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Bioeconomic analysis of a minimum size limit for Gulf of Alaska sablefish using a yield per recruit model

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ABSTRACT

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To evaluate the potential of increasing yield in the Gulf of Alaska sablefish (*Anoplopoma fimbria*) fishery with a minimum size limit, a modified yield per recruit analysis was used to explore trends in yield, equilibrium biomass, reproductive potential, and economic value. The Gulf of Alaska sablefish catch quotas are apportioned to the fixed- and trawl-gear fisheries in the approximate amounts of 86.1% and 13.9%, respectively. The traditional yield per recruit model was modified to incorporate age-specific selectivity rates for each gear type and to compute yield from the combination of the two fisheries. The model also incorporated a discard mortality on undersized fish. With no discard mortality, yield per recruit increases with increasing size limits. However, the increases are significant only at high fishing mortality rates (greater than 0.20). With discard mortality, yields decrease with increasing size limits. Equilibrium biomass and the egg production index increase with increasing size limits, both with and without discard mortality, but the increases are negligible with discard mortality. The effects of a minimum size limit on gross and net value are similar to those on yield, with and without discard mortality, except that the fishing mortality rates that maximize net value are substantially less than those that maximize yield and gross value. As the fishing mortality rate for Gulf of Alaska sablefish is low (0.13), it was concluded that minimum size limits would be ineffective and could even be a detriment because of discard mortality.

INTRODUCTION

In the management process for Alaska groundfish through the North Pacific Fisheries Management Council (NPFMC), several proposals were received from fishermen in 1986 to implement minimum size limits for the sablefish (*Anoplopoma fimbria*) fishery in the Gulf of Alaska, with the intended objective of increasing yield. To evaluate the potential for increasing yield with minimum size limits, a modified yield per recruit analysis was used to explore trends in yield, equilibrium biomass, reproductive potential, and economic value. This analysis also provides insight into the possible effects of highgrading or discarding of undesirable sizes of fish, a practice for which there may be an increased incentive if an individual quota system is implemented in the Gulf of Alaska sablefish fishery. Such a system is currently under discussion.

Traditional yield per recruit analysis assumes that knife-edged recruitment is achieved at the age corresponding to the minimum size limit. In reality, a portion of discarded undersized fish probably do not survive. Lenarz et al. (1974), Clark (1983), and Waters and Huntsman (1986) incorporated this additional mortality into their analyses. Waters and Huntsman (1986) found that discard mortality can potentially reduce the effectiveness of minimum size limits for increasing yield per recruit, dependent on the fishing mortality rate, the minimum size limit, and the probability that undersized fish survive after being discarded. Our model also incorporates a discard mortality on the undersized fish to explore the effects on the success of a minimum size limit for sablefish.

In addition to incorporating discard mortality, we model other aspects characteristic of the Gulf of Alaska sablefish fishery. Sablefish are a highly valued commercial species which are mostly harvested by longline fishermen. Beginning in 1986, the sablefish catch quotas for the Gulf of Alaska have been apportioned to the fixed- and trawl-gear fisheries in the approximate amounts of 86.1% and 13.9%, respectively, a ratio of 6.2:1. We modify the yield per recruit model to incorporate age-specific selectivity rates for each gear type and to compute separate yields for the fixed- and trawl-gear fisheries in a 6.2:1 ratio to represent the current fishery. For each longline fishing mortality rate input into the model, the corresponding trawl fishing mortality rate is computed, which provides yields in the correct ratio.

The model is used to determine the effectiveness of minimum size limits given the interactions of discard mortality and two gear types with differing selectivities. The model uses sex-specific growth parameters and computes yield for each sex separately.

THE YIELD PER RECRUIT MODEL

The basic Beverton and Holt (1957) yield per recruit model considers the combined effects of fishing, natural mortality, and growth in a single equation. The model is based on the assumption that recruitment is independent of spawning biomass. If the initial size of each year class is assumed constant from year to year, then yield in any one year from all year classes equals the yield from one cohort over its fishable lifespan.

The model we use is a modification of one developed by Funk and Bracken (1984). The yield (in weight) for a given sex, of a cohort over its fishable lifespan from the age of first retention in the catch (or the age at which a fish reaches the minimum size limit, t_c), to the oldest fishable age (t_λ) is given by the following equation

$$Y=\int_{t_c}^{t_\lambda}[F_1S_1(t)+F_2S_2(t)]\,N(t)\,W(t)\,\mathrm{d}t$$

where 1 indicates longline, 2 indicates trawl, F is the instantaneous full-recruitment fishing mortality rate modified by a selectivity function $S(t)$ which varies by age and gear type, $N(t)$ is the survival function describing numbers surviving at age t, and $W(t)$ is a sex-specific function which calculates the average weight at age t. Yield for each fishery is accumulated for males and females. Equal numbers of male and female recruits are assumed in the initial population. The integral is approximated by summing over small time intervals, where $N(t)$ is computed in small steps

$$N(t+0.05)=N(t)\,\{\exp[-F_1(H,S)-F_2(H,S)-M](0.05)\}$$

The age of recruitment to the gear (t_r) is treated as a biological constant referring to the age at which young fish first become vulnerable to the fishery. This is comparable with t_ρ of Beverton and Holt (1957), which was defined as the age at which the fish enter the exploited area and become liable to encounters with fishing gear. It is assumed that below t_r, the cohort is only subject to natural mortality (M). The age of first retention in the catch (t_c) corresponds to the age at which a fish reaches the minimum size limit and can be retained.

The fishing mortality $F_i(H,S)$ for gear type i in the survival equation, is a function of selectivity $S_i(t)$ and discard mortality H_i

$$F_i(H,S)=-\log_e\{1-H_i[1-\exp(-F_iS_i(t))]\}$$

Fishing mortality is initially modified by gear selectivity, then, according to the age of the fish, it is further modified by discard mortality H_i. Below the age of recruitment to the gear (less than t_r), the fish are subjected only to natural mortality. From the age of recruitment to the age corresponding to the minimum size limit (t_r-t_c), the catch rate is $FS(t)$, but the fish are discarded and subjected to the discard mortality, which ranges from zero to one. If H is zero, all discarded fish survive, or if H is one, the mortality rate is $FS(t)$. Beyond t_c all fish caught are retained with mortality rate $FS(t)$.

The age of recruitment to the gear (t_r) is set to 1 year. Below the age of 1 year, it is highly unlikely that the fish would be available to exploitation. Juveniles are generally found in surface and inshore waters down to depths of approximately 150 m, and the exploitable biomass is considered to inhabit depths of 150–1200 m (Low, et al. 1976). The instantaneous natural mortality rate of 0.112 is determined as an average from the results of various studies (Funk and Bracken, 1984). This compares with $M=0.22$ estimated by Low et al. (1976) before the latest ageing techniques. Johnson and Quinn (1988) used values of 0.10 and 0.20 in a catch-at-age analysis and noted that when $M=0.10$ was used, estimated abundance trends agreed better with survey results. The maximum fishable age for Gulf of Alaska sablefish has not been determined; however, ages of 35 years have been determined from samples from trap surveys (Fujioka, 1989). Canadian researchers have reported age determinations up to 55 years. The maximum fishable age for this analysis was set at 37 years given the possibility of aging errors of 1–2 years. The size limits explored in the model range from 37 to 61 cm in increments of 4 cm.

Discard mortality rates for sablefish from fixed and trawl gears have not been quantified. Funk and Bracken (1984) cited estimates of 25–75% from information received from longline fishermen. The discard mortality also depends on the behavior of fishermen, which cannot be quantified. For example, a discard mortality rate of zero assumes that all discarded fish survive, or that fishermen can avoid fish below the size limit. To represent a range of possible scenarios, the model was initially run with a zero discard mortality rate to represent the best-case scenario. The model was also run with a 100% discard mortality rate for the trawl gear and a 35% discard mortality rate for the fixed gear. Anecdotal information from fishermen describes trawl discard mortality rates of approximately 100%. As most of the catch is taken by longline gear this value is not critical. A low longline discard mortality rate is assumed in an attempt to show a benefit with minimum size limits. We explored various other combinations of discard mortality rates, but trends remained fairly constant. Therefore, results are presented only for the abovementioned rates.

The selectivity functions are chosen by examining size categories in current landings and constructing hypothetical length–frequency distributions of catch from a range of logistic shaped selectivity curves. The logistic curves for the model are subjectively chosen so that the frequency of small fish in the hypothetical distribution would be somewhat greater than is observed in the catch. This correction assures that if there were the possibility that small fish are available at a greater than apparent rate, the potential benefit of a minimum size limit would be fully measured. If fish smaller than the size limit are not available to the gear the regulation would have little effect, regardless. The current size distribution of the catch appears to have few smaller fish because it is made up of mostly older fish from the last stronger than average year-classes. Figure 1 shows the estimated selectivity curves for the fixed and trawl gear. Selectivity decreases for trawl gear after approximately 60 cm to represent the decreased vulnerability of larger sablefish. Selectivity is assumed to

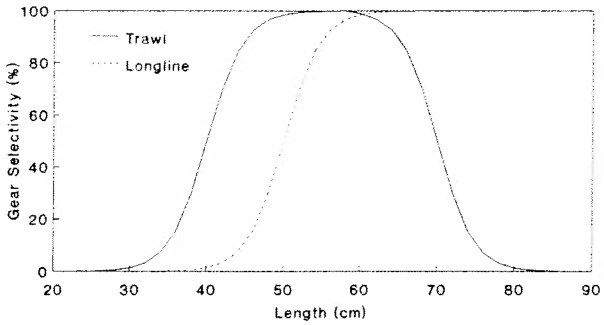

Fig. 1. Selectivity of the trawl and fixed gear.

TABLE 1

Sablefish growth parameters for a weight–length relationship and the von Bertalanffy length–age equation used in the model

Parameter	Males	Females
a	2.28×10^{-6}	3.15×10^{-6}
b	3.360	3.290
L_∞	71.820	89.280
K	0.200	0.142
t_0	−3.230	−3.210

Weight–length equation: weight (kg) $=a$ (fork-length cm)^b.
Length–age equation: length (cm) $=L_\infty\{1\text{-exp}[-K(t-t_0)]\}$.

be a function solely of length and not sex, but is expressed in the model by the corresponding function of age.

The weight function used is an allometric growth function

$$W(t)=al_t^{\mathrm{b}}$$

with length at age t (l_t) calculated by the von Bertalanffy growth equation (Gulland, 1983)

$$l_t=L_\infty\{1-\exp[-K(t-t_0)]\}$$

Separate male and female growth parameters are used in the model (Table 1). The parameters of the weight–length relationship are taken from Sasaki (1985), based on a collection of 1193 specimens taken from the Gulf of Alaska. There are no estimates of precision given for these parameters. The age–length relationship parameters are taken from McDevitt (1990), based on 1163 specimens taken in the Gulf of Alaska. Residual population variances for the age–length function are available from McDevitt (1990), but standard errors for the parameter estimates are not given.

Equilibrium biomass is calculated with the following equation

$$B=\int_{t_r}^{t_\lambda} N(t)\ W(t)\ \mathrm{d}t$$

The integral is approximated as described above, and biomass is computed for each sex separately.

The effect of minimum size limits on the reproductive potential of the stock is examined by calculating eggs per recruit

$$E=\int_{t_r}^{t_\lambda} N_{\mathrm{f}}(t)\cdot \mathrm{EGGS}(t)\cdot \mathrm{RMAT}(t)\ \mathrm{d}t$$

where E is the egg production index, $N_{\mathrm{f}}(t)$ is the number of t-year-old females, $\mathrm{EGGS}(t)$ is fecundity at age of mature females, and $\mathrm{RMAT}(t)$ is the proportion of mature females at age t. The fecundity relationship is taken from unpublished data of B.E. Bracken and J.E. Eastwood (1984) cited by Funk and Bracken (1984)

$$\mathrm{EGGS}(t)=0.02349(l_t)^{3.88}$$

where l_t is fork length in centimeters at age t. The correlation coefficient for the above regression is given, but there are no estimates of the precision of the individual parameter estimates. The maturity relationship is a logistic function

$$\mathrm{RMAT}(t)=1/\{1+\exp[a(l_t-l_{50})]\}$$

where l_{50} is the length at which 50% of the population is mature. A value of $l_{50}=65$ cm was taken from Sasaki (1985) for Gulf of Alaska females. Again, no estimates of the precision of this estimate are available. The parameter a is determined by fitting sablefish maturity data for Gulf of Alaska females, interpolated from a graph in Sasaki (1985), to the above equation. The estimate of parameter a is -0.462 with a standard error of 0.017.

The yield in gross ex-vessel value of a cohort over its fishable lifespan is defined as

$$V=\int_{t_r}^{t_\lambda} Y(t)\cdot P(t)\ \mathrm{d}t$$

where $P(t)$ is the ex-vessel price per tonne of yield in weight for fish at age t. Separate step functions describe the relationship between weight and ex-vessel price for the fixed- and trawl-gear fisheries (Table 2). The parameters of the step functions are estimated using size- and gear-specific fish ticket data from the 1989 sablefish fishery. Although ex-vessel prices by size and gear are dependent on both total sablefish catch and the distributions of total catch by size and gear (Hastie, 1989), size- and gear-specific price response functions are not available. Therefore, this analysis of the effects of size limits is based on the assumption of constant ex-vessel prices by size and gear. The significance of this assumption will not be known until such functions have been estimated and used to extend this model.

Yield in net ex-vessel value (i.e. gross ex-vessel value in longline and trawl fisheries minus the variable fishing costs in the longline fishery) is defined as

$$NV = V - C$$

where C is variable fishing cost in the longline fishery. The variable fishing cost is calculated with a cost function, and it is assumed that cost is proportional to exploitation rate

$$C = Cb(X/Xb)$$

where Cb is the estimated variable cost for a longline fishery in the base period, Xb is the exploitation rate in the base period longline fishery, and X is the exploitation rate associated with each fishing mortality rate. Estimated values of Xb and Cb of \$0.116 million and \$11.8 million, respectively, are the exploitation rate in the longline fishery in 1989 and associated variable cost of a longline fishery with that level of exploitation. The cost estimate (\$11.8 million) was generated using the 1989 distribution of catch by vessel class and estimates of variable cost by vessel class. The latter were developed as part of the analysis of individual quotas for the fixed-gear sablefish fishery off Alaska. This cost function does not include the sorting costs associated with a minimum size limit. All else being constant, this results in the benefits of a size limit being overstated.

TABLE 2

Weight and length categories, and ex-vessel prices in 1989 for the fixed and trawl fisheries

Weight (kg, round wt.)	Length (cm)	Price ($ kg^{-1})	
		Fixed	Trawl
<0.732	42.95	1.340	0.661
<1.464	52.99	1.435	1.098
<2.196	59.92	1.656	1.404
<2.928	65.38	2.132	1.841
<3.660–<5.124	69.95–76.46	2.257	2.000
≥5.124	76.46	2.264	1.887

Fixed costs in the longline fishery are disregarded because many of the longline vessels would incur the same fixed cost regardless of the exploitation rate in the longline fishery, because they participate in other fisheries. Fishing costs for the trawl fishery are not utilized because the trawl catch of sablefish is entirely designated for bycatch in other groundfish fisheries. These simplifications of the cost function are not expected to affect the nature of the results; however, they should be more fully considered.

RESULTS

Yield in weight with no discard mortality

The effect on yield of minimum size limits increases with increasing fishing mortality rates. Yields are similar for all size limits when fishing mortality rates were less than 0.125 (Fig. 2a). At these low levels of fishing mortality the potential increase in equilibrium yield with a minimum size limit is offset by natural mortality. At higher levels of fishing mortality, yields increase with increasing size limits. The highest yields for fishing mortality rates less than 0.05 are achieved with size limits of 45 and 49 cm. For fishing mortality rates of 0.05–0.10, the greatest yields are obtained with a size limit of 53 cm. For fishing mortality rates of 0.10–0.225, the greatest yield is achieved with a 57-cm size limit. A 61-cm size limit produces the highest yields when fishing mortality rates exceed 0.225.

Because the selectivity of both gear types for small fish is low, size limits of 37, 41, and 45 cm produce essentially similar yields. For example, longline gear accounts for the bulk of the catch, and at 40 cm selectivity is 1.4%. As

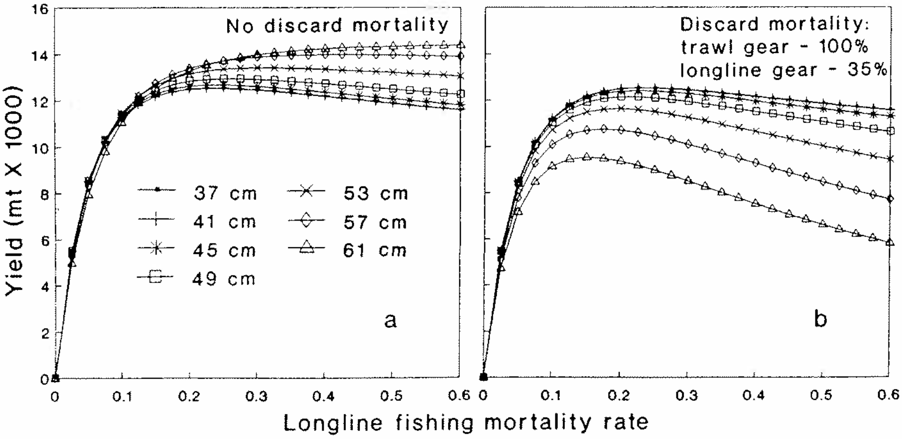

Fig. 2. Equilibrium yields for the various size limits as a function of the longline fishing mortality rate, with the assumption of (a) no discard mortality, and (b) 100% discard mortality for the trawl gear and 35% discard mortality for fixed gear.

few fish are selected at these lengths, the size limits have little effect. The smallest size limit analyzed provides a good approximation of the results of a fishery with no size limit, as few fish are selected at or below 37 cm.

As minimum size limits increase, the fishing mortality rate which maximizes yield per recruit ($F_{\max}$) increases. Maximum yields for size limits of 37 and 41 cm are achieved at a fishing mortality rate of 0.225. Maximum yields occur at a fishing mortality rate of 0.250 for size limits of 45 and 49 cm. Maximum yields for size limits of 53 and 57 cm are achieved at fishing mortality rates of 0.30 and 0.425, respectively. The yield curve produced with a minimum size limit of 61 cm does not reach a maximum over the range of fishing mortality rates analyzed (0.025–0.60). This size limit (61 cm) exceeds the size at which male sablefish would attain maximum cohort biomass, beyond which any gain because of growth would be exceeded by loss because of natural mortality. Maximum yield for $F=\infty$ occurs at 60.5 cm and age 6 years for males, and for females at 71.4 cm at 8 years of age.

A more conservative exploitation rate is the $F_{0.1}$ policy. This is the fishing mortality rate where the marginal increase in yield is one-tenth the marginal increase in a newly exploited population (Gulland, 1983). These rates are much lower than the $F_{\max}$ rates for all size limits. The $F_{0.1}$ rate for size limits of 37, 41, and 45 cm is 0.12. For size limits of 49 and 53 cm the $F_{0.1}$ rate is 0.13; and for size limits of 57 and 61 cm, the rates are 0.15 and 0.18, respectively.

Yield in weight with discard mortality

When discard mortality is incorporated into the model (100% for trawl gear, 35% for fixed gear), the opposite trend in yield is apparent (Fig. 2b), producing decreases in yield with increasing size limits. The lowest yields are produced with the largest size limit of 61 cm. The highest yields over the range of fishing mortality rates were achieved with a 37-cm size limit, equivalent to a fishery without a size limit. The maximum yield decreases with increased size limits; and the greatest effects occur at the largest size limit at high fishing mortality rates.

A sensitivity analysis of all the parameters utilized in the analysis is not undertaken, because the most dominant factor appears to be the discard mortality rates. At lower discard mortality rates, the yield trends are similar to trends obtained with the rates used in this analysis. Yield per recruit continues to decrease with increasing minimum size limits, when lower levels of discard mortality rates are used.

Equilibrium biomass and egg production

Equilibrium biomass associated with the yields assuming no discard mortality are shown in Fig. 3a. Increasing size limits produce higher biomass lev-

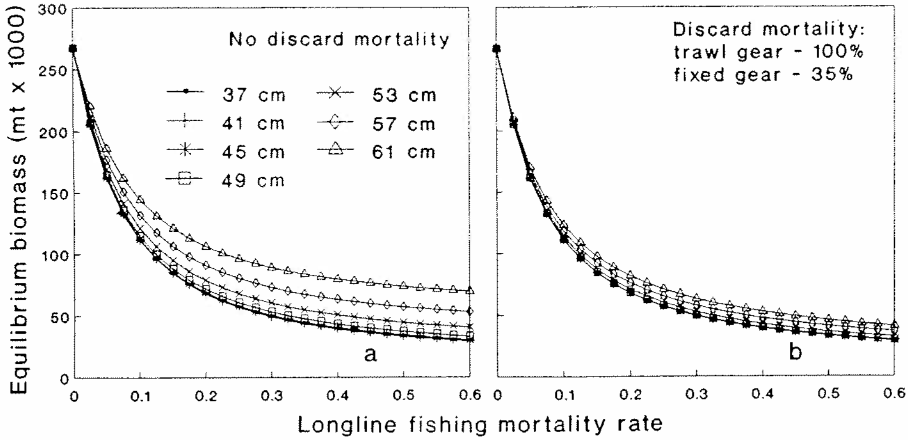

Fig. 3. Equilibrium biomass for the various size limits as a function of the longline fishing mortality rate, with the assumption of (a) no discard mortality, and (b) 100% discard mortality for the trawl gear and 35% discard mortality for fixed gear.

els, although biomass levels for size limits of 37–49 cm are similar. Large increases in biomass were achieved with size limits of 53–61 cm. With the addition of discard mortality (Fig. 3b), increasing size limits still produce higher biomass levels, but the trend is much less apparent. At low levels of fishing mortality ($F<0.10$) the increases in biomass are negligible.

Results from the eggs per recruit function are similar to those for biomass as the functions are approximately proportional. The eggs per recruit function shows that with no discard mortality, increasing size limits produce higher values of the index. With the addition of discard mortality, the application of increasing size limits produces negligible differences in the egg production index.

Gross ex-vessel value

The effects of a minimum size limit on gross ex-vessel value are similar to those on yield when there is no discard mortality. At each fishing mortality rate, gross value is higher with a larger size limit and the increase in value for a larger size limit increases as the fishing mortality rate increases (Fig. 4a). For example, with a fishing mortality rate of 0.05, there is less than a 2% difference between the gross value for size limits of 37 and 61 cm; but with a fishing mortality rate of 0.2, it exceeds 23%. The fishing mortality rate associated with the maximum sustainable gross value increases from 0.155 for a minimum size limit of 37 cm to in excess of 0.2 for a size limit of 57 or 61 cm.

When discard mortality is assumed to be 35% and 100% in the longline and

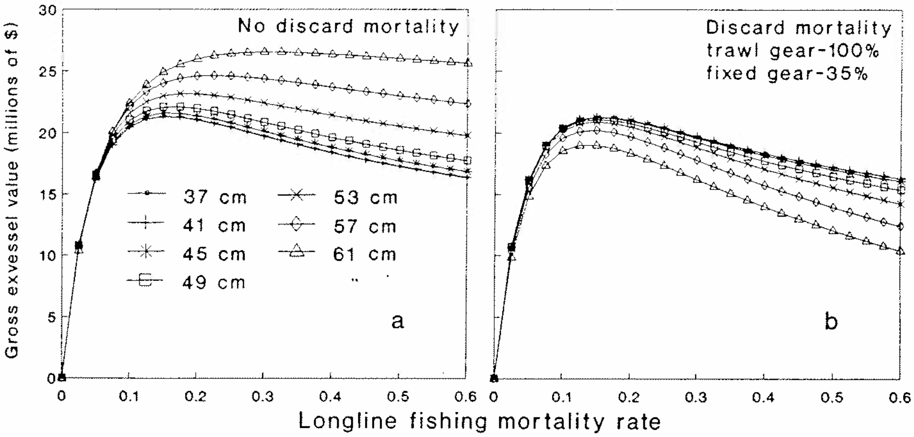

Fig. 4. Gross ex-vessel value for the various size limits as a function of the longline fishing mortality rate, with the assumption of (a) no discard mortality, and (b) 100% discard mortality for the trawl gear and 35% discard mortality for the fixed gear.

trawl fisheries, respectively, the results are very different. For each fishing mortality rate, gross value decreases as the minimum size limit is increased and the fishing mortality rate associated with the maximum sustainable gross value decreases from 0.155 with a size limit of 37 cm to 0.140 for a size limit of 61 cm (Fig. 4b).

Net ex-vessel value

The effects of a minimum size limit on net ex-vessel value are similar to those on yield and gross value when there is no discard mortality. At each fishing mortality rate, net value is higher with a larger size limit and the increase in value for a larger size limit increases as the fishing mortality rate increases (Fig. 5a). For example, with a fishing mortality rate of 0.05, there is just over a 2% difference between the net value for size limits of 37 and 61 cm; but with a fishing mortality rate of 0.09 it exceeds 14%. The fishing mortality rate associated with the maximum sustainable net value increases from 0.07 for a minimum size limit of 37 cm to 0.09 for a size limit of 61 cm. The fishing mortality rates that maximize net value are substantially less than those that maximize yield or gross value.

When discard mortality is assumed to be 35% and 100% in the longline and trawl fisheries, respectively, the results in terms of net value are very different from those for yield or gross value. For each fishing mortality rate, net value decreases as the minimum size limit is increased beyond 41 cm; however, the decrease is very small until the size limit is increased to 57 cm (Fig. 5b). The fishing mortality rate associated with the maximum sustainable net value is

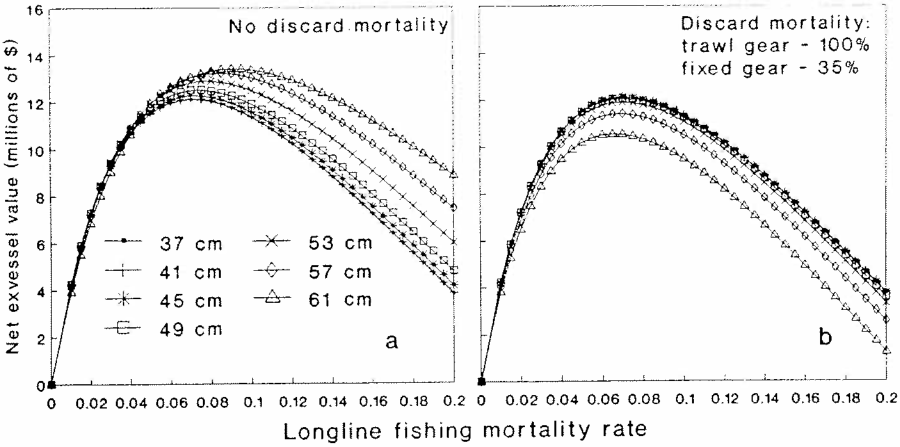

Fig. 5. Net ex-vessel value for the various size limits as a function of the longline fishing mortality rate, with the assumption of (a) no discard mortality, and (b) 100% discard mortality for the trawl gear and 35% discard mortality for the fixed gear.

0.07 for a minimum size limit of 37–57 cm and is 0.065 for a size limit of 61 cm.

DISCUSSION

Discard mortality reduces the potential effectiveness of minimum size limits for increasing yield per recruit. With discard mortality rates of 100% for trawl gear and 35% for fixed gear, yield per recruit actually decreases with increasing minimum size limits. As noted earlier, we explored further applications of the model with lower discard mortality rates, the results of which are not presented here, but are similar to results produced with the representative rates. Yield per recruit continued to decrease when discard mortality rates were further reduced to 50 and 25% for the trawl and fixed gears, respectively. Because it is unlikely that discard mortality in the fishery would be much lower, a minimum size limit would be ineffective or could be a detriment. It is also unlikely that fishermen could completely avoid catching undersized fish; therefore, the benefits of a size limit are not likely to be realized.

Even when discard mortality is zero, the increase in yield per recruit is significant only at high fishing mortality rates. Although maximizing yield or economic return per recruit would be an appropriate exploitation strategy when recruitment is fully independent of stock size, sablefish recruitment is quite variable and little is known about stock–recruitment relationships. An aggressive exploitation strategy such as F_{max} would cause the population to drop more rapidly to low levels during periods of poor recruitment. Also, economic returns may not be maximized at low stock levels.

In the Gulf of Alaska, sablefish are managed with the more conservative $F_{0.1}$ strategy. The fishing mortality rate is believed to be approximately 0.13 (NPFMC, 1989). The increases in yield (assuming no discard mortality) obtained with the various size limits are negligible at this level of fishing mortality (Fig. 2). The maximum yield for a fishing mortality rate of 0.13 with no discard mortality is obtained with a 57-cm size limit, which is only 3% higher than the yield obtained with a 37-cm size limit. Therefore, even in the best case (no discard mortality), minimum size limits are relatively ineffective at low levels of fishing mortality.

Yields obtained at the $F_{0.1}$ level for all size limits are only slightly lower than maximum yields, but occur at significantly lower fishing mortality rates. When no discard mortality occurs, the $F_{0.1}$ yields increase only slightly with increasing size limits. With the addition of discard mortality, the $F_{0.1}$ yields decrease with increasing size limits, as do the maximum $F_{\max}$ yields. Thus the conclusions on the benefits of minimum size limits based on maximum yield per recruit comparisons are valid when applied to the more realistic harvest policy.

The effect of a minimum size limit is analogous to the effect of highgrading (the discarding of less valuable catch) when small fish are less valuable. There is an increased incentive to highgrade when individual landings are limited, whether by regulation or by vessel and labor capacity. Under such conditions, the attempt of individual fishermen to increase short-term monetary yield by discarding smaller sablefish would result in a long-term decrease in yield per recruit. Individual quotas (IQs) are currently under consideration for the Gulf of Alaska sablefish longline fishery. If IQs are implemented, the lack of a time constraint would, in all likelihood, be an incentive to highgrade. However, it is noted that the amount of smaller fish that would be discarded for market reasons would be a function of the size-specific price differentials, the size composition of the catch, and cost per unit of catch. In general, all fish of a specific size would not be discarded for market reasons.

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