SIZE-SELECTIVITY OF BRITISH COLUMBIA’S SABLEFISH (ANOPLOPOMA FIMBRIA) FISHERIES AND IMPLICATIONS FOR THE ECONOMIC LOSSES ASSOCIATED WITH DISCARDING

by

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ABSTRACT

I used multiple mark-recapture experiments for British Columbia (B.C.) sablefish (Anoplopoma fimbria) to estimate size-selectivity functions for three commercial gear types employed in the B.C. sablefish fishery: (i) trap, (ii) trawl, and (iii) longline gear. Notable differences in selectivity were observed among gear types with the longline fishery selecting for large sablefish, the trap fishery selecting for intermediate-sized sablefish, and the trawl fishery selecting for small sablefish below the minimum size limit. Empirical estimates of gear selectivity were incorporated into yield-per-recruit (YPR) and spawner biomass-per-recruit models to evaluate the effects of at-sea discarding on long-term fishery yield. My results suggest that up to 49% of the total YPR is potentially lost because of at-sea discarding. Fishery regulations that minimize tx©LdFupdL FugdL Fu

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The collection of unbiased fishery-dependent data is critical to the development of robust harvest strategies for commercially exploited fish stocks. Commercial catch statistics must reflect all fishery removals from the stock, including the mortality of the discarded bycatch, which are fish caught during the fishing process that were not specifically targeted for harvest (FAO 2008). Accounting for the mortality of discarded fish can be difficult, particularly when a species is harvested by a number of gear types and in a variety of fisheries. In the directed B.C. sablefish fishery, for example, both traps and hooks are used to harvest sablefish. Additional sablefish are harvested in the non-directed trawl fishery and as bycatch in other hook and line fisheries (DFO 2007). While some sablefish bycatch is landed and recorded in catch statistics, some is released at-sea because of legal requirements and/or market/economic considerations (FAO 2008).

A formal evaluation of the impacts of discarding on long-term fishery yield and revenue requires a basic understanding of the size-selectivity of commercial fishing gears (Chen and Gordon 1997). Selection ogives, describing how fishing mortality varies with age or size, are generally estimated for each gear type in a fishery using direct or indirect methods (Millar and Fryer 1999; Clark and Kaimmer 2006). When the selective properties of commercial fishing gears are known, in addition to information on growth and mortality, quantitative population models can be used to evaluate potential losses in yield and revenue that result from at-sea discarding (Chen and Gordon 1997).

A number of alternative models are available to describe the response of exploited fish stocks to at-sea discarding, including biomass stock dynamics (Hilborn and Walters 1992). Biomass

Gear selectivity

Gear selectivity is a particularly important input into per-recruit models because it determines the probability of a fish dying before it reaches peak biomass-per-recruit and peak spawning output. When a sufficient understanding of gear selectivity is in place, fishery managers can better detect, and ideally avoid, growth and recruitment overfishing. Growth overfishing refers to a situation in which fish are removed from the population while they are still growing rapidly while recruitment overfishing refers to a scenario in which the spawning stock is reduced such that a sufficient number of recruits to the fishery is no longer produced (Walters and Martell 2004).

Gear selectivity is most commonly estimated using indirect methods, such as comparative catch studies, in which size distributions of catches among different gear variants are used to infer the relative selectivity of each gear type (e.g., Millar 1992; Suuronen and Millar 1992; Walsh et al. 1992; Millar and Fryer 1999). In comparative approaches, the selectivity of the gear and the size distribution of the population are estimated simultaneously and no prior knowledge of the size distribution of the stock is required (Millar and Fryer 1999). While such indirect experiments can provide valuable information on the relative selectivity of various gear types, unless the true size distribution of the population is known, comparative catch studies cannot be used to determine the functional form of the relationship between size and susceptibility to capture (Millar 1995; Myers and Hoenig 1997; Clark and Kaimmer 2006).

Direct estimates of selectivity are possible where the size structure of the population is known or can be reliably estimated through designed experiments, such as mark-recapture studies, in which animalsLeF9d-8kgYLsFupd_9__L YLtFu9d-g88YLeF9d-8kg_xpsFupd

2005a) producing an average annual landed value of CDN $26 million (MFCR 2001; MAFF 2001; MAFF 2002; MOE 2004). Sablefish, also referred to as black cod (AAC 2007), are endemic to the North Pacific Ocean (Allen and Smith 1988). Adult sablefish are generally found within 1 m of the ocean floor (Kreiger 1997) at depths greater than 200 m, although some sablefish have been captured at depths greater than 1,500 m (AAC the CSA makes annual financial contributions towards various management and assessment activities for B.C. sablefish including biological studies, enforcement activities, tagging experiments, and stock assessments (DFO 2007). The fishery is managed using a total allowable catch (TAC) that is set annually based on assessment and yield recommendations identified by the Pacific hook fishery (hereafter referred to as the longline fishery) operates in much shallower

CHAPTER 2

ESTIMATING THE SIZE-SELECTIVITY OF B.C.’S SABLEFISH (ANOPLOPOMA FIMBRIA) FISHERIES

Introduction

(Myers and Cadigan 1995) and led to the overestimation of spawning stock biomass (Myers et al. 1997). Erroneous assumptions regarding the size-selectivity of bottom trawlers has since been identified as a key factor in the collapse of Atlantic cod stocks in Eastern Canada (Myers et al. 1997) and an important parameter to estimate for all commercially exploited fish stocks.

This study had two primary objectives: (i) to quantify the relationship between body length and the probability of capture for tagged sablefish harvested in the B.C. sablefish fishery and (ii) to identify differences in size-selectivity among the three gear types. To accomplish these objectives, I used mark-recapture data to generate direct estimates of selectivity by length for each gear type in the fishery. Three candidate models of selectivity (asymptotic, exponential, and dome-shaped) were considered and estimation and statistical tests were used to determine the best model fit to the data.

Methods

Model development

Size-selectivity functions were estimated from multiple mark-recapture experiments conducted on B.C. sablefish during the ten-year period between 1995 and 2004 (Table 1). A tagging experiment was defined as all sablefish released in a given length class in a given year. Releases of tagged sablefish were divided into 5 cm classes between 30 cm and 95 cm fork length (all length classes hereafter refer to fork length). Minimum recapture sample size requirements were calculated for each length category l, gear type g, and year y based on pre-determined limits of error δ (Appendix). Recoveries were required in a minimum of three length classes in each year and only tags recovered within one year of release were considered in order to minimize the effects of growth and natural mortality during the time at liberty (Myers and Hoenig 1997).

Following the method of Myers and Hoenig (1997), the expected value of the reported catch of tagged fish, $E[C_{y,l}]$, is (notation for gear type g is omitted),

(1) $E[C_{y,l}] = {}_{y,l}\ \pi_{y,l}$,

where ${}_{y,l}$ is the total number of sablefish released in each length class and $\pi_{y,l}$ is the capture probability of a tagged fish in length class l.

If I assume that the probability of capture is the same for all fish of a given length and that the recoveries of tagged fish are independent of one another and occur at random during the course of the fishery, then the capture probability of a tagged fish can be separated into year- and length-based components, i.e.,

(2) $\pi_{y,l} = S_{y,l} U_y R_y$,

where $S_{y,l}$

$$(4) \qquad S_{y,l}^{asy} = \frac{1}{1 + e^{-\beta(l - L_{50})}} \ ,$$

where L_{50} is the length at which capture probability is 50% of the maximum U_y' and β is the steepness of the function at L_{50}. At sizes $l \gg L_{50}$, relative vulnerability approaches a constant maximum value of one indicating that large fish are equally vulnerable to harvest regardless of size.

In some cases, selectivity may decline as fish approach very large sizes due to either behavioural avoidance of the gear, natural factors such as spawning or migration that cause fish to leave the exploited areas (Özbilgin and Wardle 2002), or economic factors that discourage vessels from reporting large tagged fish (Haist et al. 2001). For instance, visual inspection of tag recoveries by length class indicated potential dome-uYLaFx9LeF9d9_--

tag recapture data instead. The exponential model, $S_{y,l}^{exp}$

for inclusion in the final sample. This thinning step was performed to reduce the effects of autocorrelation within the MCMC chain. I summarized the resulting marginal posterior distributions for management parameters of interest using the 2.5th, 50th, and 97.5th percentiles and posterior standard deviations.

Model checking

Identifying systematic and isolated discrepancies of the data from the fitted values is an important part of assessing the adequacy of a model for a particular data set. Deviance residuals, $r_{y,l}$, used in model checking were calculated as,

$$(8) \qquad r_{y,l} = \operatorname{sgn}(O_{y,l} - \pi_{y,l})\sqrt{d_{y,l}} \ ,$$

where

$$d_{y,l} = 2\sum_{l=1}^{L}(O_{y,l}\log(O_{y,l}/E[C_{y,l}]) + (\quad {}_{y,l} - O_{y,l})\log\left(\frac{\quad {}_{y,l} - O_{y,l}}{\quad {}_{y,l} - E[C_{y,l}]}\right),$$

$O_{y,l}$ is the observed recoveries of tagged fish in each length class l, $E[C_{y,l}]$ is the expected catch of a tagged fish, and $\quad {}_{y,l}$ is the number of fish tagged and released in each length class in a given year.

which proposes that the model with the fewest number of parameters is the optimal

Results

Sparse tag recoveries for certain year and gear combinations (Table 2) resulted in some years falling short of the minimum data requirements and thus their exclusion from the analysis. For example, in January 2002 a coast-wide closure of the B.C. sablefish fishery was imposed mid-way through the 2001/2002 fishing year (DFO 2003) and thus, all gear types recovered significantly fewer sablefish in 2002. Low tag recoveries by the longline fishery in 1995, 2001, 2003, and 2004 also resulted in these years being excluded from the analysis. In the trawl fishery, the relatively low number of tags reported in 1998, 2000, 2002 – 2004 precluded robust estimates of selectivity in these years.

The asymptotic model provided the best fit to the observed tag recovery data for the longline fishery in all years considered (Figure 3). Deviance residuals indicated no outliers or isolated departures from the model (Figure 4). Longline selectivity patterns increased rapidly between 50 cm and 65 cm and slowl with length up to between 60 cm and 65 cm before decreasing, with the size at 50% de-selection occurring, on average, at 72 cm (Table 4). Estimated values of L_{50} were slightly smaller for the commercial trap fishery relative to the longline fishery with mean L_{50} = 53 cm. The exceptions to this pattern were 1999 and 2004, in which an asymptotic model provided the best fit to the observed trap tag recovery data. The trap fishery was the only case in which the preferred selectivity model changed with time. MCMC parameter estimates did not converge for the dome-shaped model and are therefore not shown in Table 4.

An exponential model provided the best fit to tag recovery data for the trawl fishery across all years (Figure 7). Deviance residuals indicate a good fit to the exponential model (Figure 8). However, in contrast to the trap and longline fisheries, the highest vulnerabilities in the trawl fishery were observed in the smallest length classes with the average L_{50} = 24 cm (Table 5). In all years, trawl selectivity declined after approximately 60 cm, indicating the decreased vulnerability of larger sablefish to capture by trawl gear.

Discussion

Gear selectivity

Gear selectivity is of fundamental importance to fisheries stock assessment and management. Identifying the size-selectivity of commercial fishing gears, and how selectivity parameters change over time, allows fishery managers to assess the impacts of commercial fishing on an exploited fish stock and develop meaningful gear regulations for a fleet. Using direct estimates of gear selectivity from tagging experiments, I demonstrated differences in size-selectivity for B.C. sablefish among gear types as evidenced by the shape of the selectivity function and the length at 50% selection.

Gear selectivity patterns predicted for the longline fishery were similar to those observed in Alaska and Washington State, where asymptotic selectivity is commonly used to represent longline selectivity (Hanselman et al. 2005). In the trawl fishery, the pattern of selectivity was hyperbolic over the range of size classes observed with an exponential selectivity model providing the best fit to the tag recovery data. In contrast to the trap and longline fisheries, trawl selectivity declined dramatically for larger sablefish (> 60 cm), demonstrating the reduced vulnerability of large sablefish to towed gears. While estimates of L_{50} are slightly higher in the Alaskan trawl fishery (L_{50} = 40 cm; Hanselman et al. 2005), a similar decline in the vulnerability of large sablefish to trawl capture is also apparent in the Alaskan fishery (Hanselman et al. 2005). In Alaska, the reduced vulnerability of large sablefish to trawl gear is attributed, in part, to the operation of the trawl fleet in shallower waters where young sablefish reside (Hanselman et al. 2005).

trawl fishery tends to operate in shallow waters between 100 m and 200 m (DFO 2005), while the trap and longline fisheries generally operate in depths greater than 200 m. The spatial and depth distribution of the fleet is therefore likely to account for some of the variation in size-selectivity observed among gear types (Haist et al. 2001; Clark and Kaimmer 2006; Jacobson et al. 2001).

A similar decline in selectivity of large sablefish was also observed in the trap fishery in seven out of the nine years considered. A number of fishery-related mechanisms potentially explain the decline in selectivity for larger fish including spatial and depth factors (mentioned above), targeting behaviours, market considerations, In the B.C. sablefish fishery, it is possible that the trap fishery is targeting areas and depths inhabited by more abundant intermediate size-classes in order to maximize catch rates. While similar targeting behaviours may also be present in the trawl and longline fisheries, targeting is less likely in these fisheries because these gear types generally harvest sablefish in conjunction with other groundfish species, which reduces the chances that a single size class will be targeted within a given trip. A price premium for larger sablefish may also encourage fishermen to misreport catches of larger tagged sablefish resulting in an apparent ‘decline’ in selectivity for larger sablefish (Haist et al. 2001). Although tag reporting was assumed to be independent of the length of a fish, an evaluation of tag reporting compliance would greatly improve interpretation of model results.

A rapidly descending right hand limb in the dome-shaped selectivity function could also represent fish that actively avoid trap or trawl gear. Previously captured fish may become ‘gear-shy’ and actively avoid the gear. Furthermore, spawning events or migration may also place large sablefish in unfished areas (Özbilgin and Wardle 2002). Unfortunately, disentangling the reasons for the observed decline in selectivity at length in the trap and trawl fisheries trap fishery remains a difficult task.

Consequences of observed selectivity patterns

When all size-classes are equally vulnerable to the fishery, annual harvesting can lead to growth overfishing, a process in which fish are removed from the population while they are still growing rapidly (Walters and Martell 2004). In such cases, heavy fishing mortality on pre-recruits can lead to a waste of potential biomass by taking fish that would otherwise generate greater yields if they were allowed to grow larger prior to becoming vulnerable to the fishery (Armstrong et al.1990; Walters and Martell 2004).

My analysis found that 50% of the population became vulnerable to the trawl fishery at 24 cm. Female sablefish generally reach sexual maturity at approximately 61 cm fork length (Love 1996) causing a high proportion of immature female sablefish to be recruited to the trawl fishery. Current management regulations prohibit the retention of sablefish less than 55 cm fork length (DFO 2007) resulting in a large number of undersize sablefish being discarded at-sea. The mortality of discarded sablefish is highly variable and dependent on a suite of physical, biological, and environmental factors (Davis 2002; Davis et al. 2002). Research suggests, however, that smaller fish experience

help to prevent unrealistic selectivity functions in certain years where sparse tag recoveries occur (Gazey and Staley 1986).

Another useful extension of this analysis would involve an examination of tag recoveries by the annual sablefish research and assessment survey to determine whether the observed decline in selectivity in the commercial trap fishery also occurs for fishery-

(Pollock et al. 2002), and planted tags (Hearn et al. 2003). Recent technological innovations, such as Passive Integrated Transponder (PIT) tags (e.g., Pengilly and Watson 1994), coded-wire tags (Jefferts et al. 1963), and genetic tagging methods

Conclusion

Mark-recapture experiments provide an effective means of obtaining direct and reliable estimates of gear selectivity. Knowledge of gear selectivity is critical to the success of fishery regulations especially where gear regulations, such as minimum mesh sizes in trawl and seines, are designed to minimize the capture of small fish and reduce the losses associated with discard mortality. Analysis of tagging data can also yield other useful information on exploited fish stocks including estimates of total mortality (Brownie et al. 1985), population size (Haist and Hilborn 2000), and movement rates (Myers and Hoenig 1997). Unfortunately, post-hoc analyses of tagging databases are rarely conducted and valuable information on the fishery is often overlooked (Myers and Hoenig 1997).

Tables

Table 3 Parameter estimates and AIC values for asymptotic model fits to trap and longline tag release and recovery data. Values in parentheses are the posterior standard deviations for the maximum likelihood parameter estimates.

			L_{50}					
Year	Gear	U_y'	MLE	0.025	0.50	0.975	β	AIC
1996	L	0.014(0.002)	63	57	67	93	0.15(0.04)	2139
1997	L	0.012(0.002)	56	50	55	62	0.30(0.15)	1827
1998	L	0.017(0.004)	60	56	62	81	0.18(0.06)	1537
1999	L	0.030(0.003)	54	51	56	66	0.20(0.07)	4597
2000	L	0.024(0.002)	55	53	55	58	0.33(0.08)	3595
1995	Tr	0.086(0.09)	51	50	51	52	0.40(0.09)	8476
1996	Tr	0.050(0.003)	50	28	47	50	2.4(2.25)	14155
1997	Tr	0.140(0.002)	49	42	47	50	2.3(2.91)	27608
1998	Tr	0.082(0.003)	49	51	53	54	0.22(0.03)	11158
1999	Tr	0.110(0.005)	53	51	54	55	0.23(0.04)	11344
2000	Tr	0.073(0.007)	60	58	60	62	0.29(0.03)	

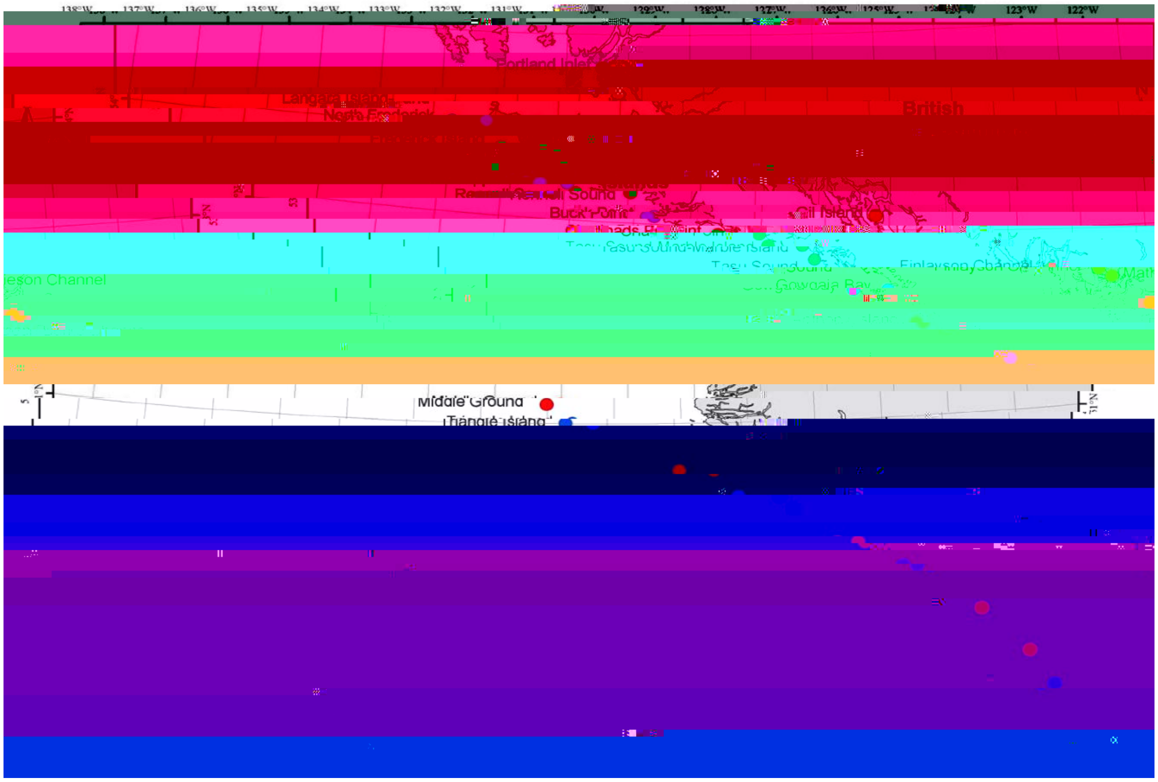
Table 4 Parameter estimates and AIC values for dome-shaped mode

Table 5 Parameter estimates and AIC values for exponential model fits to trawl tag release and recovery data. Values in parentheses are the posterior standard deviations for the maximum likelihood parameter estimates.

Year	Gear	$U^{'}$ (sd)	β (sd)
1997	Trawl	0.107(0.03)	0.010(0.002)
1999	Trawl	0.07(0.03)	0.010(0.002)
2001	Trawl	0.085(0.02)	0.020(0.002)

Figures

Figure 1 Location of sablefish tag releases between 1995 and 2004.



Source: Wyeth and Kronlund (2003)

Figure 2 Length frequencies of sablefish tag releases between 1995 and 2004. Length classes denote the length at release and ‘y’ and ‘

Figure 3 Relative selectivity-at-length for the commercial longline fishery. The solid lines represent asymptotic model fits and the solid circles represent the observed relative vulnerabilities for a given length class.

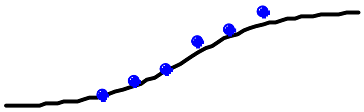


Figure 6 Deviance residuals by length for dome-shaped model fits for the commercial trap fishery.

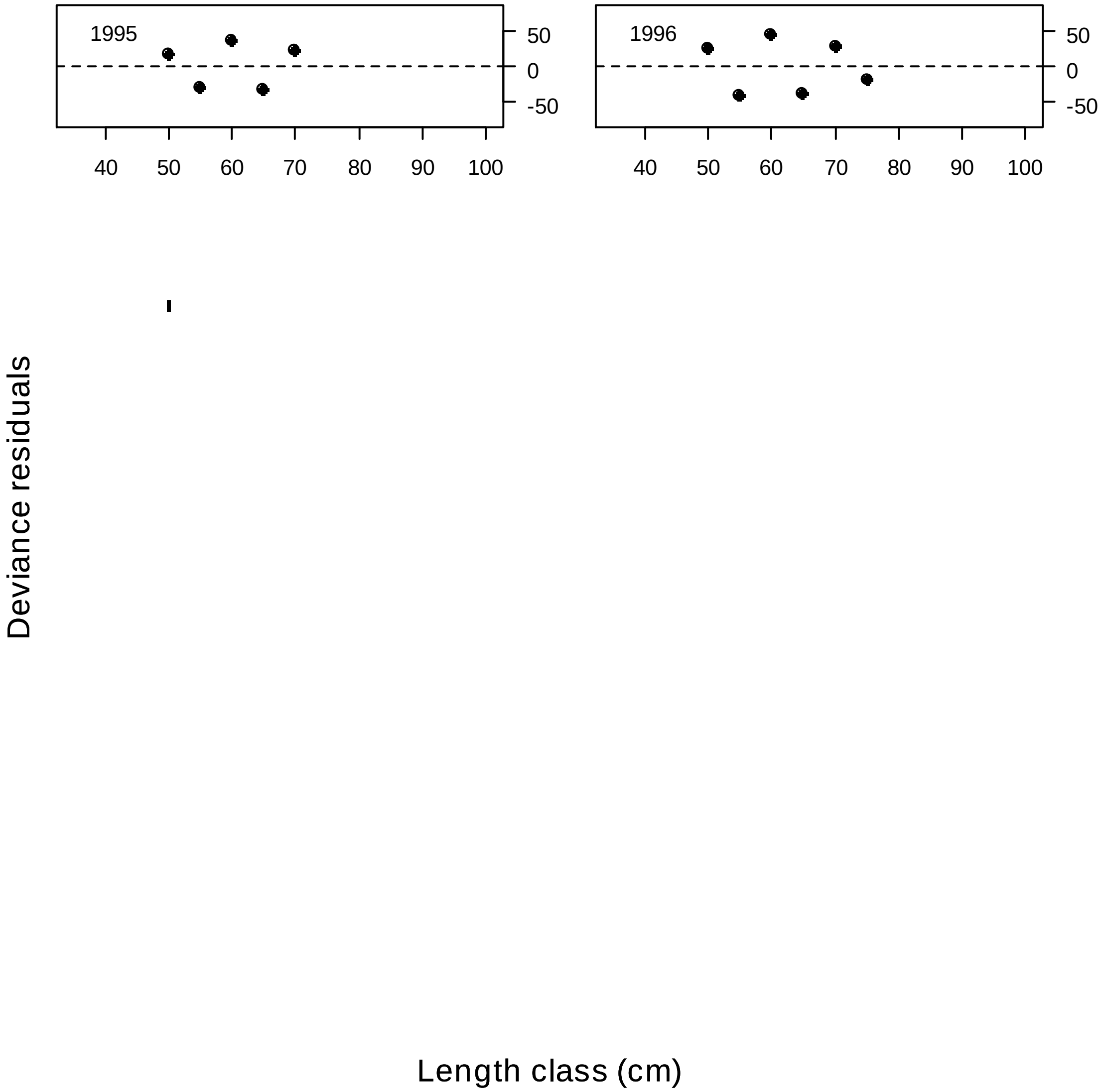


Figure 7 Relative selectivity-at-length for the commercial trawl fishery. The solid lines represent exponential model fits and the solid circles represent the observed relative vulnerabilities for a given length class.

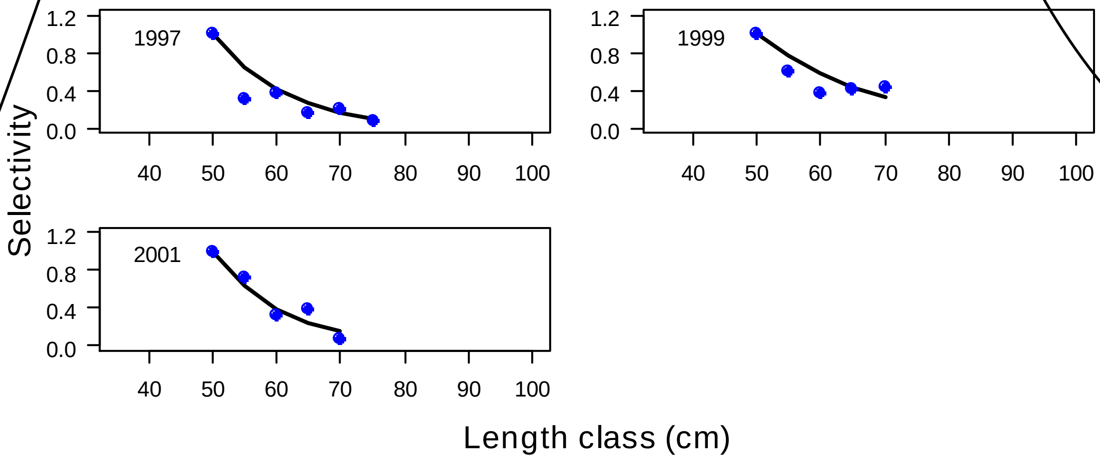
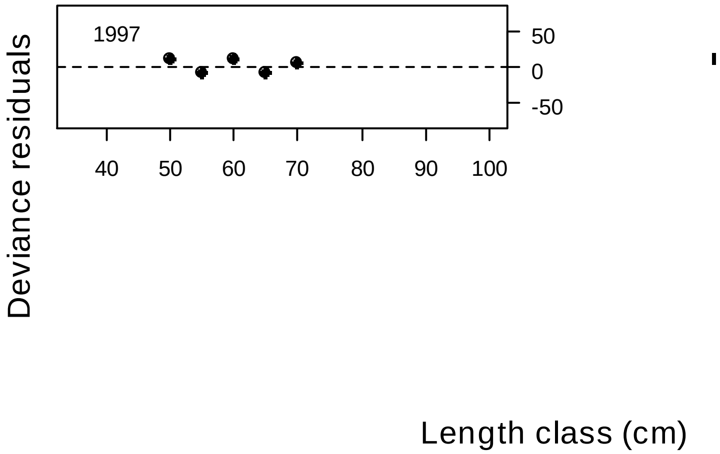


Figure 8 Deviance residuals by length for exponential model fits for the commercial trawl fishery.



CHAPTER 3
BIOLOGICAL AND ECONOMIC IMPACTS OF DISCARDING ON B.C.'S SABLEFISH FISHERIES

Abstract

In many fisheries, a portion of the total catch is discarded at-sea because of legal requirements, market preferences, or economic considerations. High mortality of the discarded catch can lead to substantial losses in fishery yield and value for commercial fisheries. I examined the impacts of at-sea discarding for the B.C. sablefish (Anoplopoma fimbria) fishery using empirical estimates of gear selectivity. Yield-per-recruit (YPR) and spawner biomass-per-recruit (SBPR) calculations were used to evaluate economic and biological losses for three discard mortality scenarios in which (i) all of the discarded catch survives, (ii) all of the discarded catch dies, but discards are still included in estimates of YPR and SBPR, or (iii) all of the discarded catch dies and is ignored in estimates of YPR and SBPR. Expected losses of YPR and SBPR resulting from at-sea discarding were substantial for the B.C. sablefish fishery. Forty-nine percent of y49HgH[áA}LfFu- ooupe

Introduction

together with adjustments allowing for subsequent reductions in discarding, indicates that current levels of discarding are approximately 20 million tonnes, or 25 percent of the reported annual production from marine capture fisheries (Kelleher 2004). If the mortality of discarded sablefish is high, the exclusion of discards from fishery assessments can lead to biased abundance estimates and large losses in fishery yield and revenue for the B.C. sablefish fishery (Pikitch 1987; Chen and Gordon 1997; Rahikainen et al 2004; Helfman 2007). Persistently failing to monitor and account for the discarded catch in estimates of total fishing mortality can also mask potential declines in stock abundance (Myers et al. 1997; Rahikainen et al. 2004) and lead to the over-exploitation of sablefish resources (Myers et al. 2000).

Considerable research has focused on estimating discard mortality rates for a wide range of species harvested by a variety of gear types (e.g., Olla et al. 1997; Davis et al. 2001; Davis 2002; Davis and Olla 2002; Davis and Parker 2004). Some of these studies (soak and trawl times), temperature, season, and a host of other factors (Olla et al. 1997; Davis 2002). The importance of exposure to elevated temperature following capture has been demonstrated in a number of studies, all of which indicate that rapid increases in temperature can magnify physiological changes and mortality, particularly for juvenile fish which generally experience more behavioural impairments and higher mortality rates relative to larger fish (Neilson et al. 1989; Richards et al. 1995; Milliken et al. 1999; Davis et al. 2001; Parker et al. 2003; Davis and Parker 2004). Rapid increases in temperature can induce mortality directly or indirectly by diminishing the capability to deal with basic ecological challenges such as food acquisition and predator avoidance (Olla et al. 1980; Schreck et al. 1997). When these behavioural impediments are added to the stress induced by capture, temperature can exert a potent influence on survival and induce acute levels of stress and mortality beyond that associated with capture processes alone (Olla et al. 1998). For demersal species such as sablefish, rapid changes in temperature are common during the gear retrieval process, particularly in the Pacific northwest Ocean where sharp thermoclines are present (Hunter et al. 1989; Tully 1964; Huyer 1977). The effects of temperature may be even more acute in years when an El Niño is present and warmer sea water temperatures follow climatic shifts (Huyer and Smith 1985).

In this chapter, I develop length-based models of yield-per-recruit (YPR) and spawner biomass-per-recruit (SBPR) to explore the impacts of at-sea discarding on biological and economic yields from the B.C. sablefish (Anoplopoma fimbria) fishery. The objective of this chapter was to use empirical estimates of selectivity, calculated in Chapter 2, to quantify the potential bias in YPR and SBPR estimates that ignore the

Methods

YPR and SBPR models incorporate the interplay between growth and survival to predict the lifetime yield from a cohort under different combinations of fishing mortality and selectivity (Punt 1992). Tracking three state variables, numbers-at-age, length-at-age, and weight-at-length through time for a single cohort, YPR and SBPR models describe the dynamics of a cohort during its lifespan in a fishery (Chen and Gordon 1997). Most YPR analyses use an age-structured model to track the size and numbers of a cohort over its lifetime. In an age-structured model, time is divided into equal discrete steps so that in early stages of growth fish of several different sizes are lumped together (Chen and Gordon 1997). In contrast, length-based models of YPR divide time into intervals spent in each length class. Because fishery processes such as discarding are more correlated with length than with age (Hilborn and Walters 1992), a length-based model was considered appropriate for an analysis of the effects of at-sea discarding.

Model development

Sablefish lengths were divided into 1 cm length classes, j, between L_1 = 35 cm and

$S_{j,g}$ is a gear-specific selectivity schedule, F_g

where

Because YPR and SBPR analyses require a single selectivity-at-length function as model inputs, the observed tag recovery data described in Chapter 2 was pooled across all years for each gear type. As in Chapter 2, two candidate models of selectivity (asymptotic and dome-shaped) were fitted to the pooled tag recoveries for the trap and longline fisheries and an exponential model was fitted to the pooled trawl tag recovery data. A small sample Akaike's Information Criterion was used to identify a single preferred model for each gear type (Table 7).

Model scenarios

The YPR and SBPR models shown above were modified to provide an indication of how YPR and SBPR change under three different assumptions about discard mortality.

Pseudo scenario

The first scenario, referred to as the "pseudo" discard scenario (Chen and Gordon 1997), optimisticall ir 8kp-LiFu©dpp©_YLoFkxg©xLoFupdk-Y8xkx-x©_©LiFé[±

Onboard scenario

The second scenario, referred to as the “onboard” discard scenario, models yield-per-recruit by including both the landed and discarded catches (Chen and Gordon 1997). Onboard YPR and SBPR were calculated using Equations 3 and 4, respectively; however, in contrast to the pseudo YPR and SBPR equations, $P_{j,g} = 0$ in the onboard YPR and SBPR models such that all fish (both landed and discarded) are subjected to the full-

Potential economic loss per-recruit, E_{IPL}, was calculated by replacing $Y_{onboard}^{max}$ with Y_{pseudo}^{max} in Equation 11. Given that the landed YPR scenario is most applicable to the B.C. sablefish fishery, potential biological and economic loses caused by at-sea discarding are best reflected by the IPL and the E

Results

Baseline yield-per-recruit

At low fishing mortality rates between 0.0 and 0.05, maximum differences in yield-per-recruit among the three scenarios were less than 25% (Figure 9). However, these differences became large as fishing mortality increased ($F > 0.05$), with the largest differences being observed between the pseudo and landed YPR scenarios at $F \geq 0.55$.

The landed YPR, which resulted in the smallest yields for a given level of fishing mortality, was dome-shaped with rapidly decreasing YPR at $F > 0.20$. The fishing mortality rates required to obtain Y^{max} were also the lowest in the landed YPR scenario relative to the onboard and pseudo discard scenarios. In contrast to the landed discard scenario, YPR was asymptotic for the pseudo and onboard scenarios. Under these scenarios, yield-per-recruit increased rapidly with increasing fishing mortality before decreasing marginally at fishing mortalities greater than F^{max}. The pseudo discard scenario produced the largest estimate of YPR and SBPR for a given level of fiuututg

At a fishing mortality rate of F

Under an asymptotic selectivity model for the trap fishery, estimates of Y^{max} increased slightly while F^{max} decreased slightly for the onboard and landed scenarios (Table 12). Changes in the IDL and IPL under an asymptotic model were also negligible (7% and 2%, respectively), as were estimates of economic losses per-recruit (Table 13). This suggests that the choice of selectivity function for a particular gear type does have an affect on estimates of fishery yield and value. While this affect was rather small when considered on a per-recruit basis, if considered in the wider context of the fishery, differences in fishery yield and value may be considered substantial.

Discussion

In this chapter, I evaluated the impacts of at-sea discarding for the B.C. sablefish fishery using empirical estimates of gear selectivity. My results suggest that expected losses in fishery yield and value resulting from at-sea discarding can be substantial. In the absence of discarding (i.e., the pseudo discard sce fishery. While the onboard discard scenario presents a more realistic way of estimating fishery yield by acknowledging the mortality of discarded fish, estimates of YPR obtained under an onboard discard scenario are still likely to be biased high because the discarded catch is still included in the catch equation. The landed discard scenario, in which YPR is calculated from the landed catch only, therefore provides a more realistic way of calculating YPR and evaluating losses in fishery yield and value associated with at-sea discarding.

The difference between the onboard and landed discard scenarios, quantified by the IDL and referred to as the "discard-per-recruit" by Chen and Gordon (1997), calculates the loss of catch that is removed from the population, but not landed by the fishery (Chen and Gordon 1997). In the B.C. sablefish fishery, approximately 43% of the total potential YPR is wasted because of at-sea discarding suggesting that improvements in efficiency of the fishery could be achieved if discarding were eliminated or reduced either through regulatory measures or economic incentives. The current price structure for B.C. sablefish is such that sablefish greater than 65 cm are considerably less valuable than smaller legal-sized sablefish (Haist et al. 2001). This incentive structure is likely to lead to an increase in the discarding of small sablefish as vessels discard sablefish to stay within the quota or highgrade part of the catch in order to retain the larger and more valuable sablefish (FAO 2008). Removing such perverse economic incentives may help to reduce discarding and mitigate potential losses in yield and revenue for the B.C. sablefish fishery. Efforts to increase the survival of the discarded catch may also help to minimize the negative biological and economic impacts of discarding. For example,

shallow waters may therefore be an effective means of reducing the interception of small sablefish and mitigating losses in fishery yield and value as a result of at-sea discarding.

The effect of highgrading the catch at-sea, represented by changes in R_{50}, on losses in fishery yield and value were also explored during sensitivity analyses. Exploring the effects of changes in R_{50} is important for developing sustainable harvest strategies for exploited fish stocks because the size at which 50% of the fish are retained is one of a handful of parameters under the control of fishery managers. Increases in R_{50} allowed more legal-sized sablefish to be discarded at-sea. In the landed YPR and SBPR scenarios, which assumed 100% mortality of the discarded catch, increases in R_{50} led to reduced all fisheries participating in the B.C. groundfish sector. Of particular importance will be estimates of sablefish discard quantities and catch rates for each gear type in the B.C. groundfish fishery. Yet, despite the best intentions of the new IFMP, further improvements to the IFMP are required to eliminate discarding in the fishery altogether. For example, longline vessels are currently required to demonstrate that all sub-legal discards are below the minimum size limit (DFO 2007). The same requirements, however, do not apply to the trap and trawl fisheries generating some uncertainty in the magnitude and size distribution of the discarded catch in these fisheries (DFO 2007). Furthermore, the new IFMP imposes no penalties for vessels for discarding sub-legal sablefish despite the fact that research suggests that smaller sablefish experience higher mortality rates relative to larger fish (Davis 2002). Until these issues are addressed within the context of the IFMP, discarding will continue to remain an ongoing problem in the management of the B.C. sablefish fishery.

The final sensitivity analysis quantified expected losses in fishery yield and revenue for alternate assumptions about the relationship between size and susceptibility to capture for the trap fishery. As we saw in the case of the Northeast Atlantic cod fishery, failure to accurately identifiso9_nye sal_o9d©k8pLsFxd-8YpxYL2LaF9d©k8pLsFu9dpYd-__©

broader context of the fishery and not just on a per-recruit basis. This final sensitivity highlights the importance of monitoring and accounting for differences in selectivity in the ongoing management strategy evaluation for B.C. sablefish.

Limitations

As with any model, YPR analyses are based on a number of assumptions that limit the conclusions that can be drawn from this analysis (Malcolm 2001). For example, assumptions that parameters for recruitment, growth, and mortality are constant over time and that the stock is in a steady state equilibrium generally impose less physical damage on the discarded catch and lead to lower rates of discard mortality than mobile gears, such as bottom trawls (Davis 2002). However, the selectivity of fishing gear is just one of many factors influencing the survival of discarded fish. Environmental factors, such as air and sea surface temperature, also play a large role in survival and even the most benign gear types impose some level of mortality on the discarded catch. Therefore, including gear-specific discard mortality rates in subsequent YPR and SBR analyses would greatly improve the accuracy and interpretation of model results.

Conclusion

The approach described in this chapter allows fishery managers to quantify expected losses in fishery yield and value for different discard mortality assumptions. By quantifying the bias present in fishery assessments that ignore the mortality of the

Tables

Table 6 Summary of parameter values used in baseline yield-per-recruit and spawner biomass-per-recruit calculations.

Symbol	Value

Table 7 Summary of length-based selectivity results for asymptotic, dome-shaped, and exponential model fits for all years combined.

Table 8 Biological Reference Points (BRPs) for each discard scenario for the baseline M = 0.10 and tw tz4vdpdkpfiuzpv/b..4fsuzvp49pkfsuzpv/b..4fsuzovdwxkwfnuz4v

Table 10 Biological Reference Points (BRPs) for each discard scenario and two alternate values for the length at 50% retention, R_{50} (± 5 cm). Values in parentheses indicate the percent change from baseline BRP estimates.

F^{max} Y^{max}

Figures

Figure 9 Yield-per-recruit versus fishing mortality for each discard scenario calculated using baseline parameter values.

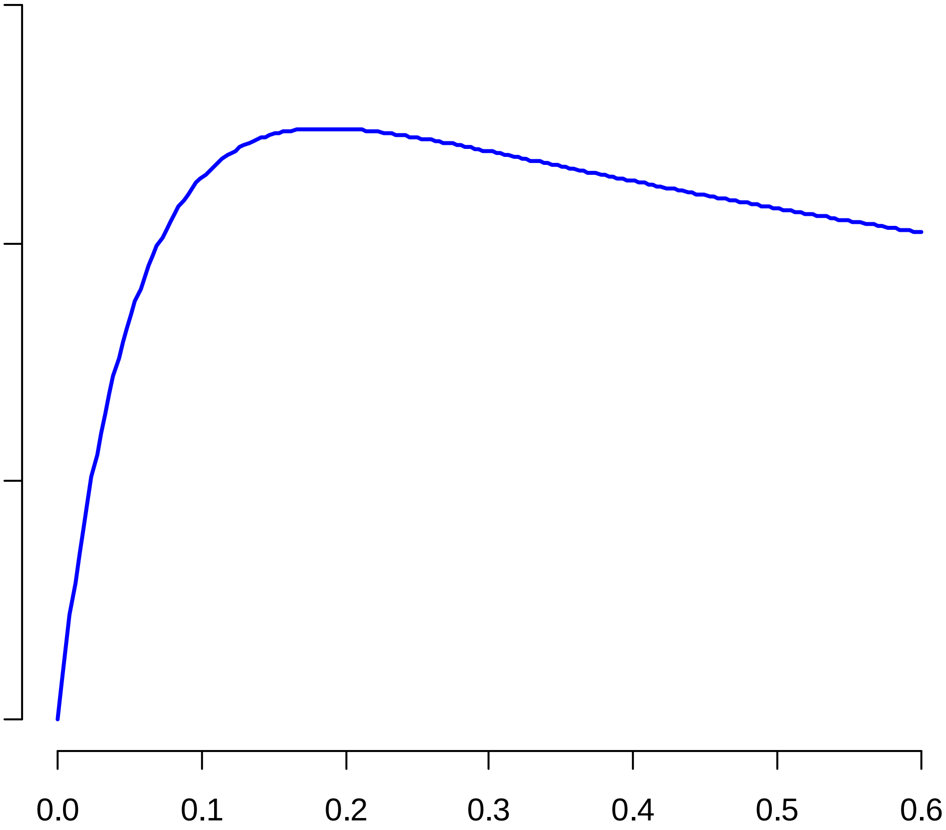
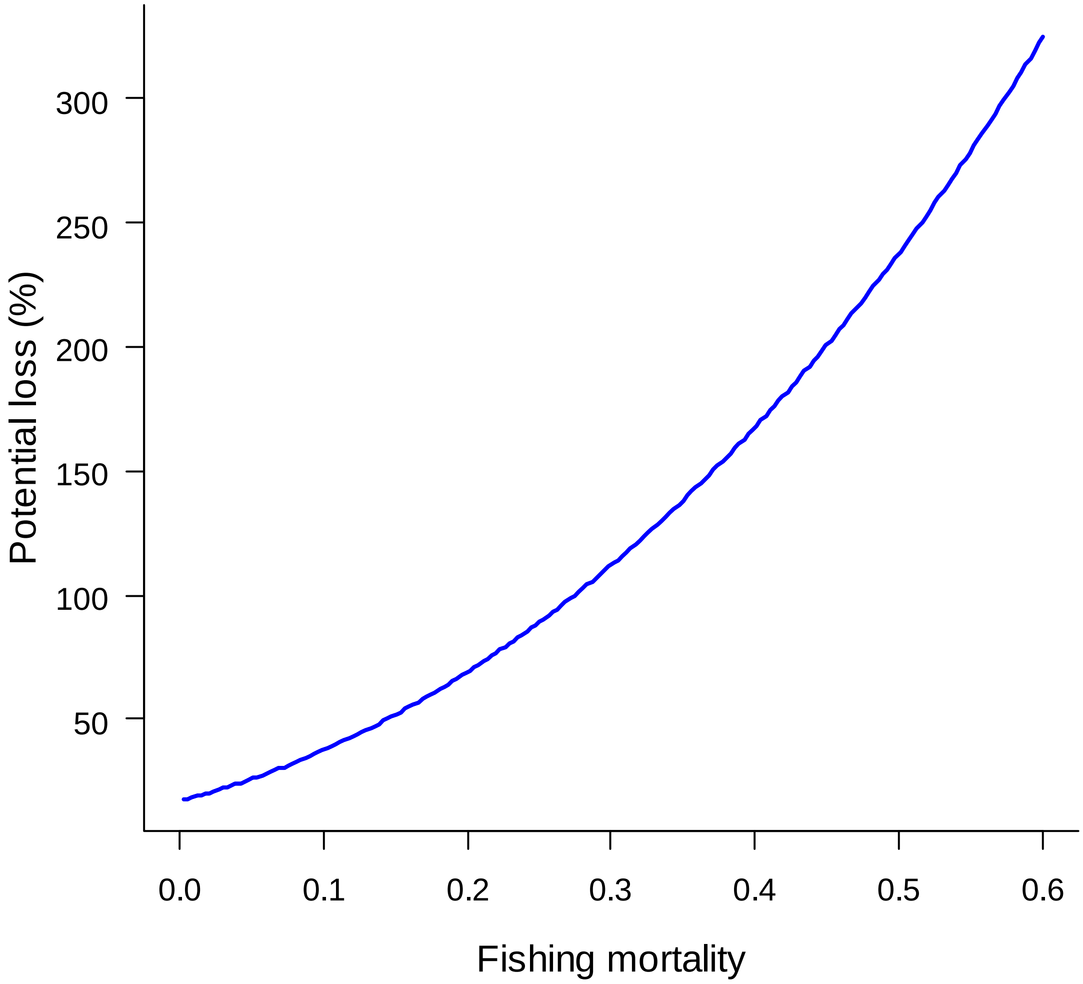


Figure 10 Spawner biomass-per-recruit versus fishing mortality for each discard scenario calculated using baseline parameter values. The dotted lines indicate reference points for F^{SB35} for each discard scenario.

Figure 11 Index of direct loss and index of potential loss calculated using baseline parameter values.



CHAPTER 4

GENERAL CONCLUSIONS

This thesis employs a direct method for estimating size-selectivity functions for three commercial gear types employed in the B.C. sablefish fishery. Quantifying the relationship between size and susceptibility to capture and understanding how the shape of this relationship may change over time in response to physical, biological, or environmental factors, is important for evaluating the impacts of the fishery on stock abundance and composition. When empirical estimates of gear selectivity are available, in addition to knowledge on growth and natural mortality, YPR analyses can be used to identify target fishing mortality rates and evaluate different management actions such as sablefish. Instead, it is recommended that further consideration be given to estimating gear selectivity in the ongoing management strategy evaluation for B.C. sablefish.

Chapter 3 incorporates direct estimates of selectivity into length-based models of YPR and SBPR to evaluate potential losses in yield and revenue as a result of at-sea discarding. YPR analyses were largely affected by discarding with the exclusion of discard mortality resulting in 49% of the total YPR being wasted because of at-sea discarding, equivalent to a maximum economic loss of CDN $5.44/recruit. With Chapter 2 indicating that small sablefish are the most vulnerable to trawl gear, accounting for the mortality of small discarded fish is critical to producing non-biased abundance estimates and identifying ‘optimal’ harvest strategies for the fishery. As I show in Chapter 3, failure to account for the discarded catch in sablefish assessments can bias model outputs and lead to large losses in fishery yield and value for the B.C. sablefish fishery. Commercial catch statistics for B.C. sablefish fishery must therefore reflect all fishery removals from the stock, including the mortality of discarded sablefish. While the appr©©L FuLiFu9d_x8-LbFupdkgY-

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APPENDIX – ESTIMATION OF MINIMUM SAMPLE SIZES

The minimum number of tag recoveries, $n_{y,l,g}$ required to estimate capture probabilities with an error no greater than δ was calculated for each length class l in each year y for each gear type g using the following equation (Zar 1984 pg. 380; Cochran 1963 pg. 74),

(1) $$n_{y,l,g} = \frac{Z^{2}_{\alpha(2)} t_{y,l,g} q_{y,l}}{\delta^{2}},$$

where $Z^{2}_{\alpha(2)}$ is the upper critical value of the normal distribution ($\alpha = 0.05$), $t_{y,l,g}$ is the number of tagged sablefish recovered in each year in each length class by gear type g, and $q_{y,l}$ is 1- $t_{y,l,g}$, or the number of tagged fish that were not recovered. A 95% confidence level is common (Cochran 1963) and, given that the allowable margin of error is arbitrary (Zar 1984), an error no greater than $\delta = 0.08$ was deemed appropriate for this study.