Soft Flesh in Sablefish, *Anoplopoma fimbria,* of Southeastern Alaska: Relationships with Depth, Season, and Biochemistry

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Introduction

The quality of fish flesh is important to both commercial and sport fishermen. Soft flesh in fish may affect the yield, the success of preservation by freezing, the palatability, and the overall quality of the fish for market or consumption.

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The condition of "soft" flesh has been noted in several species of marine fish in the North Pacific, Gulf of Alaska, and the North Atlantic. The reasons for the occurrence of soft flesh has been determined for several fish species: parasite infestations (Levsen et al., 2008), spawning and cessation of feeding (Tomlinson et al., 1967), mineral accumulation (Teeny et al., 1984), temperature/exercise (Foy et al., 2006), biochemical adaptation to the deep sea (Siebenaller and Somero, 1989), and depth of occurrence (Norris et al.[1]).

Sablefish or blackcod, *Anoplopoma fimbria*, a marine species of the shelf and slope of the North Pacific Ocean, are found in commercial quantities from northern Mexico to Alaska and as far west as eastern Siberia (Kimura et al., 1998; Low et al.[2]). United States and Canadian fishermen have fished the North American resource for over a century, but it was not until the Japanese distant-water longline fishery developed in the 1960's that the resource was subject to intense exploitation (Low et al.[2]). The fishery did not fully develop on the U.S. west coast until the advent of the pot (trap) fishery developed by the Bureau of Commercial Fisheries (BCF) Biological Laboratory in Seattle, Wash.,

[1]Norris, J. G., J. Rowley, and S. B. Mathews. 1987. Analysis of four factors affecting the sablefish soft fish problem. Contr. NA85-ABH00056, FRI-UW 8715, Fish. Res. Inst., Univ. Wash., Seattle, Final Rep. to Saltonstall/Kennedy Program, 55 p.

[2]Low, L. L., G. K. Tanonoka, and H. H. Shippen. 1976. Sablefish of the northeastern Pacific Ocean and Bering Sea. NWAFC Processed Rep., 115 p. Northwest Fisheries Science Center, National Marine Fisheries Service, NOAA. 2725 Montlake Blvd. E., Seattle, Wash.

ABSTRACT—The condition of soft-textured flesh in commercially harvested sablefish, Anoplopoma fimbria, *from southeastern Alaska was investigated by National Marine Fisheries Service (NMFS) scientists from the Alaska Fisheries Science Center's Auke Bay Laboratories (ABL) in Alaska and the Northwest Fisheries Science Center in Seattle, Wash. Sablefish were sampled by longline, pot, and trawl at five sites around Chichagof Island at depths of 259–988 m in the summer of 1985 and at depths of 259–913 m in the winter of 1986. At the time of capture and data collection, sablefish were categorized as being "firm" or "soft" by visual and tactile examination, individually weighed, measured for length, and sexed. Subsamples of the fish were analyzed and linear regressions and analyses of variance were performed on both the summer (n = 242) and winter (n = 439) data for combinations of chemical and physical analyses, depth of capture, weight vs. length, flesh condition, gonad condition, and sex.*

We successfully identified and selected sablefish with firm- and soft-textured flesh by tactile and visual methods. Abundance of firm fish in catches varied by season: 67% in winter and 40% in summer. Winter catches may give a higher yield than summer catches. Abundance of firm fish catches also varied with depth. Firm fish were routinely found shallower than soft fish. The highest percentage of firm fish were found at depths less than 365 m in summer and at 365–730 m in winter, whereas soft fish were usually more abundant at depths greater than 731 m. Catches of firm fish declined with increasing depth. More than 80% of the fish caught during winter at depths between 365 and 730 m had firm flesh, but this declined to 48% at these depths in summer.

Longlines and pots caught similar proportions of firm and soft fish with both gears catching more firm than soft fish. Trawls caught a higher proportion of soft fish compared to longlines and pots in winter.

Chemical composition of "firm" and "soft" fish differed. On average "soft" fish had 14% less protein, 12% more lipid, and 3% less ash than firm fish. Cooked yields from sablefish with soft-textured flesh were 31% less than cooked yields from firm fish.

Sablefish flesh quality (firmness) related significantly to the biochemistry of white muscle with respect to 11 variables. Summer fish of all flesh conditions averaged 6% heavier than winter fish. Regulating depth of fishing could increase the yield from catches, but the feasibility and benefits from this action will require further evaluation and study. Results of this study provide a basis for reducing the harvest of sablefish with soft flesh and may stimulate further research into the cause and effect relationship of the sablefish soft-flesh phenomenon.

Figure 1.—Photo of a very black and soft-fleshed adult sablefish, taken July 2002 on the sablefish survey at a depth of 800 m.

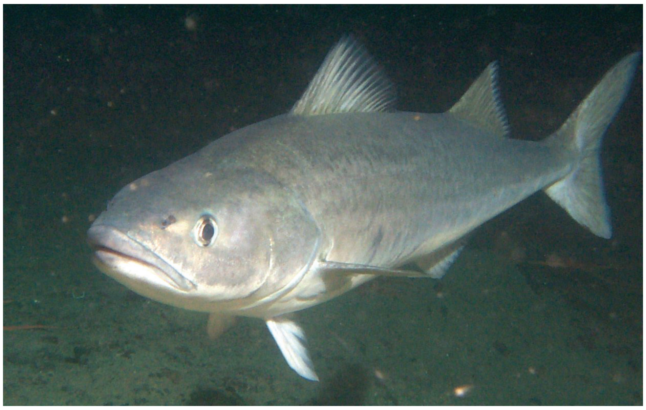

Figure 2.—Photo of a light colored firm-fleshed adult sablefish. Photo: Patrick Malecha, NOAA/NMFS Auke Bay Lab.

in the late 1960's (Hughes et al., 1970). It was then that the issue of sablefish with soft-textured flesh was noted by the commercial fishing industry and relayed to BCF fisheries personnel. Sablefish with "soft" flesh were first documented in deep-water samples taken during exploratory fishing activities in the mid 1960's off the coasts of Washington and Oregon, near the mouth of the Columbia River (Heyamoto and Alton, 1965).

Chemical analysis of sablefish, caught at depths ranging between 457 and 640 m in November and December of 1969, showed that the edible flesh of fish judged to be soft had an average water content of 81%, 10.1% fat content, and protein content of 6.7% (Patashnik et al.[3]). These data suggested that the increased water content and apparent protein depletion may be similar to a condition found in Dover sole, *Microstomus pacificus* (Patashnik and Groninger, 1964) and American plaice, *Hippoglossoides platessoides* (Templeman and Andrews, 1956) and may make these fish less suitable for processing. This condition was thought not to be unusual by Love (1970) who observed "the majority of fish experience severe (food) depletion for a part of every year of their lives and are therefore unusually adapted to mobilizing their body constituents as a fuel for survival."

Follow-up research to the 1969 study was initiated by the National Marine Fisheries Service in 1971 and again in 1979 to further study the soft flesh problem as it concerned the emerging west coast pot fisheries for sablefish. The intent of that research was to examine possible methods for detecting and separating sablefish with soft flesh from "normal" sablefish that could be used by fishermen at sea or by fish processors at dockside. To accomplish this, it was necessary to acquire a better understanding of the nature of the problem. The studies included additional chemical analyses to reconfirm results of the earlier analyses, tests to determine the degree of softness or firmness by finger pressure or by specific gravity in brine, and tests to determine whether skin color was an indicator of softness. The results of these tests were related to depth of capture, which ranged between 457 and 823 m. Results from these studies (unpublished data) essentially confirmed what had been seen previously, that sablefish with high water content and low protein content generally were soft textured, and the incidence of this condition increased with depth of capture. The subjective methods to determine if fish were soft or firm when landed were evaluated during this period. A process using depth of catch and skin color of the fish was used in conjunction with finger pressure as a rapid method for separating soft fish from firm fish at point of landing. It was also observed that sablefish caught deeper than 548 m tended to be larger, blacker or darker gray in color, sometimes with a rose-colored lateral tint, especially if spawned; these fish generally had soft-textured flesh (Fig. 1). Firm sablefish, caught shallower than 548 m and not spawned, were characteristically a green–gray color dorsally with a light gray or white underbelly (Fig. 2). These photos show the extremes of soft and firm sablefish. Soft fish ranged from very black on back and belly to black backs and dark grey bellies to dark grey backs and bellies.

Our study addressed the following questions:

- Does the occurrence of soft sablefish in Alaska waters relate to depth of capture, season, spawning condition, and type of fishing gear used?
- Do the results obtained in sablefish studies off Oregon and Washington apply to Alaska?
- Can the harvest of sablefish with soft-textured flesh be avoided by manipulating fishing seasons and fishing depths?

Specific objectives of our study were to 1) determine the effects of season, depth of capture, sex, sexual maturity, and gear type on flesh quality and 2) determine the relationships of water, protein, lipids, ash, and mineral content of muscle to flesh quality.

[3]Patashnik, M., H. Barnett, and J. Conrad. 1980. A preliminary report on soft sablefish from the pot fishery off the Washington Coast. Unpubl. rep., URD, Northw. Alaska Fish. Cent., NMFS, NOAA, 2725 Montlake Blvd. E., Seattle, Wash.

Materials and Methods

Collection and Shipboard Processing

Sablefish were collected in southeastern Alaska in the summer (June and August) of 1985 and winter (January and February) of 1986 at four locations in Chatham and Icy Straits and at one location offshore of Cape Cross (Fig. 3). Fish were captured with a 400-mesh otter trawl, longline (LL), and conical pots. Longlines were fished for 3 h, pots for 24 h, and the trawls for 0.5 h at depths ranging between 259 and 913 m. Depths of capture were recorded. Following capture, the fish were immediately sacrificed, weighed, bled, measured (fork length), and subjectively classified as soft or firm using the methods previously described, i.e. finger pressure and skin color. They were then sexed, dressed, and classified as to gonad developmental stage. There are five stages of gonad development for each sex: 1) immature, 2) maturing juvenile, 3) mature, 4) spawning, and 5) post-spawning. Stomach fullness and contents were also noted but are not reported in this study. The cleaned fish were frozen and stored at -29°C for later objective and subjective testing. A total of 681 sablefish (n = 242 summer; n = 439 winter) were processed for the study. Data from all study sites were pooled.

Sample Preparation

In preparation for conducting thaw and cooked drip analyses, 25-mm thick steaks were removed by band saw from just posterior to the pectoral fins of each frozen fish. The steaks were skinned and bones removed. Samples of nape meat frozen at the time the fish were caught were prepared for chemical analysis by partially thawing the meats and then homogenizing them by passing them through a 4-mm perforated plate attached to a food grinder.

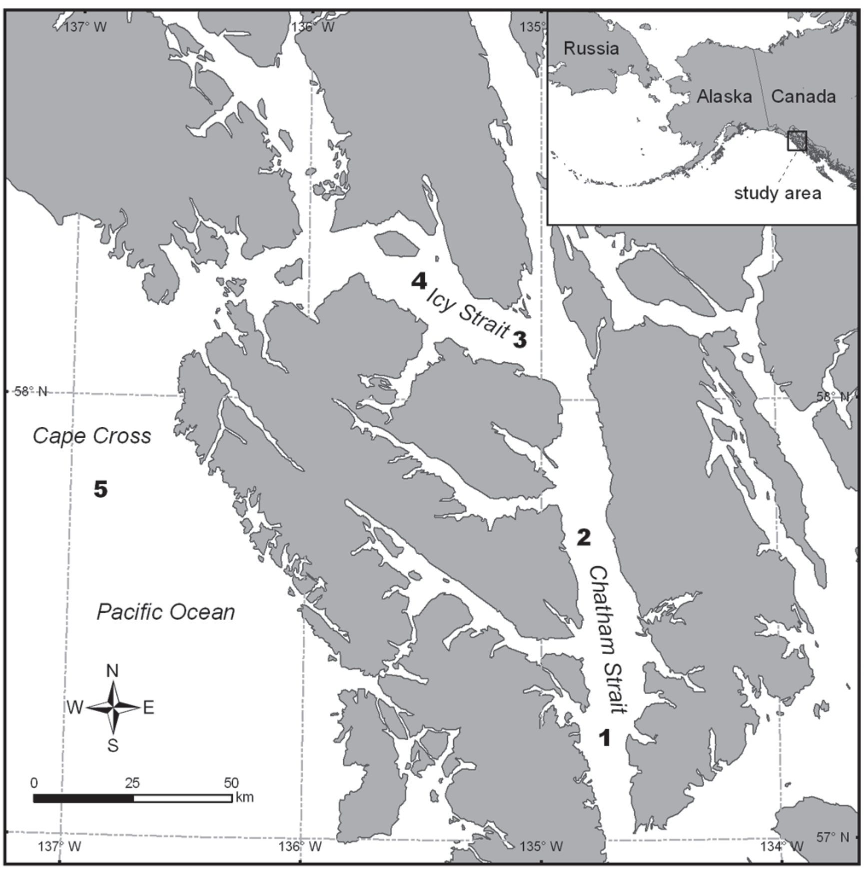

Figure 3.—Five general locations where sablefish were collected by longline, pots, or trawls: 1) near Kelp and Whitewater Bays, 2) near Tenakee, 3) Icy Strait—east entrance, 4) Icy Strait—Pleasant Island, and 5) Cape Cross. Specific locations (latitude and longitude), gear type, and catch information are available from the senior author. Trawling was done near sites 2–5 only.

Chemical Analyses

Samples were stored frozen at –29°C until analyzed chemically. Analyses for water (moisture), lipids, total protein, and ash were determined according to official AOAC methods (Horowitz, 1980). Protein was determined by the Kjeldhal[4] method and lipids were extracted using a soxhlet apparatus and methylene chloride solvent. Elemental (metal) analyses were made by atomic emission spectrometry as described by Teeny et al. (1984). Analyses were made for Na, K, Mg, Ca, P, Mn, Fe, Co, Cu, Sr, and Zn. Soluble protein was determined by the "salt extractable" nitrogen test or the modified Biuret method described by Snow (1950).

Thaw and Cooked Drip Analyses

To determine thaw and cooked drip loss, a steak sample from each fish was weighed and placed frozen in plastic, cook-in-the bag pouches with perforated bottoms that were in turn placed in slightly larger outer plastic bags. Half of the bags were weighted to ensure submersion of the sample during cooking. Samples were cooked in boiling water for 12 min. After removal from the boiling water, the samples in the inner bag were cooled and reweighed. Samples in the unweighted bags were suspended on racks and placed in a refrigerated cooler at 3°C and allowed to thaw for 24 h and reweighed after loss of water.

Data Analyses

Flesh condition—soft and firm—was tested for differences in total protein, lipid, gonad stage, pH, and yellow or yellow-green bile by capture depth

[4] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

Table 1.—Numbers of sablefish classified as firm or soft in winter catches from Chatham and Icy Straits and Cross Sound, Southeast Alaska, and in summer catches from Chatham and Icy Straits, Southeast Alaska.

Season	Flesh condition	Males	Females
		No. (%)	No. (%)
Winter	Firm	131 (74)	161 (61)
	Soft	45 (26)	102 (39)
	Total	176	263
Summer	Firm	45 (39)	52 (41)
	Soft	70 (61)	75 (59)
	Total	115	127

Table 2.—Numbers of firm and soft sablefish captured by longline (LL) and pots in the summer and winter by depth and by trawl in the winter only. Percent firm fish by season, gear, and depth are indicated.

Season	Gear	Flesh condition	Depth (m)				
			259–364	365–547	548–730	731–913	914–988
Summer	LL	Firm	45 (76%)	29 (48%)	4 (17%)	1 (4%)	6 (75%)
		Soft	14	32	19	26	2
	Pot	Firm	11 (73%)	0 (0%)	0 (0%)	1 (5%)	
		Soft	4	0	27	21	
Winter	LL	Firm		68 (89%)	24 (100%)	8 (16%)	
		Soft		8	0	42	
	Pot	Firm		39 (87%)	50 (100%)	8 (15%)	
		Soft		6	0	45	
	LL+Pot	Firm		107 (88%)	74 (100%)	16 (16%)	
		Soft		14	0	87	
	Trawl	Firm	22 (100%)	33 (63%)	40 (60%)		
		Soft	0	19	27		

with separate multiple linear regression models. Yellow or yellow-green bile is indicative of well fed or recently fed fish while progressively darker green shades to dark blue indicates fish not recently fed (Robb, 1992). Flesh condition was treated as a dichotomous predictor (Weisberg, 1985) in the models with soft fish coded as 0 and firm fish coded as 1. For a fixed depth, the estimated regression coefficient for flesh condition can be interpreted as the estimated difference in the dependent variable for the two flesh conditions. Seventeen biochemical and chemical components of flesh samples were tested with one-way ANOVA's for differences between the two flesh conditions.

The components tested for differences between the soft and firm flesh include K, Mg, P, Zn, pH, total protein, Ca, Co Mn, Fe, Na, Cu, Sr, soluble protein, lipid, ash, and water. The α-level of significance (0.05) was adjusted with a Bonferroni correction for performing multiple comparisons. Various length-weight regressions by flesh condition, season, gender, and gonad condition were fit for graphical comparison. Condition factor, computed as $K = 10^4 \times W(g) / L^3(cm)$, was compared for flesh condition and by season with a two-way ANOVA. Only immature or developing fish (maturity stages 1 and 2) were included in the analysis.

The relative weight loss of soft- and firm-flesh fish samples was compared for thawed and cooked processing with one-way ANOVA's. Relative weight loss (%) of processed samples was calculated as (post-weight–pre-weight)/pre-weight × 100. Analyses were performed separately for the summer and winter seasons. The tests were one-tailed as the soft flesh was hypothesized to lose more weight than firm flesh during thawing and cooking.

Results

Flesh Quality of Catch

By Season and Gender

More sablefish were subjectively classified as firm in the winter than in summer (Table 1). Firm males and females made up 67% of the winter catch (30% and 37%, respectively), but only 40% of the summer catch. The percentage of soft fish in the summer catch (61% males, 59% females) was, respectively, 2.3 and 1.5 times that seen in the winter. Soft females and males were about equally abundant in the summer landings, 59% and 61%, respectively, but soft females exceeded soft males in the winter catch (39% vs. 26%).

By Gear, Depth, and Season

Gear selectivity for flesh condition varied with type of gear and depth (Table 2). At the shallowest depth fished in summer (259–364 m) about three times more fish were designated firm than soft in catches from both longline and pot gear. At depths 365–547 m nearly equal numbers of firm and soft fish were taken by longline gear in the summer. At depths 548–913 m most fish were soft in longline and pot catches.

Catches in the winter with longlines and pots showed a similar trend but started deeper; at 365–547 m and 548–730 m most fish were firm while most fish were soft at 731–913 m. Trawls caught more firm fish than soft fish at all depths. In contrast, flesh quality composition of trawl catches was much different than the composition of combined longline and pot catches at the same depths in winter (Table 2). The proportion of firm fish in trawl catches was, respectively, 25% and 40% lower than pots and longline at depth intervals of 365–547 m and 548–730 m. No trawling was done in summer.

Catches of firm-fleshed sablefish on longlines and in pots declined with increasing depth in winter and summer (Table 2). Most of the fish caught in summer at depths shallower than 365 m were firm, but fish were increasingly soft-textured when caught at depths greater than 547 m. Most winter-caught fish (> 80%) were firm at depths in the shallow interval (365–547 m) and the middle interval (548–730 m). In both summer and winter the percentage of firm fish caught was low (4–16%) in the depth interval 731–913 m.

Sexual Maturation and Flesh Quality

Winter catches by gonad stage and quality of flesh were summed over depths and compared for longline plus pots (LL+POT) and trawl catches (Table 3). Most fish were gonad stage 1 or 2 (immature or developing), but a few were stage 3, 4, or 5 (gravid, ripe, or spent). The percentages of firm and soft fish of both sexes were similar and nearly overlapping for all three gear types. Spent females appear only in the soft category. Also, a greater percentage of maturity stages 3, 4, and 5 occurred among the soft fish compared to firm fish, especially for trawl catches.

Fish Condition by Season

Length-weight regressions for male fish judged to be firm or soft in flesh texture indicate that summer fish were generally heavier than winter fish of the same fork length. Fit for most of these regressions is good with R^2 values ranging from 0.76 to 0.91 (Table 4). Figure 4 shows the winter and summer maturity regressions for firm males. Firm summer males of 54 to 66 cm fork length (line 2) appear to be heavier than firm winter males of similar length (line 1). Gonad development further explains the differences in weight between firm males (Fig. 5). As gonads develop through stages 1–4, they account for an increasing proportion of weight to the overall mass of the fish. Length-weight regressions for firm and soft, winter and summer females (Fig. 6) show a similar length-weight relationship with respect to maturity stage but the slopes for the various gonad stages (Fig. 7) are different than the males.

To eliminate the influence of gonad weight on the summer and winter comparison of fish, we calculated the condition factor (K) for all fish that were immature or developing (maturity stages 1 and 2). The formula for the condition factor is $K = 10^4 \times W(g) / L^3(cm)$. Gonad weights in these fish would be less than other maturity stages. A two-way analysis of variance on condition factor (K) classified by season and flesh condition was calculated for these fish.

No evidence of interaction between season and flesh (ANOVA, $F = 1.16 \sim F_{1,577}$, $P = 0.28$) or a significant difference in flesh condition (ANOVA, $F = 0.54 \sim F_{1,577}$, $P = 0.46$) was seen but the seasonal difference was significant (ANOVA, $F = 1.16 \sim F_{1,577}$, $P = 0.02$). The summer fish had a higher mean condition factor (108.5, SE = 1.45) than the winter fish (104.6, SE = 0.70). Assuming that sablefish of all gonad developmental stages would show this difference in condition factor, we could expect fish caught in the summer to be about 3% heavier than fish caught in the winter.

Winter and summer differences in body weight were further examined by comparing the average weight of winter and summer fish (combined males and females) by length intervals (Table 5). These data show that mean weights of winter and summer caught fish differed by size groups. Small fish (< 58 cm) were 15% heavier in summer than in winter, but differences between other size groups varied from –2 to +9%. Overall, fish caught during the summer averaged 6% heavier than fish caught during the winter. We believe that gonad weights influenced the comparison of larger fish, winter versus summer, and therefore the 6% difference between mean weights of winter and summer fish is a minimum estimate. These data indicate that summer fish are clearly heavier than winter fish of the same length.

Depth of Capture vs. Proximate Analyses, Flesh Condition, and Gonad Stage

The relationships of total protein, lipid, gonad stage, pH, and green bile to depth of capture were complex and inconsistent (Table 6). Total protein, lipid, and green bile were related to flesh condition and depth of capture. Gonad

Table 3.—Numbers of sablefish with firm and soft flesh condition by gonad development caught in winter with longlines (LL) and pots versus trawls. Catches are summed over all depths and percentages by gonad stage are given in parentheses.

Gear	Gender	Flesh condition	Number by Gonad Stage[1] (%) 1	2	3	4	5	Total
LL+Pot	Male	Firm	55 (68)	16 (20)	1 (1)	9 (11)	0 (0)	81
		Soft	17 (68)	4 (16)	0 (0)	4 (16)	0 (0)	25
	Female	Firm	8 (7)	92 (79)	5 (4)	11 (9)	0 (0)	116
		Soft	0 (0)	48 (63)	6 (8)	11 (14)	11 (14)	76
Trawl	Male	Firm	14 (28)	33 (66)	3 (6)	0 (0)	0 (0)	50
		Soft	2 (10)	12 (60)	2 (10)	4 (20)	0 (0)	20
	Female	Firm	4 (9)	37 (82)	1 (2)	3 (7)	0 (0)	45
		Soft	0 (0)	11 (42)	1 (4)	12 (46)	2 (8)	26

[1] Maturity code: 1) immature, 2) maturing juvenile, 3) mature, 4) spawning, and 5) spent or post-spawning.

Table 4.—Fitted regressions of sablefish weight (*Y*) on length (*X*), associated figures, and summary statistics: residual degrees of freedom (d.f.), estimated standard error of regression ($\hat{\sigma}$), multiple correlation coefficient (R^2), the *F* statistic, and the *p*-value for the model (*P*). Gender, season, flesh condition, gonad stage, and fork length (cm) of samples are provided for each fitted regression line.

Figure	Gender	Season	Flesh condition	Gonad stage	Fork length (cm) range	Equation	d.f.	$\hat{\sigma}$	R^2	*F*	*P*
4, line 1	Male	Winter	Firm	All	37–68	$Y = -8.45 + 0.23\,X$	129	0.52	0.86	778.5	< 0.001
4, line 2	Male	Summer	Firm	All	54–67	$Y = -13.26 + 0.31\,X$	16	0.47	0.85	88.0	< 0.001
4, line 3	Male	Winter	Soft	All	51–70	$Y = -9.42 + 0.24\,X$	43	0.35	0.90	389.1	< 0.001
4, line 4	Male	Summer	Soft	All	54–72	$Y = -8.89 + 0.24\,X$	50	1.04	0.48	46.6	< 0.001
5, line 1	Male	Winter	Firm	1	37–68	$Y = -6.69 + 0.19\,X$	67	0.37	0.90	580.9	< 0.001
5, line 2	Male	Winter	Firm	2	49–64	$Y = -10.85 + 0.27\,X$	47	0.61	0.76	151.3	< 0.001
5, line 4	Male	Winter	Firm	4	55–68	$Y = -9.13 + 0.25\,X$	7	0.43	0.87	48.2	< 0.001
6, line 1	Female	Winter	Firm	All	39–85	$Y = -11.06 + 0.27\,X$	159	0.70	0.91	1653.0	< 0.001
6, line 2	Female	Summer	Firm	All	45–70	$Y = -10.11 + 0.26\,X$	15	0.47	0.90	140.5	< 0.001
6, line 3	Female	Winter	Soft	All	48–93	$Y = -17.61 + 0.38\,X$	100	1.26	0.90	927.8	< 0.001
6, line 4	Female	Summer	Soft	All	52–84	$Y = -10.33 + 0.26\,X$	53	1.37	0.77	181.1	< 0.001
7, line 2	Female	Winter	Soft	2	47–78	$Y = -12.00 + 0.29\,X$	57	0.77	0.86	349.4	< 0.001
7, line 4	Female	Winter	Soft	4	68–96	$Y = -29.18 + 0.53\,X$	21	1.21	0.91	202.7	< 0.001
7, line 5	Female	Winter	Soft	5	65–93	$Y = -22.40 + 0.43\,X$	11	1.75	0.81	45.7	< 0.001

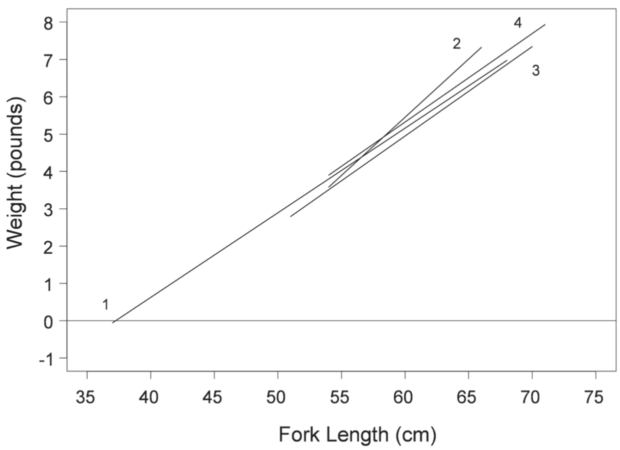

Figure 4.—Length-weight regressions for male sablefish: 1) firm winter, 2) firm summer, 3) soft winter, and 4) soft summer. See Table 4 for data on lines 1–4.

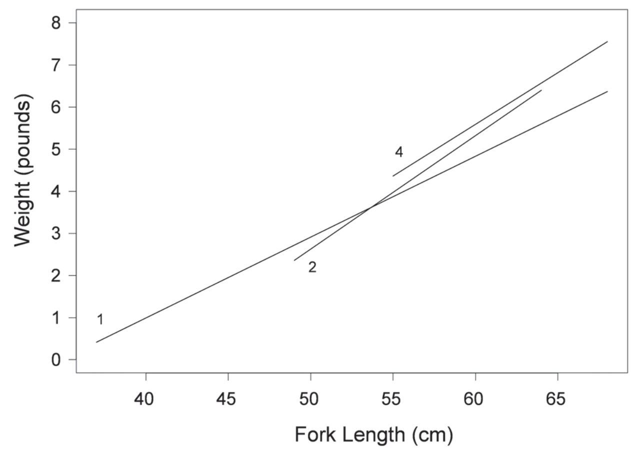

Figure 5.—Length-weight regressions for firm winter male sablefish by gonad stages 1, 2, and 4. See Table 4 for data on lines 1, 2, and 4.

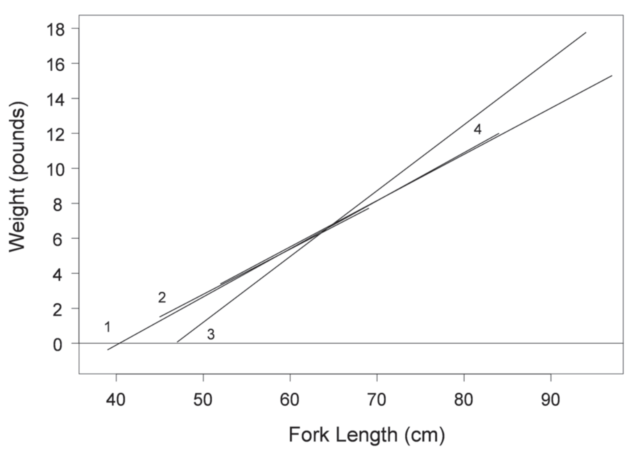

Figure 6.—Length-weight regressions for 1) firm winter, 2) firm summer, 3) soft winter, and 4) soft summer female sablefish. See Table 4 for data on lines 1–4.

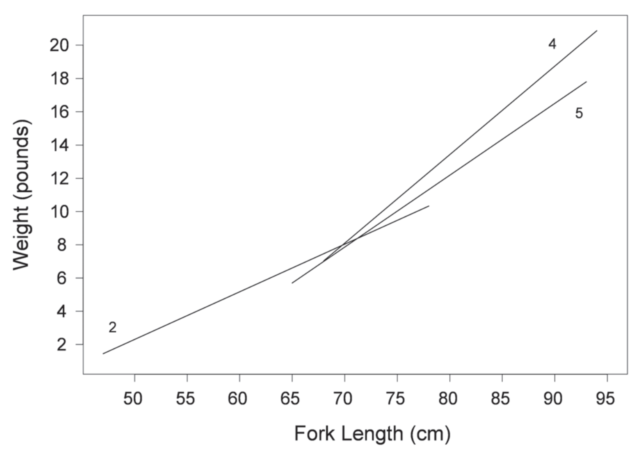

Figure 7.—Length-weight regressions for soft winter female sablefish by gonad stages 2, 4, and 5. See Table 4 for data on lines 2, 4, and 5.

development was related to depth of capture but only marginally related to flesh condition. Conversely, flesh pH was related to flesh condition but not to depth of capture.

Proximate Composition and Electrolyte Analyses and Flesh Condition

Among 17 variables (including protein, lipid, and pH previously mentioned) that we examined in sablefish flesh, 11 showed significant differences between firm and soft fish (Table 7). Variables for which the means were higher for soft fish compared to firm fish included lipid, water, and the electrolytes sodium (Na) and strontium (Sr). All other means were lower for the soft fish. Higher sodium and lower potassium (K) in white muscle of fish are usually indicative of starvation (Love, 1980). Similar differences in sodium

Table 5.—Average weight (g), sample sizes (*n*), and percent difference in weight by length interval for combined male and female sablefish in winter and summer. Only sablefish of maturity stages 1 and 2 were included. The average percent difference in weight was 6%.

	Length interval (cm)					
Weight	< 58	58–60	60–63	63–66	66–69	69–97
Winter	1,525	2,104	2,444	2,881	3,253	3,979
n	173	38	54	37	30	21
Summer	1,749	2,135	2,636	2,931	3,195	4,354
n	16	18	34	21	20	33
% difference	15	2	8	2	–2	9

Table 6.—Summary statistics for the multiple linear regressions of total protein, lipid, gonad stage, pH, and green bile on flesh condition (soft coded as 0 and firm coded as 1) and depth of capture. Summary statistics are the estimated regression coefficients (Coefficient), the standard error of the estimate (SE), the *t*-statistic (*t*), and the marginal *p*-value (*P*). Also reported are the estimated standard error of regression ($\hat{\sigma}$), multiple correlation coefficient (R^2), the *F* statistic and associated degrees of freedom, and the *p*-value (*P*).

Variable	Coefficient	SE	*t*	*P*
Total Protein				
Intercept	132.79	4.36	30.4	< 0.001
Flesh condition	12.75	2.60	4.9	< 0.001
Depth	–0.02	0.01	–3.5	< 0.001
$\hat{\sigma}$ = 12.8; multiple R^2 = 0.36; $F_{2, 176}$ = 49.7; $P < 0.001$				
Lipid				
Intercept	192.11	15.25	12.6	< 0.001
Flesh condition	–33.08	9.09	–3.6	< 0.001
Depth	–0.06	0.02	–3.0	0.003
$\hat{\sigma}$ = 44.5; multiple R^2 = 0.07; $F_{2, 176}$ = 7.0; P = 0.001				
Gonad				
Intercept	1.06	0.29	3.7	< 0.001
Flesh condition	0.25	0.17	1.5	0.14
Depth	1.6e–3	3.7e–4	4.2	< 0.001
$\hat{\sigma}$ = 0.8; multiple R^2 = 0.10; $F_{2, 176}$ = 10.2; $P < 0.001$				
pH				
Intercept	6.74	0.06	119.1	< 0.001
Flesh condition	0.18	0.03	5.4	< 0.001
Depth	–4.1e–5	7.4e–5	–0.6	0.58
$\hat{\sigma}$ = 0.2; multiple R^2 = 0.24; $F_{2, 176}$ = 28.1; $P < 0.001$				
Green bile				
Intercept	–6.25	1.16	–5.4	< 0.001
Flesh condition	5.71	0.69	8.2	< 0.001
Depth	0.01	1.5e–3	8.2	< 0.001
$\hat{\sigma}$ = 3.4; multiple R^2 = 0.32; $F_{2, 176}$ = 41.1; $P < 0.001$				

Table 7.—Means, standard deviations (S.D.), and probabilities (*P*) for the ANOVA models for firm (*n* = 64) and soft (*n* = 115) sablefish tested for differences among 17 biochemical variables.

	Flesh condition		
	Firm	Soft	
Variable[1]	Mean (S.D.)	Mean (S.D.)	*P*
K	3669.8 (461.7)	3351.5 (252.4)	< 0.001[2]
Mg	260.1 (28.5)	215.1 (23.1)	< 0.001[2]
P	1928.9 (150.4)	1700.8 (116.1)	< 0.001[2]
Zn	3.1 (0.6)	2.5 (0.4)	< 0.001[2]
pH	6.9 (0.1)	6.7 (0.2)	< 0.001[2]
Protein (Total)	136.8 (12.0)	118.2 (13.8)	< 0.001[2]
Ca	60.9 (21.6)	49.1 (17.7)	< 0.001[2]
Co	0.02 (0.02)	0.01 (0.007)	< 0.001[2]
Mn	0.08 (0.07)	0.05 (0.03)	< 0.001[2]
Fe	4.6 (4.2)	3.0 (1.3)	< 0.001[2]
Na	494.1 (95.2)	595.9 (206.3)	< 0.001[2]
Cu	0.25 (0.09)	0.21 (0.1)	0.01
Sr	0.22 (0.11)	0.26 (0.1)	0.02
Protein (Soluble)	64.3 (8.9)	60.5 (11.2)	0.02
Lipid	132.6 (53.4)	148.1 (40.6)	0.03
Ash	10.6 (1.1)	10.3 (0.9)	0.04
Water	720.7 (49.0)	726.1 (48.4)	0.48

[1] Protein, lipid, ash, and water are in units of mg/g; all others except pH are in units of µg/g.
[2] Significant test with α = 0.05 and a Bonferroni correction of 1/17.

Table 8.—Means, standard errors of the means (SE), and sample sizes (*n*) for the relative drip and cook drip loss (%) of the winter and summer samples. Relative weight loss (%) is calculated as (post-weight–pre-weight) / pre-weight × 100.

	Winter						Summer					
	Firm			Soft			Firm			Soft		
	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*
Thaw	5.6	0.41	93	14.6	0.68	138	8.3	0.80	33	6.7	0.64	84
Cook	21.7	0.70	94	29.8	0.44	128	18.9	1.43	36	24.0	0.89	84

and potassium have also been observed in spawning salmon (Tomlinson et al., 1967). In laboratory studies, Sullivan and Somero (1983) were able to induce physiological changes in starved sablefish that closely resemble the biochemical and physical characteristics of soft fish that we observed in the research reported here.

Differences in mean chemical constituents in soft compared to firm fish were as follows: protein was lower by 14% from 137 mg/g to 118 mg/g, water was higher by 1% from 721 mg/g to 726 mg/g (but not significantly), lipid was higher by 12% from 133 mg/g to 148 mg/g, and ash was lower by 3% (Table 7).

Yield Analysis

Changes in weight of winter and summer samples during the processes of thawing and cooking are shown in Table 8. Soft sablefish lost 45% more thaw drip loss in 24 h and 24% more cooked drip loss than the firm sablefish. Average weight loss in the thaw drip loss test was 6% for the firm fish and 12% for soft fish. In the cooked drip loss test, average losses for firm- and soft-textured fish were 21% and 27%, respectively.

Yield differed in winter and summer by flesh quality, but not consistently. Thaw drip loss for soft fish in winter was more than twice that of summer caught fish (14.6% vs. 6.7%). Thaw drip loss for firm fish averaged 8.3% in summer and 5.6 % in winter.

Differences in cooked drip loss in winter and summer were not great between firm and soft fish. Cooked drip loss for firm fish in winter averaged 21.7%, while soft fish averaged 29.8%. In summer the cooked drip loss was 18.9% for firm fish and 24.0% for soft fish.

The relative weight loss of the soft-flesh samples in winter was significantly higher than the firm-flesh samples for both the thawed (ANOVA, $F = 99.0 \sim F_{1,229}$, $P < 0.001$) and cooked samples (ANOVA, $F = 106.1 \sim F_{1,220}$, $P < 0.001$) (Table 8, Fig. 8). The relative weight loss of the summer, thawed samples was not significantly higher for the soft-flesh samples than for the firm-flesh samples (ANOVA, $F = 2.0 \sim F_{1,115}$, $P = 0.16$) (Fig. 9a); however, the soft-flesh samples lost significantly more relative weight during the cooking process (ANOVA, $F = 9.3 \sim F_{1,118}$, $P = 0.003$) (Fig. 9b).

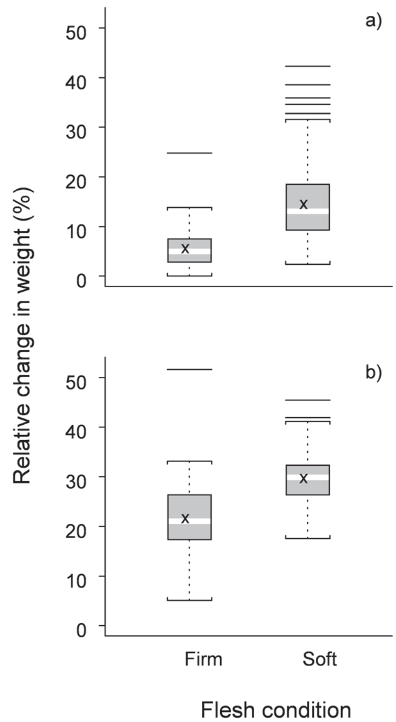

Figure 8.—Boxplots of relative change in weight (%) for a) thawed and b) cooked winter samples by flesh condition. The mean is indicated by X.

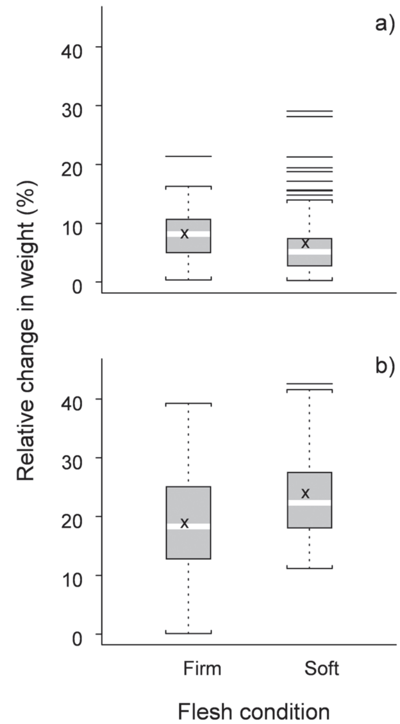

Figure 9.—Boxplots of relative change in weight (%) for a) thawed and b) cooked summer samples by flesh condition. The mean is indicated by X.

Discussion

Biological, Physiological, and Environmental Factors

Several factors may be contributing to the observed incidence of soft flesh in sablefish: reproductive cycle, distribution of fish over a greater depth range as they mature and grow, changes in diet as they move deeper in the water column, and physiological changes induced by increased pressure. We have noted soft flesh in sablefish after spawning but have not determined whether spawning itself or their presence at great depth (> 300 m) contributes to the incidence of soft flesh. Most of the soft fish are dark black in color, and their size range extends from small, recently-maturing fish to very large females that have spawned several times. This suggests that depth of occurrence may have a major influence on the development of soft flesh but the reproductive cycle may exacerbate its development. We need to examine available tag data reports on soft female sablefish to determine if individual fish remain soft following spawning at great depth.

Effects of Time and Depth of Fishing and Gear Type on Catch Composition and Yield

Results of our study indicate that regulating time of fishing, depth of fishing, and gear type may increase the number of firm sablefish in catches. Yield from soft fish is considerably less than from firm fish (this study; Norris et al.[1]; Patashnik et al.[3]); therefore, it is important to optimize the catch of firm fish. Yield is also dependent upon the condition factor of the fish or weight per given length. Our study shows that summer fish of all flesh conditions are on average 6% heavier than winter fish; therefore, yield from summer fish would be expected to be higher. Summer catches of sablefish, however, have 27% more soft-fleshed fish, which would reduce their overall yield.

If fishing were in late summer, would the increased yield from heavier fish offset the loss from soft fish? Probably not, because loss of yield from soft sablefish is considerable: 45% greater thaw drip loss from thawed raw fillets and 24% greater cooked drip loss. Although not measured here, there is also a loss of quality associated with the loss of drip in that nutrients such as protein, nitrogen, essential electrolytes, and other flavor components are removed with the drip (Miyauchi and Spinelli, 1967). Storage temperature could also significantly affect the composition and amount of drip produced in soft-textured sablefish. Storage temperatures of –20°C, commonly used in commercial cold storage facilities, would be expected to produce a higher thaw and cooked drip loss than storage at –30°C (Miyauchi, 1963).

The numbers of sablefish with soft flesh are probably of more importance to overall yield than small differences in physical conditions. A detailed calculation of overall yields from summer and winter catches is beyond the scope of this paper, but based on available information, winter catches would probably produce higher yields. Fishing all depths in winter (Jan.–Feb.) would yield a catch consisting of 67% firm fish, whereas the summer catch (June–Aug.) would yield only 40% firm fish. Presently the season in Chatham Strait is from 15 Aug. to 15 Nov. We have no information on the composition of the catch regarding flesh condition from this area from September to November but expect it would be between 40% and 60% firm fish over all fishing depths. Based on the results of our research, it appears that the commercial season in Chatham Strait may already be at the optimum time.

Regulating the depth of fishing also has the potential for increasing the yield from sablefish landings. Depth distribution of sablefish changes by season; however, all appeared to move deeper in winter. Firm fish were located at shallower depths (< 365 m) in summer but appeared to be located in deeper water (< 548 m) in the winter. Soft fish also appeared to be in deeper water in the winter from 548 to 730 m or more. Limiting fishing to depths where soft fish are less abundant may increase yield from the catch and reduce waste of soft fish. If fishing were limited to less than 731 m in winter, the catch would produce about 82% firm fish.

How much this would affect the overall catch is not clear; 23% of the winter catch in our study was from depths greater than 730 m. If, on the other hand, fishing in the summer were limited to less than 548 m, the catch would yield about 63% firm fish. However, the overall catch may be reduced because 44% of the summer catch in our study came from depths greater than 547 m. Catches from depths greater than 730 m have more large fish in winter and summer; therefore, the average weight of fish would probably be less if the above depth changes were adopted.

How changes in fishing depth and season would affect the offshore fishery is not clear. Presently, the sablefish fisheries in both the Gulf of Alaska and the Bering Sea use fixed gear (longlines and pots) under Individual Fishing Quota (IFQ) programs. The fixed gear seasons open 15 Mar. and close 15 Nov. Only one of our study sites (Cross Sound) was in offshore waters. Distribution of firm- and soft-textured fish by depth at this site was similar to the Chatham Strait sites, so perhaps our study results could be applied.

Whether regulating fishing depth is feasible and beneficial to yield depends upon several factors: 1) the present depth distribution of fishing effort, 2) the area of depth strata available, and 3) the distribution of fish by depth. Clearly more information is needed before one can determine the impact of depth regulations on yield.

The effect of gear selectivity for soft fish seems clear. Longlines and pots took similar proportions of soft fish in both summer and winter. Trawl catches contained a higher proportion of soft fish compared to longlines and pots, perhaps because soft fish may be less attracted to bait and are, therefore, less available to longlines and pots. Trawls would take them regardless of feeding behavior.

Relationship of Biochemistry to Soft Flesh

Biochemistry of sablefish flesh differs from soft to firm. A better understanding of the cause-effect relationship of the soft flesh problem would help us predict its distribution in time and location. Differences in flesh quality may be the result of genetic variability or the prolonged exposure to different environmental factors associated with depth as hypothesized in previous studies (Norris et al.[1]). Food availability, food quality, activity level, temperature, and pressure are all factors associated with depth, which could change the physiology and biochemistry of sablefish. Sablefish (Sullivan and Smith, 1982) and many other mesopelagic and bathypelagic fishes living at great depths (Siebenaller and Somero, 1989; Drazen, 2007) have been shown to have higher water content and lower protein and lipid content than species living at shallow depths. Deepwater species adapt biochemically by lowering metabolic and enzyme rates to conserve energy and change physiological processes by reducing locomotory activity in response to living in an environment where food resources are sparse and meals infrequent (Drazen, 2007). Metabolic rates of vertically migrating mesopelagic fish decreased with increase in depth of occurrence (Karinen, 1965), but the duration of time at depth necessary to initiate biochemical changes has not yet been established. Foy et al. (2006) investigated the roles of temperature, pH, and exercise in the development of "chalkiness" in Pacific halibut, *Hippoglossus stenolepis*, but were not able to reproduce the effects in halibut held and exercised to exhaustion in a laboratory experiment. Reproductive development may also influence the biochemical composition of fish flesh as shown by our data.

Results of our study seem contradictory with respect to determining the cause of soft flesh in sablefish. Is it diet, parasites, depth of occurrence, life stage, or genetics? High sodium, low potassium, and yellow to yellow-green bile in soft fish are all indicative of well-fed fish (McCormick and Podoliak, 1984). Parasites can cause soft flesh; myxosporean parasites are known to cause soft flesh in Atlantic mackerel, *Scomber scombrus* (Levsen et al., 2008). Some species of these parasites are known to be present in the North Pacific but it is unlikely that such parasites were present in our study because cysts (black or white) in the flesh can usually be seen with the naked eye and the flesh liquefies when cooked. Perhaps one way to answer the question of cause and effect would be to determine the genetic types and variability of firm and soft sablefish (Tsuyuki and Roberts, 1969).

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