable was included, estimates for both seasons are given. The solid line is the median of the posterior, the short dashed lines are the 25th and 75th percentiles of the posterior predictive distribution, and the long dashed lines are the 5th and 95th percentiles. The number of data sets used in each meta-analytic group is  $N$  and  $n$  is the number of data sets for the particular season. The range of values of length correspond to that observed for the group.

## Appendix 1: Database format

To facilitate data input and manipulation a standard data file format has been designed. There will be four different files:

1. .dat file - containing the catchability data.
2. .doc file - details pertaining to the data in the .dat file..
3. .survey file - details of each survey series that is used.
4. .bibtex file - one file containing all of the references used above.

For each stock/survey there will be a pair of files whose names end in .doc and .dat. Thus if there are three surveys for which catchability is estimated for a stock, there will be three pairs of .dat and .doc files. Names of files should be of the format

species/area/survey

For example, data for a Canadian research survey for cod in NAFO division 3NO might be stored in files called cod3nocan.dat and cod3nocan.doc.

Each .dat file is composed of lines with the following format:

```
AGE/LENGTH CATCHABILITY STANDARD_ERROR SELECT SELECT_M SELECT_F
```

AGE is the age (e.g., 5), LENGTH is in cm, CATCHABILITY is the “raw” estimates given, STANDARD\_ERROR is the estimated SE for each estimate, and SELECT is survey selectivity at age (where survey selectivity has been assumed). If selectivity differs by sex, then SELECT\_M and SELECT\_F are used.

NOTE: In the .dat, .doc, and .survey files, a dot (.) represents a missing value. Each .doc file is composed of lines with the following formats:

```
SPECIES @ <-- Species name
LATIN @ <-- Scientific name
FAMILY @ <-- Scientific family
LIFESTYLE @ <-- pelagic / demersal / semi-pelagic
REGION @ <-- Region (e.g., NAFO division, ICES region)
SOURCE @ <-- Reference code (to reference in .bibtex file)
SURVEY @ <-- Survey code (corresponding to .survey file)
ORGANIZ @ <-- Organization conducting the assessment (e.g., NAFO)
MODEL @ <-- Assessment procedure used (e.g., ADAPT, Stock synthesis)
MUNIT @ <-- Populations units used in the model (e.g., '000's fish)
SUNIT @ <-- Survey units used for fitted data (e.g., fish per km^2)
SCALAR @ <-- Scalar (magic number) *SEE BELOW
PROP @ <-- Proportion of population outside survey area.
TYPE @ <-- *SEE BELOW
QNOTES @ <-- Other instructions on how q's should be corrected
LINFIN @ <-- 'L_infinity' von Bertalanffy growth parameter (cm)
k @ <-- 'k' von Bertalanffy growth parameter
t0 @ <-- 't0' von Bertalanffy growth parameter
LINFIM @ <-- 'L_infinity' von Bertalanffy growth parameter (male)
kM @ <-- 'k' von Bertalanffy growth parameter (male)
t0M @ <-- 't0' von Bertalanffy growth parameter (male)
LINFINF @ <-- 'L_infinity' von Bertalanffy growth parameter (female)
```

```

kF      @      <-- 'k' von Bertalanffy growth parameter (female)
t0F     @      <-- 't0' von Bertalanffy growth parameter (female)
aLTWT   @      <-- 'a' length-weight parameter (w=a*(l^b); cm to kg)
bLTWT   @      <-- 'b' length-weight parameter
aLTWTM  @      <-- 'a' length-weight parameter (male)
bLTWTM  @      <-- 'b' length-weight parameter (male)
aLTWTF  @      <-- 'a' length-weight parameter (female)
bLTWTF  @      <-- 'b' length-weight parameter (female)
MORT     @      <-- combined natural mortality
MORTM   @      <-- male natural mortality
MORTF   @      <-- female natural mortality
NOTES   @      <-- Miscellaneous notes on the data

```

TYPE: a = q at age; b = one q scaled by select-at-age; c = q at length; d = one q scaled by select-at-length.

SCALAR: Scalar (magic number) for transforming catchability to swept-area / population ratios (for biomass estimates it should be 1). This will generally be for assessments where the survey data is in units of mean catch per tow etc.

PROP: Proportion of population outside survey area if this is not already corrected for in the estimation method. For example, consider the case when a survey only covered 50% of the stock. If the survey data was only fitted to the part of the population known to be in the survey area (available to the survey) then this has already been accounted for, however, if the data is fit to the entire population the 'PROP' value is required to correct for availability

For every survey series for which catchability has been estimated for a .survey file must be made. This file is composed of lines with the following formats:

```

SURVEY  @      <-- Name of the survey series (e.g., Yankee spring survey)
CODE    @      <-- Code for the survey used in .doc (e.g., yank36spr)
VESSEL  @      <-- Name of vessel(s)
REGION  @      <-- Regions surveyed (e.g., NAFO division, ICES region)
SOURCE  @      <-- Reference code (to reference in .bibtex file)
SEASON  @      <-- Time of year of survey (e.g., Fall)
TIMES   @      <-- Time of day of tows (e.g., day / night / both)
TRAWL   @      <-- Trawl type (e.g., Yankee 36)
BODY    @      <-- Body mesh size (mm)
CODEND  @      <-- Codend mesh size (mm)
CODEND2 @      <-- Codend mesh type (e.g., square / diamond)
LINER   @      <-- Liner mesh size (mm) if used
DURATION @      <-- Tow duration (minutes)
SPEED   @      <-- Tow speed (knots)
HEIGHT  @      <-- Headline height (m)
WINGSP  @      <-- Wing spread (m)
DOORSP  @      <-- Door spread (m)
SWEEPS  @      <-- Length of sweeps
CHAIN   @      <-- Presence or absence of a tickler chain
GROUND  @      <-- Ground gear setup (e.g., rope / rollers / hoppers)
AREASW  @      <-- Area-swept calculation method (e.g., DOOR_SP / WING_SP)
NOTES   @      <-- Miscellaneous notes on the data

```

All references will be entered in Bibtex format to allow compatibility with the general reference files. There will be one .bibtex file. An example is given below:

```

@TechReport{Gavaris:VanEeckhaute:1999,
  author = "S Gavaris and L {Van Eeckhaute}",
  title = "Assessment of haddock on {E}astern {G}eorges {B}ank",
  institution="Fisheries and Oceans Canada",
  year = "1998",
  type="Canadian Stock Assessment Secretariat",

```

```

number="99/72",
}

```

Examples of the .dat, .doc, and .survey are given below:

Here is an example .dat file:

```

1 0.05    0.02    1    1    1
2 0.09    0.03    1    1    1
3 0.12    0.05    1    1    1
4 0.18    0.04    1    1    1
5 0.35    0.15    1    1    1
6 0.27    0.26    1    1    1
7 0.22    0.11    1    1    1
8 0.20    0.15    1    1    1

```

Here is the corresponding .doc file:

```

SPECIES @ Cod
LATIN @ Gadus morhua
FAMILY @ .
LIFESTYLE @ demersal
REGION @ 3NO
SOURCE @ Scr.99/42
SURVEY @ yank36spr
ORGANIZ @ NAFO
MODEL @ ADAPT
MUNIT @ thousands
SUNIT @ mean catch per tow
SCALAR @ 23432
PROP @ 1
TYPE @ b
QNOTES @ multiply estimates by scalar
LINFIN @ 62
k @ 0.12
t0 @ -1.2
LINFINM @ .
kM @ .
t0M @ .
LINFINF @ .
kF @ .
t0F @ .
aLTWT @ 0.04667
bLTWT @ 2.793
aLTWIM @ .
bLTWIM @ .
aLTWTF @ .
bLTWTF @ .
MORT @ 0.2
MORTM @ .
MORTF @ .
NOTES @ .

```

Here is the .survey file:

```

SURVEY @ Yankee 36 spring survey)
CODE @ yank36spr
VESSEL @ Titanic
REGION @ 3LNO
SOURCE @ .
SEASON @ spring
TIMES @ both

```

TRAWL	@	Yankee 36
BODY	@	200
CODEND	@	50
CODEND2	@	diamond
LINER	@	.
DURATION	@	30
SPEED	@	4
HEIGHT	@	6
WINGSP	@	25
DOORSP	@	40
SWEEPS	@	.
CHAIN	@	absent
GROUND	@	rollers
AREASW	@	DOOR_SP
NOTES	@	.

## Appendix 2: Bayes and empirical Bayes hierarchical models

In general, let  $\theta$  denote the parameter of interest, suppose we have data on  $N$  populations, let  $\mathbf{x}_i$  be the data for the  $i$ th population, and let  $\mathbf{x} = (\mathbf{x}_1, \dots, \mathbf{x}_N)$  be the complete data set (Figure 3). In what follows, we will use the generic notation  $p(\cdot | \cdot)$  to indicate the probability density of the first argument given the second.

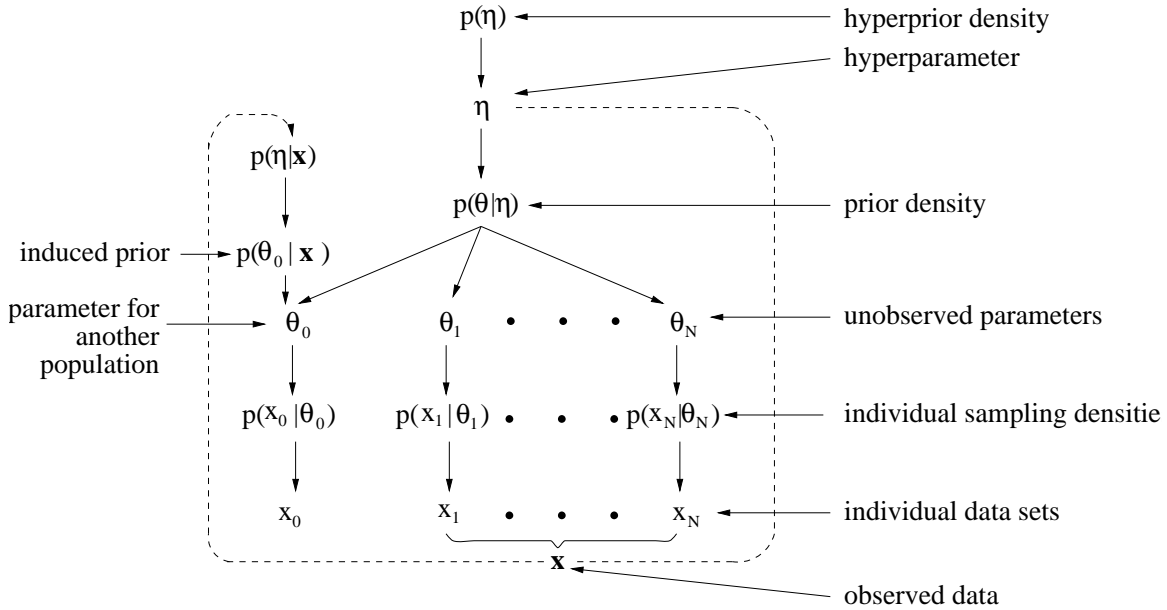


Figure 3: A depiction (following Efron (1996)) of the hierarchical model.

Let  $p(\theta|\eta)$  be the prior for  $\theta$ , depending on a hyperparameter vector  $\eta$ , which in turn has hyperprior  $p(\eta)$ . Suppose we wish to make inferences about the parameter of interest for another population, which we denote  $\theta_0$ . The *induced prior* (Efron 1996) (referred to sometimes as the “posterior distribution [for the parameter of interest] for a stock with no data”) is given by

$$p(\theta_0|\mathbf{x}) = \int p(\theta_0|\eta) p(\eta|\mathbf{x}) d\eta.$$

In the above equation,  $p(\eta|\mathbf{x})$  is the posterior for  $\eta$  which, by Bayes’ theorem is

$$p(\eta|\mathbf{x}) \propto p(\mathbf{x}|\eta) p(\eta),$$

where  $p(\mathbf{x}|\eta)$  is the marginal likelihood for  $\eta$ .

To make inferences about the parameter of interest for an additional population, the empirical Bayes approach substitutes, in place of the induced prior, the *MLE prior*,

$$p(\theta_0|\hat{\eta}),$$

where  $\hat{\eta} = \operatorname{argmax}_{\eta} p(\mathbf{x}|\eta)$ . This amounts to an approximation to the induced prior, which will be reasonably good when the hyperprior is uninformative and the marginal likelihood is relatively peaked.