

SURVEY METHODS FOR FISHERIES: CHALLENGES AND STATISTICAL ISSUES

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ABSTRACT

For many marine fisheries, research surveys provide the main source of fishery-independent monitoring data. Indeed in many situations, where fisheries have been closed, these surveys provide the only information on the abundance of commercial stocks. While the field procedures for these surveys (i.e., gear, standardization of sampling unit definition and data acquisition methods) are more or less standard throughout the world, data analysis procedures remain variable and controversial. The three main areas of controversy are:

- 1) Survey Design: Random or fixed designs.
- 2) Increasing precision/efficiency: Design-based vs. Distribution-based.
- 3) Detecting trends in populations: Is it wise to ignore the variance?

I will present the statistical issues concerning each of the above along with the results of current research in the field.

KEY WORDS: Fisheries management; field surveys; precision.

RÉSUMÉ

Pour plusieurs pêcheries marines, les études de recherches fournissent la source principale de données de surveillance indépendantes des pêcheries. En effet dans plusieurs situations où les pêcheries ont été fermées, ces études fournissent l'unique information sur l'abondance des stocks commerciaux. Alors, que les procédures de terrain pour ces études (i.e., équipement, normalisation des méthodes d'échantillonnage unitaire et méthodes de saisie des données) sont plus ou moins normalisées dans le monde entier, les procédures d'analyse de données demeurent variables et controversées. Les trois principaux domaines de polémique sont:

- 1) Plan de sondage: Plans aléatoires ou fixes.
- 2) Précision/efficacité croissante: Basée sur le plan versus sur la distribution.
- 3) Détection des tendances dans les populations: Est-il sage d'ignorer la variance?

Je présenterai les problèmes statistiques associés chacun des points énoncés ci-dessus ainsi que les résultats de la recherche actuelle dans le domaine.

MOTS CLÉS: Gestion des pêcheries; enquête sur le terrain; précision.

1. INTRODUCTION

1.1 Background

Fisheries scientists in agencies such as the Department of Fisheries and Oceans in Canada are responsible for monitoring the current state of fisheries resources,

evaluating the impact that a fishery has had on a fish population and advising on potential impacts of future fisheries. Information on catch and effort from the entire fishing fleet provides the best spatial and temporal coverage for monitoring the fishery. However, the value of this information for detecting population trends can be compromised by

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technological innovations introduced by the fishermen, management restrictions on areas fished, gears used and trip limits, discarding of non-targeted species, high-grading of catches to keep only desired species (or sizes) and misreporting of catch by species, area or amount. Restricting the coverage to a select or index group of "representative" fishermen can provide some control over the quality of the information collected but problems associated with availability and commitment of the participants can limit the usefulness of this kind of data.

Trawl or dredge research surveys provide the major source of fisheries independent information for monitoring fish and invertebrate stock abundance. Gunderson (1993) presents an overview of these types of fishery-independent surveys as well as acoustic, aerial, and scuba-based methods and surveys of eggs and larvae by plankton tows (see also Doubleday and Rivard, 1981; Helser and Hayes, 1995). Research surveys are usually conducted on an annual basis by agencies (e.g., Department of Fisheries and Oceans (Canada), National Marine Fisheries Service (US), Institute of Marine Research (Norway), International Council for the Exploration of the Seas (Europe)) responsible for providing scientific advice for the management of fisheries. Lately, commercial fishermen have been enlisted to conduct or augment these surveys in many jurisdictions. While research surveys can collect many kinds of information such as spatial distribution, seasonal movements and species associations, it is the abundance estimates that are used most in the evaluation of fish stock history, current stock status and the effect of future management plans on fish stock. In fact, for many of the fisheries currently closed to commercial fishing because of depleted populations, research surveys may provide the only source of monitoring data.

1.2 Focus of Paper

There has been considerable amount of research into the physical process of catching fish with a towed net. Differences in catchability of fish to a particular fishing gear could be due to size selective catchability (Godø and Sunnanå, 1992; Aglen and Nakken, 1994), environmental effects (He, 1991; Smith and Page, 1996), changes in horizontal and/or vertical distribution due to the noise of the survey vessel or fishing gear (e.g., trawls) (Ona and Godø, 1990) and changes in the configuration of the net with depth

(Godø and Engås, 1989; Koeller, 1991). Methods for correcting trawl data for size selective catchability are discussed by Godø and Sunnanå (1992), Dickson, (1993ab) and Aglen and Nakken, (1994). Corrections due to changes in gear geometry are given in Koeller (1991), Engås and Ona (1993) among others. Recently, visual observations from submersibles have been used to ascertain catchability for acoustic surveys (Starr et al., 1995) and trawl surveys (Krieger and Sigler, 1996) of rockfish.

While methods of physically conducting a survey such as deploying and monitoring the fishing gear, acquiring and storing data, etc., are becoming standard for most surveys, survey design with respect to locating fishing locations within the survey area and methods for analysing the survey data are still relatively non-standard and controversial. In this report, I briefly review three areas of survey design and analysis where controversy exists. Examples from actual surveys are presented along with outstanding statistical issues.

2. SURVEY DESIGN

2.1 Design

There are two basic approaches to survey design. Fishing stations are located randomly within the survey area using a standard design-based approach or station location is fixed using a grid or transect design. Examples of design-based surveys are trawl surveys of groundfish on the eastern coasts of Canada (Doubleday, 1981) and the United States (Azarovitz, 1981), dredge surveys of scallops (*Placopecten magellanicus*) on Georges Bank (Mohn et al., 1987) and in waters off of Northeastern United States (Serchuk and Wigley, 1986), and acoustic surveys of pelagic fish off of South Africa (Jolly and Hampton, 1990). The stratified random design is the most common design used for fishery-independent surveys (Gunderson, 1993). Strata are usually defined by water depth or species distributional patterns, but may also reflect management boundaries.

Examples of surveys which use non-random survey designs are fixed station trawl surveys (e.g., walleye pollock trawl survey, Traynor et al., 1990) and fixed transect methods common to acoustic surveys (MacLennan and Simmonds, 1992) but also used for other types of gear (e.g., longline survey for halibut, Pelletier and Parma, 1994).

The real controversy arises when it comes to analysing data from either kind of survey design. While standard formulae from sampling texts (e.g., Cochran, 1977; Thompson, 1992) are used for many design-based surveys, there exists the general misconception that the standard survey estimates are only valid if the frequency distribution of the observations (catches) exhibits a normal distribution. Typically, the frequency distribution of the number of fish caught in a survey is quite skewed with a large proportion of the observations close to or equal to zero and a few very large catches. As a result, estimates of mean abundance have large variances associated with them when standard survey estimates are used.

A number of parametric distributions such as the negative binomial (Taylor, 1953; Houser and Dunn, 1967), the lognormal and Poisson (Brodie and Wells, 1985) and the Δ -distribution (Pennington, 1983, 1986, 1996; Smith, 1988) have been suggested as being useful models for survey catch data which exhibit a skewed distribution. The basic idea is to use estimates of mean and variance of the mean specific to these distributions instead of the standard survey estimates. The Δ -distribution, which is a combination of a bernoulli process (catch/did not catch fish) with a lognormal distribution to model the number of fish caught, has received a great deal of attention lately (Caveriviere, 1993; Conquest et al., 1996; Jay, 1996). There has also been ongoing debate over the robustness of using the minimum variance mean estimates from this distribution when the catches may not actually exhibit a Δ -distribution (Myers and Pepin, 1990; Pennington, 1996).

Spatial models have become popular with either implicit (e.g., contouring; Delaunay triangles; Robert et al., 1994) or explicit spatial models (e.g., kriging; Simard et al., 1992) used to estimate abundance. Applications of spatial models to data from sample surveys have reported that design-based methods require the assumption of spatial independence for their estimates to be valid, especially the variance estimates (e.g., Simard et al., 1992; Foote and Stefánsson, 1993; Ecker and Heltshe, 1994). Although finite population methods may ignore fine-scale spatial structure in the population being sampled, it is not true that spatial independence is required for the properties of the estimates to hold (i.e., concerning bias and precision; see Cochran, 1977; Smith and Robert, 1998). However, spatial structure need not be completely ignored in finite population survey designs, because large-scale spatial structure can be

incorporated using stratification and fine-scale structure by using a predictive model with covariates (see discussion in Smith and Robert, 1998).

2.2 Issues

Most research surveys have to cover a large area with a limited and probably decreasing budget. The trawl survey of the Scotian Shelf off of Nova Scotia is a typical example (Fig. 1). There are 52 strata in this survey area and the number of fishing locations ranges between 2 and 8 per strata. Even with this low sampling intensity, the survey takes close to a month to complete. The large number of strata was used in an attempt to capture the distributional aspects of a number of the major commercial species (e.g., cod, haddock, pollock, yellowtail flounder, American plaice, witch flounder, silver hake, redfish) that are caught by the survey. However, the large number of strata and the associated low sampling intensity generally results in very imprecise estimates of abundance. Often, 70 to 90 percent of the stratified mean for any one species can be due to very large catches in 1 to 5 fishing locations. The distributional patterns of fish are known to be patchy and in some cases can be associated with environmental variables (e.g., Perry and Smith, 1994). The application of statistical models such as the Δ -distribution or spatial models such as kriging have been attempts to deal with the patchy distribution patterns without worrying about the cause of the patchiness.

On the other hand, there may be more promise of improvement in precision if ancillary information such as environmental variables could be incorporated into the standard survey estimates. This could be achieved by using a design-based predictive framework that partitions the finite population of fishing locations within any stratum into two parts: the observed sample units and unobserved sampled units (Little, 1983). While we observe the units in the sample, our real interest is in the units that we did not observe. If we found relationships between fish catch and environmental variables and could know the values for the environmental variables at the unsampled (unfished) sample units, then it may be possible to predict the catches for these unsampled units. It is likely that these relationships will be more complex than can be accommodated by the design-based regression estimates already available in sample texts and therefore more research needs to be done on broadening the scope of models that can be used.

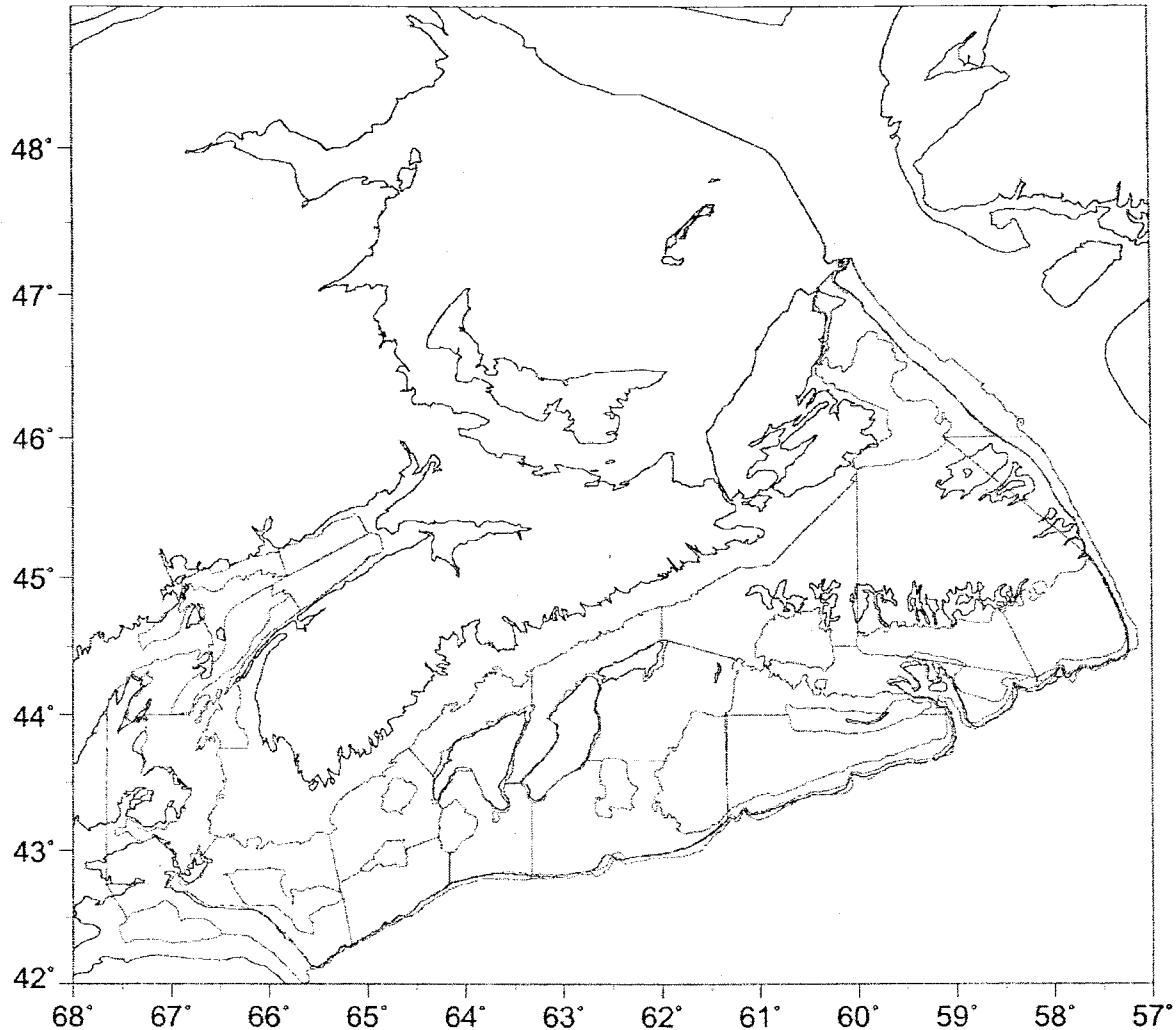


Figure 1. Stratification map for eastern Scotian Shelf trawl surveys in July (1970 to present). Stratum boundaries are based primarily on depth ranges (originally measured in fathoms: 1 fathom = 1.83 m).

3. PRECISION AND EFFICIENCY

In design-based theory, the precision of the estimates is a function of the survey design. Improving the precision of the estimate is accomplished by incorporating more information into the survey design. Stratified random designs are good examples of this principle. The difference between the simple random sampling variance of the mean and the stratified random variance of the mean has two components (Sukhatme and Sukhatme, 1970). The first is due to scheme for allocating stations to strata and can be zero, positive or negative, depending upon whether the allocation scheme was proportional to area, proportional to area and standard error (Neyman

allocation) or arbitrary. The second component compares the variance between strata with the variance within strata and will be greater than or equal to zero. This component will get larger as the within stratum variance decreases and the between strata variance increases. The stratified random design will result in a more precise estimate of the mean when stations are allocated to strata in an optimal manner with respect to strata variance and when strata boundaries result in observations being more homogenous within strata than between strata. The difference between the simple random sampling variance and the stratified variance (scaled by the simple random sampling variance) measures the efficiency of the stratified design.

Consider the example of the haddock catches in the 1988 survey of the eastern Scotian Shelf (Table 1). This survey used the stratified random design in Fig. 1 with stations allocated to strata in an arbitrary manner, although haddock distribution was a consideration for the design when the survey series was established in 1970. The stratified design was quite efficient resulting in a 47 percent decrease in the variance of the mean from the simple random sampling case. This decrease was mainly due to the allocation component (44.7 percent decrease in variance) indicating that the strata boundaries were only loosely associated with the

distribution of haddock but that the larger number of stations were in the more variable strata. It is interesting to note that for the haddock example, the expected gain in precision from doubling the number of stations (i.e., increasing the budget) would not be as great as had we been able to optimally allocate the original number of stations with respect to strata variance and size (Table 1). Preliminary investigations indicate that previous year's survey results can be used to improve the current year's survey for haddock because this species tends to remain in the same general area from year to year (Smith, 1998).

Table 1. Variance of the mean and design efficiency estimates for various improvements to the 1988 survey of haddock on the eastern Scotian Shelf.

Survey Design	Sample Size	Variance	Efficiency
Simple Random Sampling	106	1455.40	
Original stratified	106	769.12	47.2
Stratified Double	212	546.08	62.5
Stratified Optimal	106	86.13	94.1

Kenchington and Smith (1997) successfully redesigned the station allocation scheme for dredge surveys of scallops in the Bay of Fundy using previous years' results. However, this approach has been less successful with other species that are less sedentary.

An alternative approach to using results from previous surveys to design allocation schemes is to use observations collected during the current survey. Thompson and Seber (1996) have presented a number of "adaptive" sampling methods to this purpose. The method of adaptive allocation appears to be quite useful and I have applied it in a number of pilot studies with success. In this method the allocation of stations to strata is conducted as a two-phase process as follows.

1. Partition the total sample size into $n_T = n_1 + n_2$.
2. Allocate n_1 samples over the strata using some rule (past allocation, proportional to strata size, etc.).
3. Conduct survey for n_1 observations.
4. Calculate mean and variances for each stratum based on the n_1 samples.
5. Allocate the remaining n_2 according to some predefined rule (e.g., allocate additional samples to stratum h if the first phase stratum mean or variance exceeds some threshold.).
6. Conduct survey to collect data on second set of observations.

This approach is not new, in the context of conducting research surveys, having been suggested in one form or another by Francis (1984) and Jolly and Hampton (1990). However, the application of standard formulae for means and variances to the combined data from both phases results in biased estimates (Francis, 1991; Jolly and Hampton, 1991; Thompson and Seber, 1996). In cases where n_1 is much larger than n_2 this bias may not be too serious (Jolly and Hampton, 1991) but such a restriction may limit the usefulness of this approach.

On the other hand, the first and second phase means are unbiased estimates by themselves and as a consequence Thompson and Seber (1996) proposed an unbiased estimate by conditioning the first stage estimates on a sufficient statistic of the first and second stage data. This is done using Rao-Blackwell theory and the reader is encouraged to read Thompson and Seber (1996) for details on this approach.

An example of an application of adaptive allocation is presented in Table 2 for a survey of scallops on Georges Bank (Robert et al., 1999). In this example, the threshold was set as having at least 20 percent of the first phase stations in a stratum with catches of more than 100 two year old scallops before additional samples would be allocated. It turned out that two year old scallops were quite plentiful in 1998 and every stratum received additional sampling.

Table 2 Results from adaptive allocation for 1998 Georges Bank scallop survey. Note that the rule was defined: extra sampling carried out if at least 20 percent of the stations in a stratum contained more than 100 two year old scallops (Robert et al., 1999).

Stratum	Proportion of area in stratum	First stage sample size	First stage mean	First stage variance	Total sample size	Rao-Blackwell Mean	Variance of RB mean
1	0.43	65	885.80	259235.64	78	759.59	180637.84
2	0.16	24	400.79	37362.46	29	344.21	25993.15
3	0.13	20	685.60	138672.60	24	577.42	98027.29
4	0.14	21	342.95	8748.77	25	456.40	29666.54
5	0.13	20	218.40	9931.10	24	218.33	8495.04
Stratified			618.25	52832.23		555.45	37321.10

3.1 Issues

Evaluation of the efficiency of a survey design is a useful but rarely reported exercise. One exception is given in Smith and Gavaris (1993a) where efficiency estimates were used retire an old design and evaluate a new one for cod on the Scotian Shelf. However, the focus of this kind of approach as an aid to redesign surveys is limited to either a single species or groups of species that share similar spatial distributional characteristics over time. Most surveys are designed to monitor a large number of species, many of which do not cohabit similar areas or exhibit temporally stable spatial distributions (e.g., pollock which are highly mobile, semi-pelagic and form large schools vs. flounders which are demersal and do not school). Adaptive allocation offers a means of using the current distribution of the fish to design the survey but this method is also limited to single species or similar groups of species. Given current budgets and limited vessel time, surveys will continue to be multispecies in nature and therefore allocation schemes that take this into account are needed. Cochran (1977) does offer some formulae for compromise allocation schemes but there is the need for more flexible methods that could incorporate weightings to differentiate between more or less important species. Also, methods that allow additional sampling by a second vessel for single species situations could be quite useful.

4. DETECTING TRENDS

4.1 Expressing Uncertainty

In the end it is the trends over time of the survey means or total abundance estimates that are used to evaluate changes in the fish population. Most evaluations of fish stock status will only present the mean or total abundance estimates over time and use these as an index for a population model that may incorporate other sources of information such as commercial catch, age or size composition of the catch, etc. (see Quinn and Deriso, 1999) for details on the population models used in fisheries.). Often the time trends from surveys exhibit changes in abundance from year to year too large to be realistic given the underlying dynamics of the population. Fisheries scientists will usually but not always treat these abrupt changes as outliers. Although variance estimates are available if design-based methods have been used, these estimates are rarely used to evaluate the uncertainty inherent in the abundance estimates. In fact, there has been a great deal of debate in unpublished agency reports, meeting documents, etc., about whether the standard variance estimates mean anything given the apparent presence of spatial autocorrelation or non-normal frequency distribution of catches or the low sampling intensity.

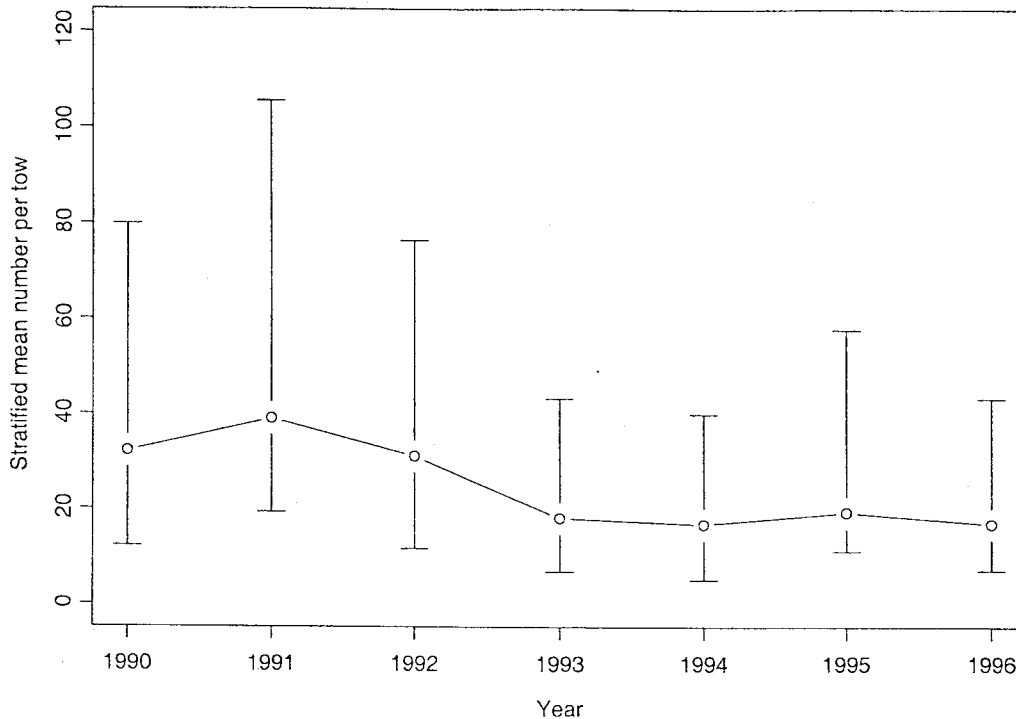


Figure 2. Stratified mean number per tow with 95 percent bootstrap confidence intervals for yellowtail flounder, eastern Scotian Shelf.

Estimates of confidence intervals for the mean or total numbers (or weight) using the Student's *t* method (along with Satterthwaite's approximation, Cochran, 1977) often results in lower limits being less than zero — results which only add fuel to the non-normal debate.

The time trend for the stratified mean number per tow for yellowtail flounder on the eastern Scotian shelf suggests that there has been little change in abundance since a decline in 1993 of about 50 percent from levels observed in the early 1990's. Confidence intervals were calculated for the stratified means using the BWR bootstrap as suggested by Sitter (1992ab) [see also Rao and Wu (1988) for discussion on bootstrap methods for sample surveys and Smith (1997) for an application to fisheries survey data] and percentile limits. The bootstrap confidence intervals suggest that there is no trend in these data at all.

4.2 Issues

The major issues here are determining whether or not it is appropriate to use the sampling variance from the survey when evaluating whether or not trends actually

exist in the survey data and if so, then how does one incorporate information on uncertainty into fishery models. For most of its history, sample survey research has concentrated on estimation rather than model building and inference. Thompson (1997) has some discussion on the analytical uses of survey data but there is need for more attention to this subject area, especially for methods which incorporate the survey design in some manner. The impact of survey variability on fisheries models has been addressed by Smith and Gavaris (1993b) and Nandram et al. (1997). In the first case, bootstrap replications of the survey means were used to construct individual estimates of the projected catch from an age-structured model to evaluate the magnitude of the uncertainty associated with predictions from fishery models. The second case used replications from a Gibbs sampler to evaluate the impact of priors for age composition from a survey on the precision of estimates of population size from an age-structured model. In both cases, the impact of improvements to the precision of the survey estimates on the final fishery model predictions could be evaluated. There has been very little research on other methods of incorporating uncertainty from surveys into the fishery models. In addition, reviews

of sampling levels in surveys (and precision or efficiency concerns) very rarely consider the impacts on the fisheries models that use the information.

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