Available online at www.sciencedirect.com
SCIENCE DIRECT®
ELSEVIER
Fisheries Research 79 (2006) 239–250
FISHERIES RESEARCH
www.elsevier.com/locate/fishres

Including discard data in fisheries stock assessments: Two case studies from south-eastern Australia

André E. Punt[a,b,*], David C. Smith[a], Geoff N. Tuck[a], Richard D. Methot[c]

[a] *CSIRO Marine and Atmospheric Research, GPO Box 1538, Hobart, TAS 7001, Australia*
[b] *School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98195-5020, USA*
[c] *NOAA Fisheries, Office of Science and Technology, Northwest Fisheries Science Center, Seattle, WA, USA*

Received 4 November 2005; received in revised form 4 April 2006; accepted 13 April 2006

Abstract

Discarding of target species can be substantial in some fisheries. For fisheries managed using Total Allowable Catches, such as Australia's Southern and Eastern Scalefish and Shark Fishery (SESSF), discarding of target species can occur for reasons related to the size of the fish caught, markets, and the amount of quota held by individual quota holders. This paper illustrates how the assessments for two of the species in the SESSF, blue grenadier, *Macruronus novaezelandiae*, and the western stock of blue warehou, *Seriolella brama*, are conducted to take account of discards. Discards of blue grenadier are predominantly small fish so the assessment distinguishes between retained and discarded fish, and includes likelihood components related to the weight of the discards and the age-structure of the discards. In contrast, discards of blue warehou are due primarily to quota-related issues, so the assessment adds the discards to the catches and the catch-rate indices, and fits to total catches and catch-rates. Model outputs suggest that strong year-classes can be detected before they enter the fishery by including data on discards in assessments while ignoring such data when conducting assessments can lead to biased assessment outcomes. Several caveats related to the use of data on discards in stock assessments are outlined.

Keywords: Australia; Bayesian methods; Discard rate; Fisheries stock assessment; Southern and Eastern Scalefish and Shark Fishery

1. Introduction

It is well-known that a substantial fraction of world's fisheries catch is discarded (Alverson et al., 1994; Kelleher, 2004). This is a source of conservation concern because many of the species that are discarded are unassessed. Much of the discussion on discards has therefore focused on non-target species. However, discards of target species can be substantial in some fisheries and these are often not included in assessments (Borges et al., 2005; ICES, 2004). One example of a fishery in which discards of target species can be substantial is Australia's Southern and Eastern Scalefish and Shark Fishery (SESSF). The SESSF is one of the more valuable fisheries in Australia (landings of over 35,000 t annually at a value of around A$95 million, Caton and McLoughlin, 2004). The SESSF is a complex fishery consisting of multiple species and gears (Smith and Smith, 2001), with the bulk of the catch taken by a trawl sector. The primary management tool in the SESSF is a system of Total Allowable Catches (TACs) implemented as Individual Transferable Quotas (ITQs), although other management tools such as gear restrictions and closed areas are also used. Twenty-four species or species-groups are currently under quota management in the SESSF.

Estimates of discard rates (the fraction of the total catch that is discarded) for the species in the SESSF are based on an at-sea observer program (e.g. Liggins et al., 1997; Knuckey et al., 1999). This observer program has covered 1.5–2.4% of all tows made in the fishery between 1994 and 2004 (603–991 observed tows per annum) and results in estimates of discard rate that have sampling-based coefficients of variation ranging from under 3% to about 13% when the discard rate is 5% or more (Matt Koopman, PIRVic, Pers. Commn.). The

* Corresponding author. Tel.: +61 3 6232 5377; fax: +61 3 6232 5000.
E-mail addresses: andre.punt@csiro.au, aepunt@u.washington.edu (A.E. Punt).

0165-7836/$ – see front matter. Crown Copyright © 2006 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.fishres.2006.04.007

Table 1
Discard rates (weight discarded divided by the total weight caught, expressed as percentage) for trawl gear for stocks of teleost fish under quota management in Australia's Southern and Eastern Scalefish and Shark Fishery (Matt Koopman, PIRVic, Pers. Commn.)

Fish stock	Year		
	2002	2003	2004
Blue eye trevalla, *Hyperoglyphe Antarctica*	0.1	0.0	0.0
Blue grenadier, *Macruronus novaezelandiae* (spawning)	0.1	0.1	0.2
Pink ling, *Genypterus blacodes*	0.3	0.1	0.1
Blue grenadier, *Macruronus novaezelandiae* (non-spawning)	0.1	0.6	1.5
John dory, *Zeus faber*	0.8	1.3	0.3
Silver trevally, *Pseudocaranx dentex*	0.2	0.6	1.6
Orange roughy, *Hoplostethus atlanticus*	1.6	0.9	0.1
Eastern School whiting, *Sillago flindersi*	0.5	6.9	1.1
Jackass morwong, *Nemadactylus macropterus*	2.3	6.0	4.5
Tiger flathead, *Neoplatycephalus richardsoni*	5.1	4.3	4.1
Western gemfish, *Rexea solandri*	5.8	6.8	6.0
Ocean perch—offshore, *Helicolenus barathri*	11.0	6.7	10.3
Spotted warehou, *Seriolella punctata*	8.9	15.1	21.1
Mirror dory, *Zenopsis nebulosus*	12.2	18.4	16.3
Blue warehou, *Seriolella brama*	2.6	6.3	51.4
Eastern gemfish, *Rexea solandri*	18.9	38.8	51.9
Redfish, *Centroberyx affinis*	51.7	35.7	36.1
Ocean perch—inshore, *Helicolenus percoides*	64.2	66.4	86.0

The species are sorted by the average discard rate over 2002–2004. Results are presented separately for the two main components of the fishery for blue grenadier (spawning and non-spawning).

sampling coefficients of variation can be very high when the discard rate is less than 1% owing to the rareness of observing a discard event, but the confidence intervals for such estimates nevertheless remain fairly tight.

The discard rates for species caught by trawlers range from almost negligible (e.g. blue eye trevalla, *Hyperoglyphe antarctica* and silver trevally, *Pseudocaranx dentex*) to values close to (and sometimes above) 50%, i.e. half of the total catch is discarded (inshore ocean perch, *Helicolenus percoides* and redfish, *Centroberyx affinis*, Table 1). Over 30% of the total catch of all species in the SESSF is discarded, including about two-thirds of the weight of non-quota species caught by the fishery (Fig. 1). Table 1 also shows that there is considerable inter-annual variation in the estimated discard rates for some species. For example, the estimated discard rate for

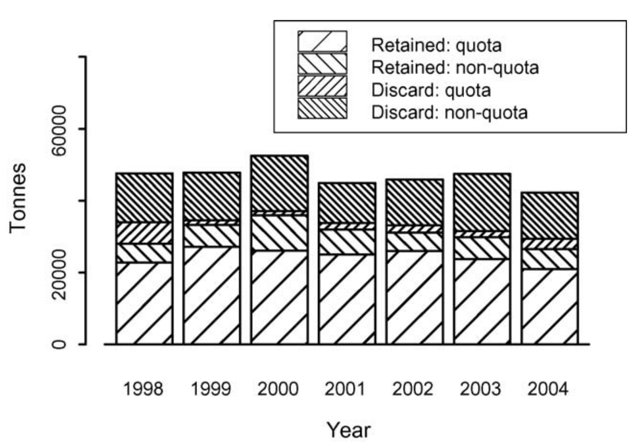

Fig. 1. Retained and discarded catches in the SESSF for quota and non-quota species, 1998–2004.

blue warehou, *Seriolella brama*, varied from 2.6 to 51.4% over 2002–2004 (Table 1).

Discarding is common in many fisheries, but it is often argued that it increases following the adoption of output controls such as ITQs (e.g. Copes, 1986; Tilzey, 1994, but see Branch, 2004 for arguments to the contrary). Although there are several reasons for discarding of target species in the SESSF (Knuckey and Liggins, 1999; Liggins and Knuckey, 1999), they tend to fall into two categories: (a) size-based discarding of small and (hence) unmarketable fish, often referred to as high-grading, and (b) quota-related discarding where landings are constrained by available quota holdings or lack of markets. Similar factors influence discarding in the U.S. west coast groundfish fishery (Pikitch, 1991).

Length–frequency distributions for the retained and discarded components of the catches of blue grenadier, *Macruronus novaezelandiae*, are shown in Fig. 2 and for the western stock of blue warehou in Fig. 3 (there are two stocks, eastern and western, of blue warehou off southern Australia; Talman et al., 2003). The data for blue grenadier pertain to the catches outside of the winter spawning season off Tasmania (the "non-spawning" fishery). Results are shown in Figs. 2 and 3 for 4 years, 2 in which the discard rate was high (>50% of the total catch discarded) and 2 in which it was low (3% or less of the total catch discarded). The discards of blue grenadier were always small fish (<60 cm) although not all fish <60 cm are discarded (e.g. a substantial fraction of the landed catch in numbers during 1997 consisted of small fish). In contrast, the length–frequency distribution for discarded blue warehou is almost identical to that for the landed component of the catch when discarding is high (e.g. during 1997 and 2004) whereas only small fish are discarded when the

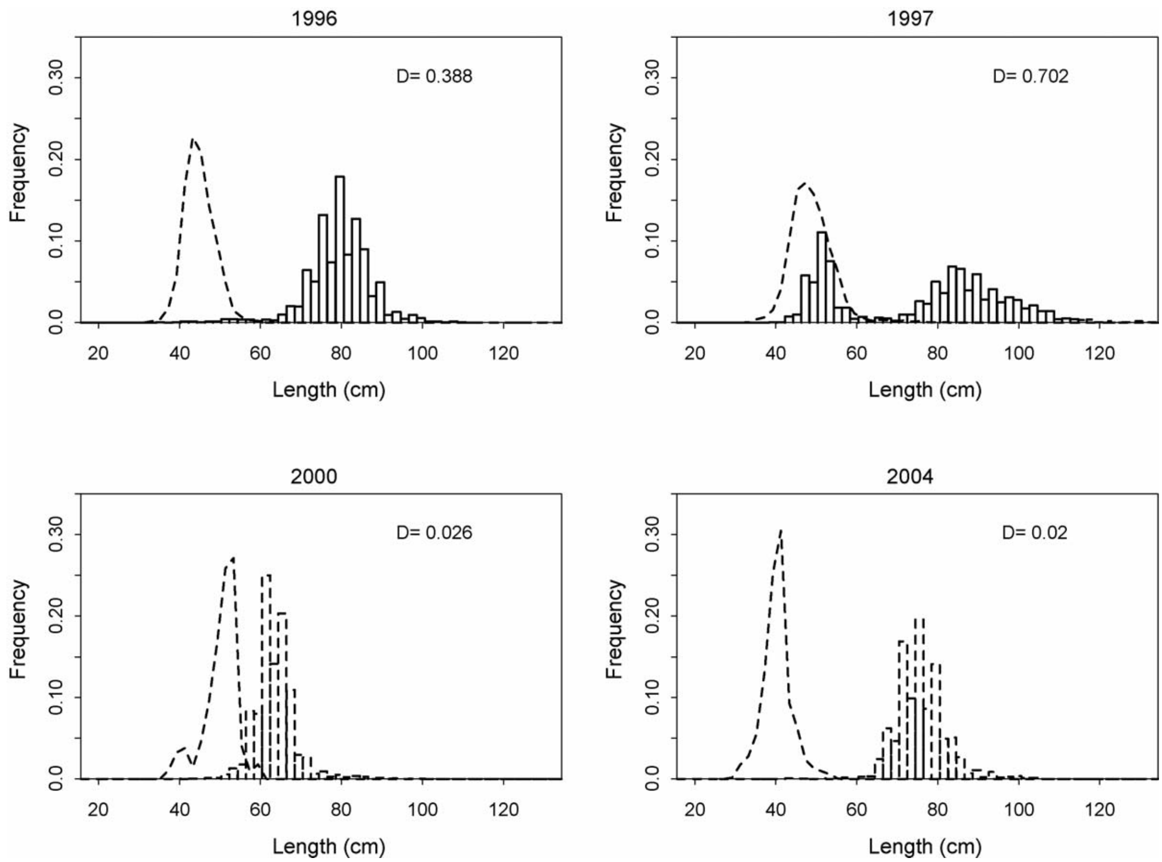

Fig. 2. Length–frequency distributions for the landed (bars) and discarded (dotted lines) components of the catch of blue grenadier in the non-spawning fishery. "*D*" denotes the discard rate.

discard rate is low (e.g. during 2000 and 2002). Therefore, years of high discards of blue grenadier can be attributed largely to availability of small (and largely unmarketable) fish whereas years of high discards of blue warehou are more related to operators having insufficient quota to cover catches (and hence having to discard to avoid over-quota penalties).

It is clearly necessary to account for the impact of discards when conducting stock assessments of species for which discarding is substantial (Williams, 2002). However, the way discards are included in an assessment needs to reflect the nature of how discarding occurs. This paper outlines the approaches used to assess blue grenadier and the western stock of blue warehou, in particular how information on discards is treated in these assessments. It also shows how the results of the assessments of these stocks, and hence scientific management advice for them, depend on assumptions regarding the treatment of discards in assessments.

2. Methods

2.1. Overview of the assessment methods

The assessments of blue grenadier and blue warehou are based on the Integrated Analysis paradigm, in common with those for most species in the SESSF (e.g. Smith et al., 2001; Tuck and Smith, 2004). Integrated Analysis (also referred to as statistical catch-at-age analysis) is preferred for the following reasons: it can make use of a wide variety of data sources; it is sufficiently flexible to represent many hypotheses about the population dynamics and the relationship between the data collected and the model predictions; it separates the development of the model of the population dynamics from that of how the data are observed; and it does not require continuous time series of, for example, catch-at-age data (Smith et al., 2001). Simulation testing has also revealed that it is the most robust assessment method for a variety of SESSF species (Punt et al., 2002).

The method of assessment therefore involves developing a population dynamics model appropriate for the species being assessed and fitting it to the data available for assessment purposes. The estimable parameters of the population dynamics model include the initial age-structure, the annual recruitment residuals (deviations from a Beverton-Holt stock-recruitment relationship), and parameters which determine selectivity and the probability of discarding. Uncertainty is quantified through sensitivity tests that vary the structural assumptions of the assessment and the data used for fitting purposes, and through the use of Bayesian methods to estimate posterior distributions for key model outputs. These key

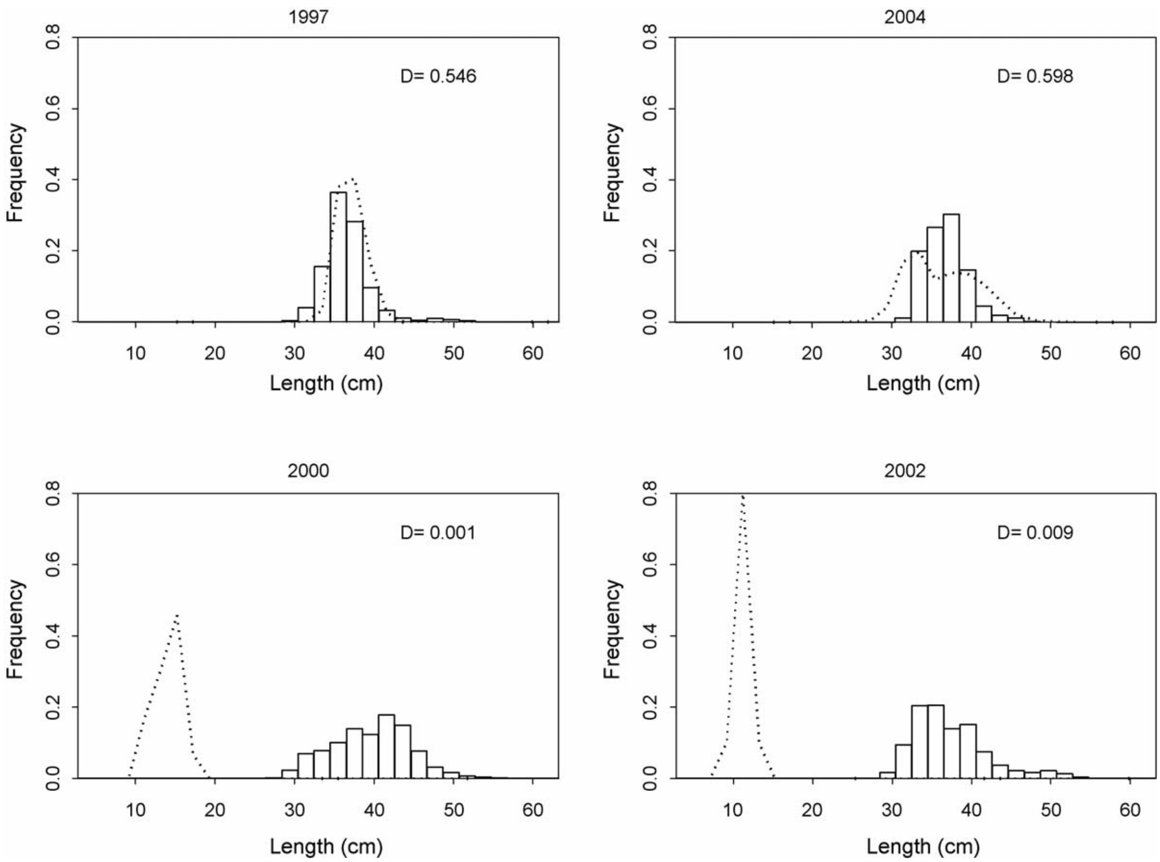

Fig. 3. Length–frequency distributions for the landed (bars) and discarded (dotted lines) components of the catch of the western stock of blue warehou. "*D*" denotes the discard rate.

model outputs are: (a) time-trajectories of exploitable and spawning biomass, (b) the implications, in terms of probabilities of being above limit and target reference points, of different future sequences of catches, and (c) the outcomes from agreed harvest control rules.

The full mathematical specifications of the assessments are not included in this paper because the focus of this paper is on the use of discard data in assessments rather than the specific results for blue grenadier and blue warehou. Interested readers can consult Punt et al. (2001), Punt and Smith (2004), and Tuck et al. (2004) for these mathematical details. Tables 2 and 3 contrast the two assessments qualitatively by outlining their structural aspects (Table 2) and the data used for fitting purposes (Table 3).

Table 2
Key structural assumptions made when conducting the assessments of blue grenadier and blue warehou

Assumption	Blue grenadier	Blue warehou
Sex-structure	Yes, two sex	No, single sex
Fleets	Spawning season, non-spawning season	Single trawl fleet
Natural mortality	Age-independent, sex-specific	Age-independent
Fishing mortality	Continuously throughout the year	Instantaneously in the middle of the year
Selectivity	Spawning: logistic as a function of length. Non-spawning: dome-shaped as a function of length	Logistic as a function of length
Initial state	Unfished equilibrium age-structure (1979)	Exploited non-equilibrium age-structure (1986)
Stock-recruitment relationship		
Deterministic form	Beverton-Holt (steepness = 0.9)	Beverton-Holt (steepness = 1.0)
Variation in recruitment	Log-normal (recruitment variation, $\sigma_R = 1$)	Log-normal (recruitment variation, $\sigma_R = 1$)
Recruitments estimated for	1979–2004	1986–2004
Growth curve		
Functional form	Observed mean lengths-at-age	Fitted von Bertalanffy growth equation
Variation in length-at-age	Assumed to be 0	Estimated

The assumptions related to discarding are omitted from this table as they are discussed in detail in Section 2.2.

Table 3
Data (excluding data on discards) used when fitting the population dynamics models for blue grenadier and blue warehou

Assumption	Blue grenadier	Blue warehou
Catches by fleet	Yes	Yes
Catch-rates by fleet	Yes	Yes
Landed catch-at-age	Yes	No
Landed catch-at-length	No	Yes
Age-length keys	No	Yes[a]
Survey estimates of absolute abundance	Yes, egg production method; acoustics	No

[a] Allowance is made for ageing error when fitting the model to these data.

An aspect of the assessment of blue warehou that is somewhat unusual for assessments in Australia is that rather than estimating catch-at-age by multiplying length–frequencies by age–length keys and including a likelihood component for the catch-at-age data, the age–length keys are fitted to directly. This approach, which is included in the stock assessment package Stock Synthesis (e.g. Methot, 2000, 2006), is taken so that it is possible to estimate the parameters of the von Bertalanffy growth equation as part of the assessment and because, for some years, there are some length-classes for which there is length–frequency information, but no age data. Under the assumption that animals are sampled randomly with respect to age within each length-class, the component added to the negative of the logarithm of the likelihood function for the age–length keys (ignoring constants independent of the model parameters) is

$$-\sum_{y}\sum_{L}W_{y,L}\sum_{a}A^{obs}_{y,L,a}\ln(\rho_{y,L,a}) \tag{1}$$

where $A^{\text{obs}}_{y,L,a}$ is the observed fraction during year y which animals of age a constituted of the landed catch of fish in length-class L and $\rho_{y,L,a}$ is the model-estimate of $A^{\text{obs}}_{y,L,a}$:

$$\rho_{y,L,a} = \frac{1}{\sum_{a''}A_{a'',L}N_{y,a''}}\sum_{a'}A_{a',L}N_{y,a'}\Omega_{a',a} \tag{2}$$

$N_{y,a}$ is the model-estimate of the number of animals of age a at the start of year y, $A_{a,L}$ the model-estimate of the fraction of animals of age a that are in length-class L, determined from the estimated growth curve (and the variation in length-at-age), $W_{y,L}$ the number of fish in length-class L that were aged during year y, and $\Omega_{a',a}$ is the probability that an animal of actual age a' will be aged to be age a (the age-reading error matrix).

2.2. Including data on discards in an assessment

The approach for including data on discards in an assessment depends on the causes for discarding.

2.2.1. Discarding is size- or age-based

In this case, the total catch can be partitioned into landed and discarded components, where the probability of discarding depends on length (or age). This is modelled (by fleet) by estimating a selectivity pattern for the total catch and a curve that defines the probability of being discarded. As a result, the model can be used to predict the landed and discarded catches by number. For example, ignoring any dependencies on sex and fleet, assuming that there is a single fleet and that selectivity is age- (rather than size-) based, the model-predicted catches-in-number (landed and discarded) are given by

$$\hat{C}_{y,a} = \frac{(1-P_a)S_aF_y}{Z_{y,a}}N_{y,a}(1-\mathrm{e}^{-Z_{y,a}}) \tag{3a}$$

$$\hat{D}_{y,a} = \frac{P_aS_aF_y}{Z_{y,a}}N_{y,a}(1-\mathrm{e}^{-Z_{y,a}}) \tag{3b}$$

where $\hat{C}_{y,a}$ is the model-estimate of the landed catch of animals of age a during year y, $\hat{D}_{y,a}$ the model-estimate of the discarded catch of animals of age a during year y, S_a the selectivity of the gear on fish of age a, F_y the fully selected ($S_a \to 1$) fishing mortality during year y, P_a the probability of discarding a fish of age a, $Z_{y,a}$ the total mortality on fish of age a during year y ($=M+S_aF_y$), and M is the instantaneous rate of natural mortality.

The functional form chosen to model P_a, usually a logistic curve, partitions the model-predicted catch between landings and discards. It should be noted that when discarding and/or selectivity is size-based, the estimates of size-at-age from the landed catches are biased compared to the population size-at-age because of the differential capture and discarding of smaller fish at each age.

When discards are modelled in this way, it is necessary to include components in the likelihood function related to fitting to the age- (or size-) compositions of the discards as well as those of the retained catches. If the estimates of the discards are assumed to be log-normally distributed (Tuck et al., 2004) and the age-composition of the discarded catch is assumed to be multinomially distributed, the following two components (ignoring constants independent of the model parameters) related to the discards are added to the negative of the logarithm of the likelihood function:

$$L_1 = \sum_{y}\left(\ln\sigma_y + \frac{1}{2\sigma_y^2}[\ln D_y - \ln\hat{D}_y]^2\right) \tag{4a}$$

$$L_2 = \sum_{y}W_y\sum_{a}\pi_{y,a}\ln\hat{\pi}_{y,a} \tag{4b}$$

where D_y is the observed weight of discards for year y (based, for example, on the results of an observer program) and $\hat{D}_y$ is the model-estimate of the weight of discards for year y:

$$\hat{D}_y = \sum_{a}w_a\hat{D}_{y,a} \tag{5}$$

where σ_y is the standard error of the logarithm of the observed weight of discards for year y, w_a the weight of an animal of age a, W_y the effective sample size for the age-composition of the discards for year y, $\pi_{y,a}$ the observed proportion which animals of age a constituted of the discards in numbers during year y, and $\hat{\pi}_{y,a}$ is the model-estimate of the proportion which animals of age a constituted of the discards in numbers during year y $(= \hat{D}_{y,a}/\sum_{a'} \hat{D}_{y,a'})$.

Several variants of this basic approach can be implemented. For example, (a) Eq. (4a) can be based on the discard rate rather than the weight of discards, (b) a sampling distribution other than the log-normal distribution (e.g. the gamma distribution) could be assumed for the discards, and (c) a sampling distribution other than the multinomial distribution (e.g. the robust normal distribution for proportions, Fournier et al., 1990) could be assumed for the age-composition of the discards. Eqs. (3)–(5) can be generalized to deal with, for example, sex-specific data, data on the size- rather age-structure of the discarded catch, and time-varying selectivity, growth and the probability of discarding, etc. Note also that it is not necessary to have data on discards in weight (or the age-/size-composition of the discards) for all years of the assessment period if it can reasonably be assumed that selectivity and the probability of discarding did not change over time.

Eqs. (3a) and (3b) can be extended to handle the case in which there are multiple fleets, each of which has a different discarding practice:

$$\hat{C}^f_{y,a} = \frac{(1-P^f_a)S^f_a F^f_y}{Z_{y,a}} N_{y,a}(1-\mathrm{e}^{-Z_{y,a}}),$$
$$\hat{D}^f_{y,a} = \frac{P^f_a S^f_a F^f_y}{Z_{y,a}} N_{y,a}(1-\mathrm{e}^{-Z_{y,a}}) \tag{6}$$

where $\hat{C}^f_{y,a}$ is the model-estimate of the landed catch by fleet f of animals of age a during year y, $\hat{D}^f_{y,a}$ the model-estimate of the discarded catch by fleet f of animals of age a during year y, S^f_a the selectivity of fleet f on fish of age a, F^f_y the fully selected ($S^f_a \to 1$) fishing mortality for fleet f during year y, P^f_a the probability of fleet f discarding a fish of age a, and $Z_{y,a}$ is the total mortality on fish of age a during year y $(= M + \sum_f S^f_a F^f_y)$.

2.2.2. Discarding is quota-related

When discarding is due to quota-related reasons (as appears to be the case for the western stock of blue warehou) so that the length–frequency distribution for the discards is essentially the same as that for the landings, the discarded catch can simply be added to the landings and there is no need to explicitly model the process of discarding.

However, a complication arises when commercial catch-rates are treated as indices of relative abundance because the analyses used to develop the catch-rate indices (at least in Australia, e.g. Maunder and Punt, 2004; Haddon and Thomson, 2005) are based on retained catch per unit of effort. This is because the discarded component of the catch is rarely recorded in logbooks. Furthermore, only a relatively small percentage of hauls is observed annually, so it is infeasible to base catch-rate indices on the total catches (i.e. by adding haul-specific estimates of discards to haul-specific retained catches and then using estimates of total catch so constructed in analyses of catch and effort). An approximate way to account for the fact that the catch-rate indices based on landings data will under-estimate the true catch-rate when there is discarding is to divide the annual catch-rate indices by the annual retention rate (one less the discard rate). This assumes that the discard rate is the same for all hauls which, although clearly not the case exactly, will nevertheless correct catch-rates in the right direction.

2.2.3. Summary of methods

There are therefore two approaches to accounting for discards in assessments: (a) treat the discard rates and the age-/size-composition of the discards as data in the assessment, and (b) adjust the landed catches and catch-rates by the discard rates so they are based on the total catches.

2.3. Diagnostics for Bayesian analyses

The uncertainty associated with the model outputs given a particular set of structural assumptions and choices for the data used for parameter estimation is quantified using parameter vectors sampled randomly from Bayesian posterior distributions. The samples from the posterior distributions are generated using the Markov Chain Monte Carlo (MCMC) algorithm (Gelman et al., 1995) as implemented in the software package AD Model Builder.[1] Lack of convergence of the MCMC algorithm is evaluated using the statistics developed by Geweke (1992), Heidelberger and Welch (1983), and Raftery and Lewis (1992). The number of cycles, burn-in period and thinning rate are selected so that there is no evidence for a lack of convergence for the quantities of interest.

3. Results and discussion

3.1. Blue grenadier

The selectivity patterns for the two fleets for blue grenadier differ markedly. The fishery during the spawning season (the spawning fishery) almost exclusively captures large, mature and marketable fish whereas the fishery at other times of the year (the non-spawning fishery) takes a wide range of sizes and can, on occasion, discard large quantities of small blue grenadier.

Figs. 4 and 5 show the fits of the model to the discard data for the non-spawning fishery (the weight and the age-composition of the discards). The model mimics the trend in the weight of discards well, although there are some years for which the estimated time-trajectory of discards fails to intersect the 95% confidence intervals for the estimates of the discarded catch (Fig. 4). The model is also able to mimic the

[1] Otter Research Ltd., http://otter-rsch.com/.

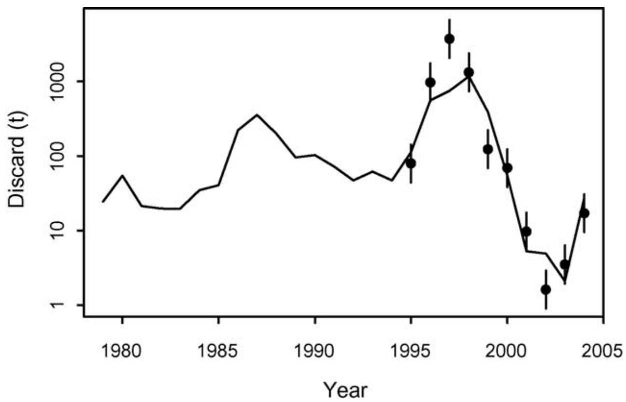

Fig. 4. Estimates of the catches of blue grenadier discarded by the non-spawning fishery (with 95% confidence intervals; points and vertical bars) and the estimates of discarded catch for the model parameters corresponding to the maximum of the posterior distribution (solid lines).

age-structure of the discards when the discarding is fairly high (1996–1998 and 2004), but fits the age-structure of discarded fish in 1999 and 2000 fairly poorly (Fig. 5). The latter result is not surprising given that very small amounts of blue grenadier were discarded in these 2 years, so the sample sizes for the discard length–frequencies are correspondingly very small.

Fig. 6 shows retrospective analyses for the number of animals in the 1994 and 1995 year-classes (the largest 2 year-classes spawned since the start of substantial harvesting of blue grenadier in 1979). Results are shown in Fig. 6 for analyses that use the discard data (solid lines) and which ignore these data (dashed lines). As expected, the estimates for the 1994 and 1995 recruitments converge over time irrespective of whether or not the assessment makes use of the discard data. However, the estimates based on the analysis that uses the discard data tends to approach the final (and presumably converged) values sooner than those based on the analysis that does not use these data. The converged estimates of recruitment are similar for the analyses based on using and ignoring the discard data because the analysis that ignores the discard data still allows for discarding by setting (pre-specifying) the probability of discard to that from the analysis which fits to the discarding data. The 95% posterior intervals tend to be wider for the analysis which ignores the discard data. These results highlight the potential value of using discard data when conducting stock assessments. The estimates of

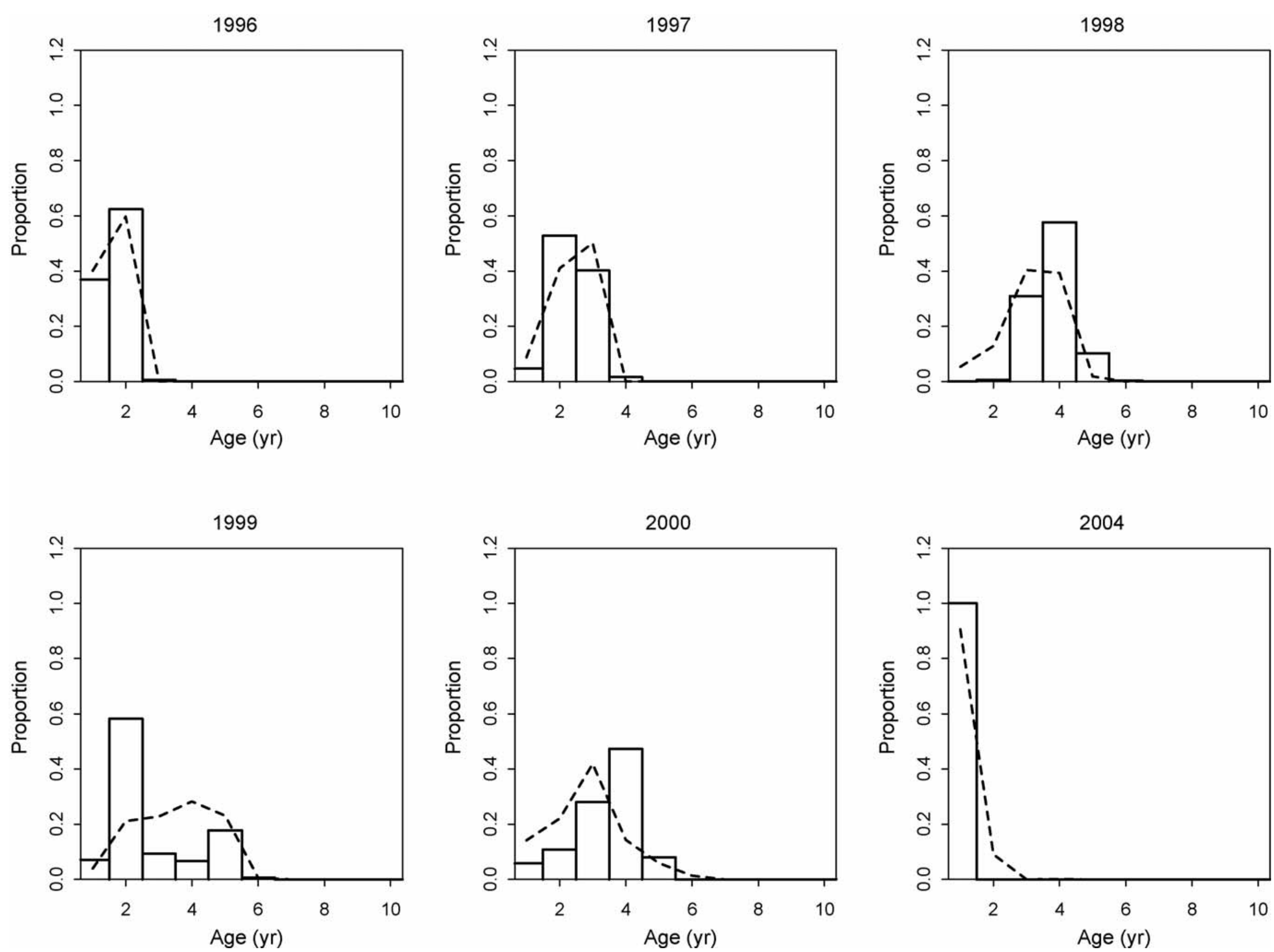

Fig. 5. The observed (solid bars) and model-predicted (dotted lines) age-structure of the discards of blue grenadier by the non-spawning fishery for years in which data on the age-structure of the discards are available. The model estimates are those corresponding to the maximum of the posterior distribution.

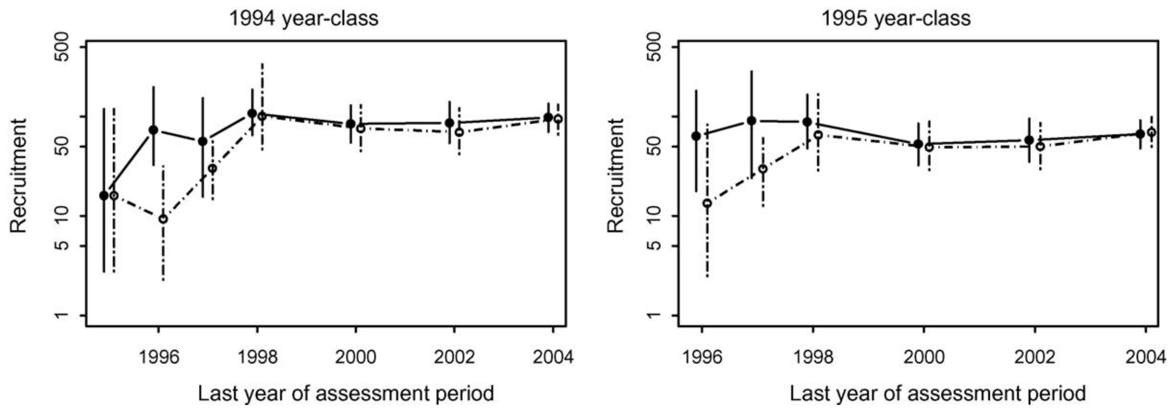

Fig. 6. Retrospective analyses for the posterior median and 95% probability intervals for the number of animals in the 1994 and 1995 year-classes of blue grenadier (points and vertical bars). Results are shown for analyses that use (solid lines) and ignore (dashed lines) the discard data.

the two recruitments tend to increase over time. This occurs because the assessment includes a prior distribution which forces recruitment to be equal to the value expected from the stock-recruitment relationship in the absence of data; the influence of this prior is reduced to effectively nothing as informative data accumulate over time.

3.2. Blue warehou

The years in which there was substantial discarding of blue warehou were 1997, 1998 and 2004 (Fig. 7). Discard data are not available for the years before 1993. However, as the quota system was only implemented in 1992, there is little reason (or indeed evidence) for large scale discarding due to market drivers prior to 1993. The impact of adding the discarded catch to the landed catch is to substantially increase the catches and catch-rates for 1997, 1998 and 2004 (Fig. 7).

Analyses are conducted for blue warehou for two cases: (a) one in which the catches and catch-rates are adjusted by the discard rates and (b) one in which the discard rates are fitted in the same manner as for blue grenadier. The model is able to fit the catch-rate indices irrespective of whether the discards are added to the landed catches or not (Fig. 8). However, the fits to the discard rates for case (b) are very poor (Fig. 9) even though the method used to model discards is essentially identical to that used for blue grenadier, which was able to mimic large changes in discarding over time (Fig. 4). The poor fits are, however, not totally unexpected because discarding of blue warehou is not only due to the availability of small fish, but, more importantly, due to Total Allowable Catches that significantly constrain landed catches. In years with low TACs, but relatively high availability of fish, fishers would have to actively avoid blue warehou to prevent discarding.

Fig. 10 summarizes the posterior distributions for the spawning biomass of blue warehou expressed relative to the 1991 spawning biomass. Forty percent of the 1991 spawning biomass (the dashed line in Fig. 10) has been taken to be a reference point for management of this species (Punt and Smith, 2004). The results for the analysis in which the model is fitted (albeit poorly) to the discard data suggests that the stock is well below this reference point with no evidence for recovery in recent years. In contrast, adding the discards to the catches (and adjusting the catch-rate indices upwards) leads to a much more optimistic appraisal of stock status (above rather than below the reference point).

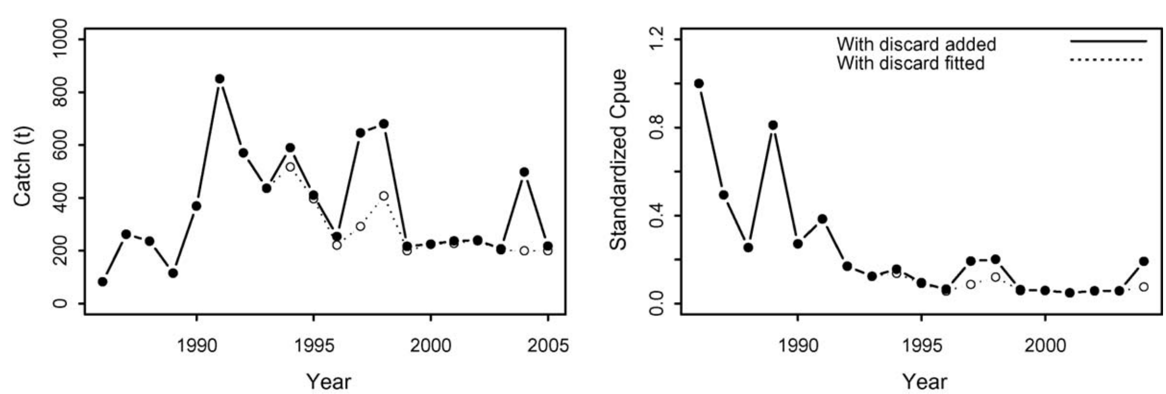

Fig. 7. Catch and catch-rate time series for the western stock of blue warehou. Results are shown for the observed landed catches and when these catches are adjusted by the estimated discards.

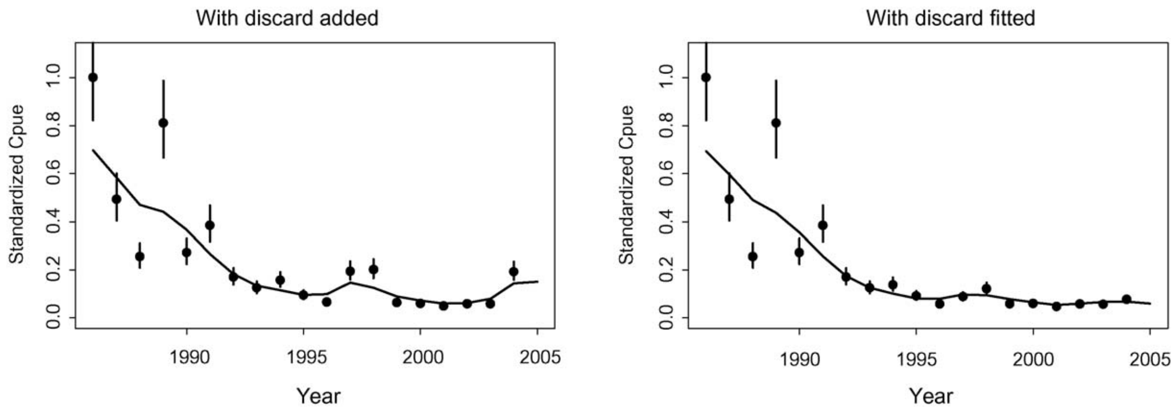

Fig. 8. Fits to the catch-rates indices corresponding to the maximum of the posterior distribution for the two variants of the assessment for the western stock of blue warehou. The vertical bars denote the 95% confidence intervals for the catch-rate indices.

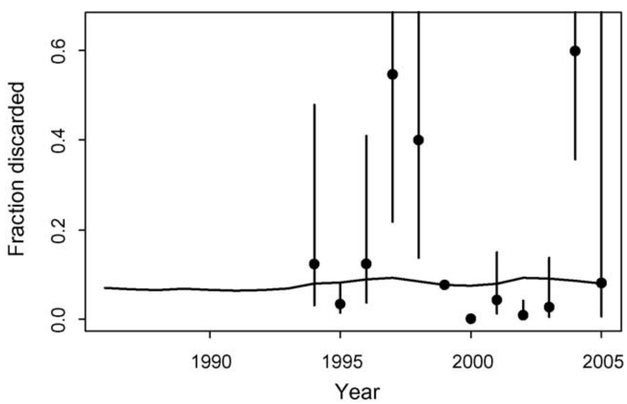

Fig. 9. Fit to the discard rates for the western stock of blue warehou corresponding to the maximum of the posterior distribution for the case when the discards are not added to the catches. The vertical bars denote the 95% confidence intervals for the discard rates.

The current TAC for blue warehou was selected to allow for stock rebuilding following a period of declining catches and catch-rates. However, the level of the TAC is such that it may discourage targeting and increase discarding. Consequently, it is unlikely that catch-rates derived from logbook records reflect abundance. Industry reported that catch-rates in 2004 were considerably higher than in previous years, and considerable discarding was occurring. The results of the analysis that adjusts catch-rates are clearly more consistent with these anecdotal industry observations than the analysis in which the model is fitted to the discard data. If catch-rate is actually proportional to abundance, these results indicate some stock recovery.

3.3. Discussion

The results of this paper indicate the value of making full use of discard data in stock assessments. In the case of blue grenadier, including discard data in the assessment improves the ability to detect strong year-classes prior to their recruiting to the fishery (Fig. 6) while, in the case of the western stock of blue warehou, ignoring the discard data would lead to the conclusion that no recovery of this stock has occurred despite large reductions in the TAC and field-based indications to the contrary. For blue grenadier, the ability to predict the sizes of incoming year-classes (specifically detecting occasional

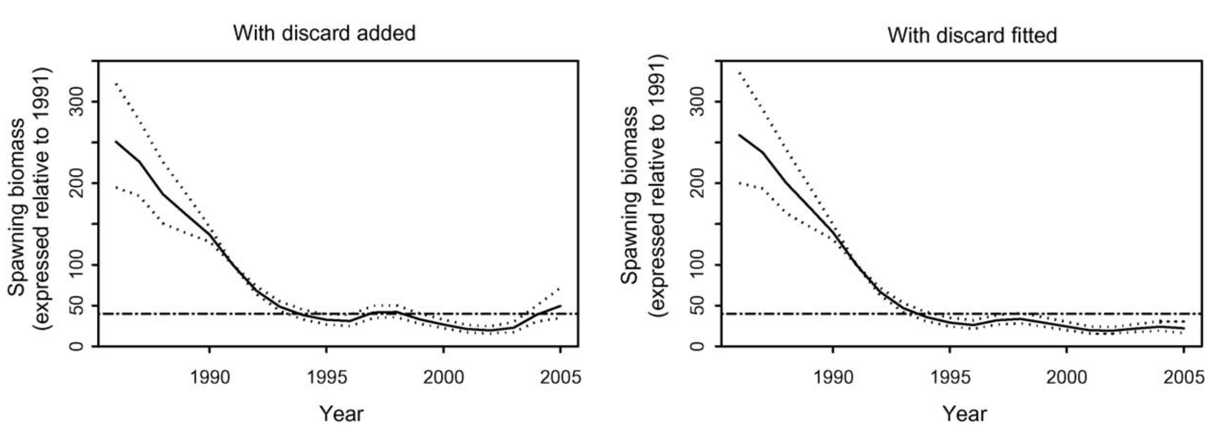

Fig. 10. Posterior distributions (medians and 95% probability intervals) for the time-trajectory of spawning biomass of blue warehou, expressed as a percentage of the spawning biomass in 1991. Results are shown for analyses in which the discards are added to the historical catches (left panel) and in which the model is fitted to discard data (right panel).

strong year-classes) based on the extent of discarding leads to greater certainty regarding likely future catch levels and hence provides industry with an improved ability to plan their operations. In general, however, only short-term catch predictions are impacted markedly by including discard data in stock assessments because the sizes of year-classes spawned several years in the past can be determined from the age-composition data for the landed catches.

Explicitly including discards in assessments should therefore be expected to lead to improved parameter estimates and consequently discards are included in several of the stock assessments conducted in Australia and elsewhere in the world. For example, discarded catch has been an important issue for the U.S. Pacific coast groundfish fishery since the early 1980s when trip limits began to be used to slow the pace of the fishery. Discarding in this fishery occurs due to small fish size, market limits imposed by processors, and regulatory trip limits (Pikitch, 1991). Beginning with the 1988 assessment of sablefish, *Anoplopoma fimbria* (Methot and Hightower, 1988), the Integrated Analysis model used for most of these groundfish assessments (Stock Synthesis; Methot, 1990, 2000, 2006) has incorporated the capability to analyze the effect of discarding on the assessment data. Similar to the model described in this paper for blue grenadier, Stock Synthesis uses a logistic function to partition the total catch size-composition into a discarded and retained component. The partition function has a third parameter to define the asymptotic level of retention, which will be less than 1.0 when marketable fish are discarded due to trip limits. The model can include data on the discard-rate (by weight), and on the size- and age-composition of discarded and retained catches. When the model is supplied with sufficient data, it is possible to estimate the parameters of the retention function within the model. In contrast to the situation for sablefish, the assessment of widow rockfish, *Sebastes entomelas*, off the west coast of the United States (He et al., 2003) increased the landed catches by 16% to account for discarding, primarily owing to regulations related to trip limits.

The results in Figs. 9 and 10 highlight the importance of correctly selecting (and basing the model on) the nature of the discard process; assuming that discarding is driven by the size of fish when it is in fact driven by quota holdings can lead to incorrect inferences regarding trends in stock size (e.g. Fig. 10). The examples considered in this paper were such that discarding could be attributed almost exclusively to either size-based issues or quota-related issues. This is not always the case, however, because some species are discarded for both reasons, as seen, for example, in the SESSF species spotted warehou, *Seriolella punctata* (Thomson, 2001). One way to deal with cases like this is to fit the discard rates and discard age-/length-compositions with a function that determines the probability of discarding that allows for non-zero rates of discarding for all lengths/ages.

In the SESSF, fishery independent surveys are only currently conducted for some species, and fishery-dependent catch-rate indices are used in the assessments of all species. Similar to blue warehou, very low TACs have been set for several other species in the SESSF. This poses the question of how to detect recovery for species when changes in catch-rates reflect a response to the management system rather than to stock abundance. The analyses presented indicate that using robust estimates of discards to adjust catch-rates provides a means of dealing with this problem.

A key assumption of the blue grenadier assessment is that the relationship between the probability of discarding and size has not changed over time and that selectivity has also not changed over time. Selectivity (and the probability of discarding of small fish) could change if the mesh size used in the fishery changed, if the places where the fishery was prosecuted changed, or if market acceptance for small fish, hence the ogive that defines the probability of retaining fish of various sizes, changed. Fig. 11 shows posterior distributions for recruitment for assessments that assume that selectivity has not changed over time and in which the length-at-50%-selectivity increased by 5 cm in 2003, but this is ignored when the assessment is conducted. The results in Fig. 11 suggest that ignoring (or simply not detecting) an increase in the length-at-50%-selectivity can lead to not detecting a strong recruitment (the 2003 recruitment is twice as large when account is taken of the change in selectivity). A reduction in the length-at-50%-selectivity will lead to the opposite effect; the additional discarding caused by the change in selection will initially (incorrectly) be interpreted as there being a strong year-class. Clearly where there are suspected changes in either the selectivity or retention curves over time, it is necessary to consider the possibility that the other curve has changed as well. Some changes in mesh size have occurred in the SESSF, in particular fishers in the western part of the fishery are moving to larger (110 m diamond) mesh to avoid catching smaller blue grenadier. A change in mesh size has not occurred throughout the fishery to date because, in some parts of the fishery, this would lead to loss of access to smaller,

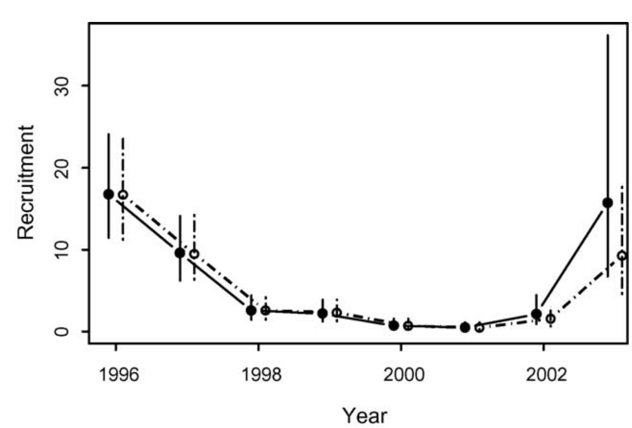

Fig. 11. Posterior distributions (medians and 95% probability intervals) for the time-trajectory of recruitment for blue grenadier for analyses in which selectivity for the non-spawning fishery is assumed to have remained constant over time, and in which a 5 cm increase in the length-at-50%-selectivity occurred in 2003, but was not considered in the assessment.

but commercially valuable, species on which those components of the fishery depend for their profitability (M. Miriklis, Jack Miriklis Marine Pty Ltd., Pers. Commn.). Recently, however, the Management Advisory Committee responsible for the trawl sector has advocated changes to gear, including mesh sizes, to reduce discards (A.D.M. Smith, CSIRO, Pers. Commn.). The changes in mesh size over time will lead in the future to the need to define fleets in terms of mesh size as well as time of the year, as is currently the case.

Including discard data in the assessments leads to a reduction in uncertainty (Fig. 6). However, the approach of adding the discarded catches to the historical catches does not currently allow the uncertainty associated with the estimates of the discarded catches (which can be substantial, e.g. Fig. 9) to be taken into account.

The implementations outlined in this paper are based on there being one fishing sector that discards. However, it is more common for there to be multiple fleets (cf. Eq. (6)), each of which has a different discarding pattern. For example, recreational fisheries may implement a catch-and-release program which could lead to some 'discard' mortality. The approach outlined in this paper can be extended straightforwardly to deal with such cases, as long as there are sufficient data to allow the parameters related to discarding to be estimated.

Finally, although the results of this paper suggest that there may be benefits to using data on discarded catch because, for some species, discarding provides an indication of future recruitment, discarding is clearly a poor use of the resource. It seems likely that, for almost all species, conducting a pre-recruit survey of some sort will be a more appropriate means of collecting data to predict future recruitment.

Acknowledgements

Matt Koopman (PIRVic, Marine and Freshwater Systems, Queenscliff, Victoria) is thanked for providing the data on which Table 1 and Fig. 1 are based. Sally Wayte and Richard Little (CSIRO Marine and Atmospheric Research) and two anonymous reviewers are thanked for comments on an earlier draft of this paper.

References

Alverson, D.L., Freeberg, M.H., Pope, J.G., Murawski, S.A., 1994. A global assessment of fisheries bycatch and discards. FAO Fish. Tech. Pap. 339, 1–233.

Borges, L., Rogan, E., Officer, R., 2005. Discarding by the demersal fishery in the waters around Ireland. Fish. Res. 76, 1–13.

Branch, T.A., 2004. The influence of Individual Transferrable Quotas on discarding and fishing behaviour in multispecies fisheries. Ph.D. Thesis. University of Washington, WA, USA.

Caton, A., McLoughlin, K., 2004. Fishery Status Reports 2000: Status of Fish Stocks Managed by the Australian Government. Bureau of Rural Sciences, Canberra, pp. 1–243.

Copes, P., 1986. A critical review of the Individual Quota as a device in fisheries management. Land Econ. 62, 278–291.

Fournier, D.A., Sibert, J.R., Majkowski, J., Hampton, J., 1990. MULTIFAN: a likelihood-based method for estimating growth parameters and age composition from multiple length frequency data sets illustrated using data for southern bluefin tuna (*Thunnus maccoyii*). Can. J. Fish. Aquat. Sci. 47, 301–317.

Gelman, A., Carlin, J.B., Stern, H.S., Rubin, D.B., 1995. Bayesian Data Analysis. Texts in Statistical Science. Chapman & Hall, New York.

Geweke, J., 1992. Evaluating the accuracy of sampling-based approaches to the calculation of posterior moments. In: Bernardo, J.M., Berger, J., Dawid, A.P., Smith, A.F.M. (Eds.), Bayesian Statistics 4. Oxford University Press, Oxford, pp. 169–193.

Haddon, M., Thomson, R., 2005. Standardized commercial catch-effort data for selected shelf and slope Assessment group species. Document submitted to the 30 June and 1 July meetings of SlopeRAG. p. 32 (Available on request from the Australian Fisheries Management Authority, Canberra.).

He, X., Ralston, S.V., MacCall, A.D., Pearson, D.E., Dick, E.J., 2003. Status of the widow rockfish resource in 2003. Pacific Fishery Management Council, 2130 SW Fifth Ave, Suite 224, Portland, OR 97201.

Heidelberger, P., Welch, P.D., 1983. Simulation run length control in the presence of an initial transient. Oper. Res. 31, 1109–1144.

ICES, 2004. Report of the ICES Advisory Committee on Fishery Management and the ICES Committee on Ecosystems. ICES Advice 1 (2), 1–1520.

Kelleher, K., 2004. Discards in the world's marine fisheries—an update. FAO Fish. Tech. Pap. 470, 1–152.

Knuckey, I.A., Liggins, G.W., 1999. Focussing on bycatch issues in Australia's South East Fishery. In: Buxton, C., Ayers, S. (Eds.), Establishing Meaningful Targets for Bycatch Reduction in Australian Fisheries. Australian Society for Fish Biology Workshop. Hobart, September 24–25, 1998, pp. 46–55.

Knuckey, I.A., Grieve, C., Smith, D.C., 1999. Evolution of the integrated scientific monitoring programme in Australia's South East Fishery. In: Nolan, C.P. (Ed.), Proceedings of the International Conference on Integrated Fisheries Monitoring. FAO, Rome, pp. 231–248.

Liggins, G.W., Knuckey, I.A., 1999. Factors affecting discarding in the South East Fishery. In: Buxton, C., Ayers, S. (Eds.), Establishing Meaningful Targets for Bycatch Reduction in Australian Fisheries. Australian Society for Fish Biology Workshop. Hobart, September 24–25, 1998, pp. 56–71.

Liggins, G.W., Bradley, M.J., Kennelly, S.J., 1997. Detection of bias in observer-based estimates of retained and discarded catches from multi species trawl fishery. Fish. Res. 32, 133–147.

Maunder, M.N., Punt, A.E., 2004. Standardization of catch and effort data: a review of recent approaches. Fish. Res. 70, 141–159.

Methot, R.D., 1990. Synthesis model: an adaptable framework for analysis of diverse stock assessment data. Int. N. Pac. Fish. Comm. Bull. 50, 259–277.

Methot, R.D., 2000. Technical Description of the Stock Synthesis Assessment Program. NOAA Tech memo NMFS-NWFSC-43, p. 46.

Methot, R., 2006. User Manual for the Integrated Analysis Program Stock Sythesis 2 (SS2). Model Version 1.23a.

Methot, R.D., Hightower, J., 1988. Status of the Washington–Oregon–California sablefish stock in 1988. In: Status of the Pacific coast groundfish fishery through 1988, recommended acceptable biological catches for 1989. Pacific Fishery Management Council, Portland Oregon 97201.

Pikitch, E.K., 1991. Technological interactions in the U.S. West Coast groundfish fishery and their implications for management. ICES Mar. Sci. Symp. 193, 253–263.

Punt, A.E., Smith, D.C., 2004. Stock assessment of blue warehou (*Seriolella brama*) based on data up to 2003. In: Tuck, G.N., Smith, A.D.M. (Eds.), Stock Assessment for the South East and Southern Shark Fishery. FRDC report 2001/005, CSIRO, Hobart, pp. 49–120.

Punt, A.E., Smith, D.C., Thomson, R.B., Haddon, M., He, X., Lyle, J.M., 2001. Stock assessment of the blue grenadier *Macruronus novaeze-*

landiae resource off south-eastern Australia. Mar. Freshw. Res. 52, 701–717.

Punt, A.E., Smith, A.D.M., Cui, G., 2002. Evaluation of management tools for Australia's South East Fishery. 2. How well do commonly-used stock assessment methods perform? Mar. Freshw. Res. 53, 631–644.

Raftery, A.E., Lewis, S., 1992. How many iterations in the Gibbs sampler? In: Bernardo, J.M., Berger, J., Dawid, A.P., Smith, A.F.M. (Eds.), Bayesian Statistics 4. Oxford University Press, Oxford, pp. 763–773.

Smith, A.D.M., Smith, D.C., 2001. A complex quota-managed fishery: science and management in Australia's South East Fishery. Introduction and Overview. Special Issue: A Complex Quota-managed Fishery: Science and Management in Australia's South East Fishery. Mar. Freshw. Res. 52, 353–359.

Smith, D.C., Smith, A.D.M., Punt, A.E., 2001. Approach and process for stock assessment in the South East Fishery, Australia: a perspective. Mar. Freshw. Res. 52, 671–681.

Talman, S., Hamer, P., Robertson, S., Robinson, N., Skinner, A., Smith, D.C., 2003. Stock structure and spatial dynamics of the warehou: a pilot study. Final report of FRDC Project 2001/004, PIRVic, Marine and Freshwater Systems, Queenscliff.

Thomson, R., 2001. Spotted warehou (*Seriolella punctata*). In: Thomson, R., He, X. (Eds.), Modelling the Population Dynamics of High Priority SEF Species. Report of FRDC project 1997/115, CSIRO Hobart, pp. 82–113.

Tilzey, R.D.J. (Ed.), 1994. The South East Fishery. Bureau of Resource Sciences, Canberra, pp. 1–360.

Tuck, G.N., Smith, A.D.M., 2004. Stock assessment for the south east and southern shark fishery. Report of FRDC project 2001/005, CSIRO Hobart, pp. 1–412.

Tuck, G.N., Thomson, R.B., Smith, D.C., Talman, S., Punt, A.E., 2004. Stock assessment for blue grenadier (*Macruronus novaezelandiae*) based on data up to 2003. In: Tuck, G.N., Smith, A.D.M. (Eds.), Stock Assessment for the South East and Southern Shark Fishery. FRDC report 2001/005, CSIRO, Hobart, pp. 11–47.

Williams, E.H., 2002. The effects of unaccounted discards and misspecified natural mortality on harvest policies based on estimates of spawners per recruit. N. Am. J. Fish. Manage. 22, 311–325.