Survey- and fishery-derived estimates of Pacific cod (*Gadus macrocephalus*) biomass: implications for strategies to reduce interactions between groundfish fisheries and Steller sea lions (*Eumetopias jubatus*)

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Abstract—Survey- and fishery-derived biomass estimates have indicated that the harvest indices for Pacific cod (*Gadus macrocephalus*) within a portion of Steller sea lion (*Eumetopias jubatus*) critical habitat in February and March 2001 were five to 16 times greater than the annual rate for the entire Bering Sea-Aleutian Islands stock. A bottom trawl survey yielded a cod biomass estimate of 49,032 metric tons (t) for the entire area surveyed, of which less than half (23,329 t) was located within the area used primarily by the commercial fishery, which caught 11,631 t of Pacific cod. Leslie depletion analyses of fishery data yielded biomass estimates of approximately 14,500 t (95% confidence intervals of approximately 9,000–25,000 t), which are within the 95% confidence interval on the fished area survey estimate (12,846–33,812 t). These data indicate that Leslie analyses may be useful in estimating local fish biomass and harvest indices for certain marine fisheries that are well constrained spatially and relatively short in duration (weeks). In addition, fishery effects on prey availability within the time and space scales relevant to foraging sea lions may be much greater than the effects indicated by annual harvest rates estimated from stock assessments averaged across the range of the target species.

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For the past 30 years, the Steller sea lion (*Eumetopias jubatus*) population in western Alaska has declined (Braham et al., 1980; Sease and Gudmundson[1]). The species was listed as threatened under the U.S. Endangered Species Act (ESA) in 1990 after evidence of a major decline in abundance in the core of its range from the Kenai Peninsula in south-central Alaska to Kiska Island in the western Aleutian Islands (Braham et al., 1980; Merrick et al., 1987). After the decline was first observed in the eastern Aleutian Islands in the early 1970s (Braham et al., 1980), it spread eastward to Prince William Sound and westward through Russia during the next decade (Merrick et al., 1987; Loughlin et al., 1992). From the early 1970s to 1990, counts of adult and juvenile Steller sea lions declined by over 70%, but annual rates of decline were most severe between 1985 and 1989 (–15%/yr; Loughlin et al., 1992). During the 1990s, the decline slowed to approximately –5%/yr and may have temporarily abated in many areas by 2002 (Sease and Gudmundson[1]).

Understanding the causes for the decline and lack of recovery in the Steller sea lion population has largely eluded scientists and managers, despite the millions of dollars spent on scientific research (Ferrero and Fritz[2]) and numerous reviews by academic (Alaska Sea Grant[3]; DeMaster and Atkinson[4]; NRC, 1996; 2003) and governmental panels (Kruse et al.[5]; NMFS[6,7,8,9]). Although recent reviews

[1] Sease, J. L., and C. J. Gudmundson. 2002. Aerial and land-based surveys of Steller sea lions *(Eumetopias jubatus*) from the western stock in Alaska, June and July 2001 and 2002. NOAA Tech. Memo. NMFS-AFSC-131, 45 p. Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle WA 98115.

[2] Ferrero, R. C., and L. W. Fritz. 2002. Steller sea lion research coordination: a brief history and summary of recent progress. NOAA Tech. Memo. NMFS-AFSC-129, 34 p. Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle WA 98115.

[3] Alaska Sea Grant. 1993. Is it food?: Addressing marine mammal and seabird declines. Workshop summary rep. AK-SG-93-01, 59 p. Univ. Alaska Fairbanks, Alaska Sea Grant College Program, Fairbanks AK 99775.

[4] DeMaster, D., and S. Atkinson. (eds.). 2002. Steller sea lion decline: Is it food? II. Workshop summary. rep. AK-SG-02-02, 80 p. Univ. Alaska Fairbanks, Alaska Sea Grant College Program, Fairbanks AK 99775.

[5, 6, 7, 8, 9] *See next page.*

(Kruse et al.[5]; DeMaster and Atkinson[4]; NRC, 2003) concluded that "top-down" forces, such as predation or illegal shooting, are greater threats to recovery of the Steller sea lion population, they could not eliminate "bottom-up" factors from consideration. NRC (2003) suggested that NMFS conduct an adaptive management experiment to determine the magnitude of one such "bottom-up" force, nutritional stress resulting from competition with fisheries for prey (NMFS[6,7,8,9]; NRC, 2003). The North Pacific is home to some of the largest fisheries in the world, particularly those for groundfish such as Pacific cod (*Gadus macrocephalus*) and walleye pollock (*Theragra chalcogramma*). Steller sea lions eat a wide variety of fish and cephalopods, including Pacific cod, walleye pollock, Atka mackerel (*Pleurogrammus monopterygius*), arrowtooth flounder *(Atherestes stomias*), salmon (*Oncorhynchus* spp.), herring (*Clupea pallasi*), capelin (*Mallotus villosus*), eulachon (*Thaleichthys pacificus*), sand lance (*Ammodytes hexapterus*), squid, and octopus (Sinclair and Zeppelin, 2002). A large proportion of their diet, however, is composed of semidemersal or pelagic schooling fish, particularly fish in spawning migrations or aggregations nearshore. These same species are often targeted at the same time and in the same areas by groundfish fisheries, particularly those fisheries that use trawl gear. Concerns about the potential of fisheries to create localized depletions of prey in important sea lion foraging habitats have led to controversial groundfish fishery restrictions throughout most of Alaska (NMFS[8,9]).

Assessment models and fisheries harvest strategies have determined the overall fishing mortality rate that can be allowed for the stock and the amount of biomass that can be removed. In practice, however, catches are not uniformly distributed across the range of the assessed stock nor are they distributed equally throughout the year. Although there is evidence that the Atka mackerel trawl fishery has created localized depletions of its target species (NMFS[6] Lowe and Fritz, 1997; NRC, 2003), this finding has not been generally applied to fisheries for other sea lion prey. Trawl fisheries in the Aleutian Islands may have, in certain instances, reduced local abundances of Atka mackerel by as much as 90% (Lowe and Fritz, 1997). Atka mackerel and its fishery have characteristics that permitted analysis of fishery data in this way. The species does not possess a swim bladder and thus makes a poor acoustic target. As a consequence, the Atka mackerel fishery does not target on an acoustic signal, but instead trawls in areas where the species is known to congregate. Through the analysis of time series of catch and effort statistics from local fisheries with Leslie's equation (Ricker, 1975; Hilborn and Walters, 1992; Gunderson, 1993), estimates of the initial abundance of Atka mackerel (prefishery) and its catchability (proportion of the stock caught with one unit of effort) were made within the context of certain assumptions, which included the following: 1) the population being fished is closed, or alternatively that immigration and growth are equal to emigration plus natural mortality, 2) catchability over the course of the fishery remains constant, and 3) changes in catch per unit of effort (CPUE) are directly related to changes in fish density. These assumptions may be met for marine species if the area fished is well defined (e.g., is surrounded by habitat that is unsuitable for the species), the duration of the fishing season is relatively short, or the species is relatively sedentary (Polovina, 1986; Ralston, 1986; Joll and Penn, 1990; Miller and Mohn, 1993). Although they indicate that fisheries have created local depletions of Atka mackerel, these models are difficult to apply to other North Pacific fisheries because of a lack of fishery-independent estimates of biomass and by circumstances unique to the Atka mackerel fishery (e.g., the fishery trawls in areas where the species is known to congregate rather than uses acoustic signal, Atka mackerel are patchily distributed, and patches are separated by areas with low fish density).

To obtain information on the winter distribution of groundfish in areas used by foraging Steller sea lions and groundfish fisheries, the Alaska Fisheries Science Center of the National Marine Fisheries Service conducted a bottom trawl survey for groundfish in the southeastern Bering Sea north of Unimak Island in February–March 2001 (Fig. 1). This area is important to the Pacific cod fishery in winter because cod aggregate in this area to spawn (Shimada and Kimura, 1994). It is also recognized as an important foraging area for Steller sea lions because it is designated as critical habitat under the ESA (NMFS[7,8]).

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[5] Kruse, G. H., M. Crow, E. E. Krygier, D. S. Lloyd, K. W. Pitcher, L. D. Rea, M. Ridgway, R. J. Small, J. Stinson and K. M. Wynne. 2001. A review of proposed fishery management actions and the decline of Steller sea lions (*Eumetopias jubatus*) in Alaska: a report by the Alaska Steller sea lion restoration team. Regional information report 5J01-04, 106 p. Alaska Dep. Fish and Game, P.O. Box 25526, Juneau AK 99802.

[6] NMFS (National Marine Fisheries Service). 1998. Endangered Species Act Section 7 Consultation on an Atka mackerel fishery under the BSAI groundfish FMP between 1999 and 2002; authorization of a walleye pollock fishery under the BSAI FMP between 1999 and 2002; and under the GOA FMP between 1999 and 2002, 189 p. NMFS Protected Resources Division, Alaska Region, P.O. Box 21668, Juneau, AK 99802.

[7] NMFS. 2000. Endangered Species Act. Section 7: Consultation, biological opinion and incidental take statement on the authorization of the Bering Sea-Aleutian Islands and Gulf of Alaska groundfish fisheries based on the Fishery Management Plans, 352 p. NMFS Protected Resources Division, Alaska Region, P.O. Box 21668, Juneau, AK 99802.

[8] NMFS. 2001. Endangered Species Act. Section 7: Consultation, biological opinion and incidental take statement on the authorization of the Bering Sea-Aleutian Islands and Gulf of Alaska groundfish fisheries based on the Fishery Management Plans as modified by Amendments 61 and 70, 206 p. NMFS Protected Resources Division, Alaska Region, P.O. Box 21668, Juneau, AK 99802.

[9] NMFS. 2003. Supplement to the Endangered Species Act. Section 7: Consultation, biological opinion and incidental take statement of October 2001, 179 p. NMFS Protected Resources Division, Alaska Region, P.O. Box 21668, Juneau, AK 99802.

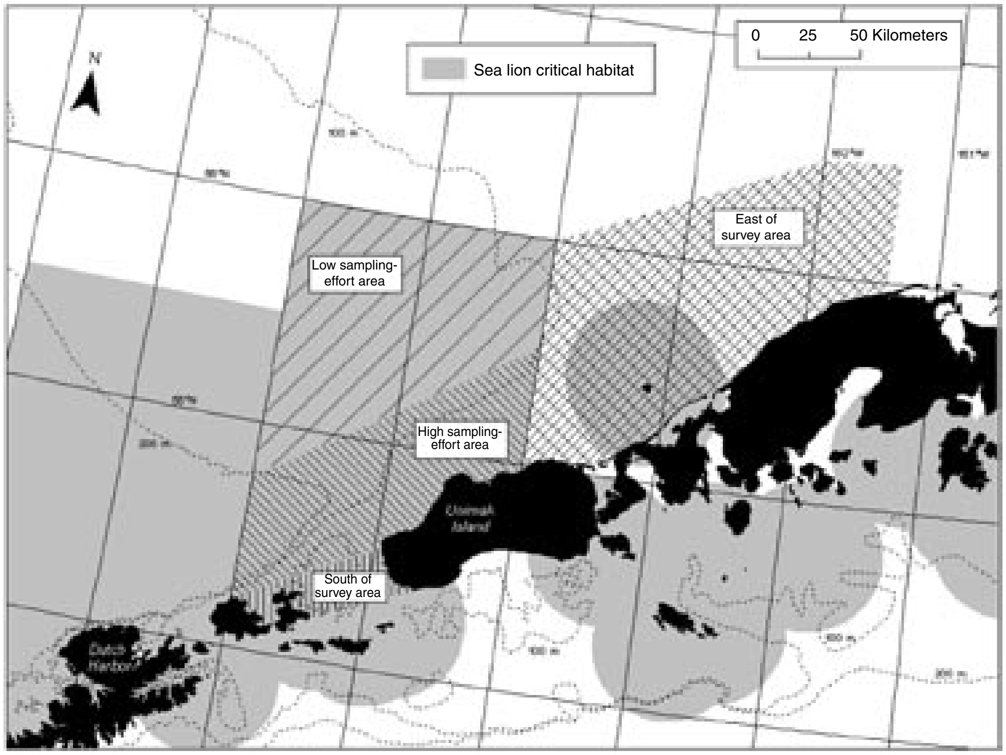

Figure 1

The four areas (high and low sampling-effort survey areas, the area east of the survey area, and the area south of the survey area) in the southeastern Bering Sea that were surveyed in February–March 2001 for groundfish with a bottom trawl and used for analysis of Pacific cod (*Gadus macrocephalus*) fishery data. Steller sea lion (*Eumetopias jubatus*) critical habitat is also shown.

In this article, estimates of Pacific cod biomass from Leslie depletion analyses of fishery data are compared with those derived from a bottom trawl survey conducted in the same area at the same time. These two methods are independent because they use completely different data to estimate the same parameter, Pacific cod biomass. If they yield similar results, they would support each other in the estimate of local area cod biomass and support the use of Leslie depletion analyses of data from relatively short and spatially well-defined fisheries operations for making such estimates. Furthermore, these comparisons increase our understanding of the potential local effects of a fishery in areas important for sea lion foraging and permit comparison with the results of assessments of the Pacific cod stock in the entire eastern Bering Sea (Thompson and Dorn, 2002). In this instance, if the change in Pacific cod abundance attributable to the fisheries north of Unimak Island is not greater than what would have occurred if catch were evenly distributed throughout the year and across the range of the stock, then it could be argued that no localized depletion occurred. However, if the local change in abundance is greater than expected, does this constitute a localized depletion of the species? The answer ultimately depends on the extent to which the fishery negatively affects the target species (e.g., by reducing recruitment) or, as in our case, by reducing the foraging success of sea lions, which, in turn, could lead to reduced survival or reproductive rates. Although we do not know what the threshold levels of change in local prey densities are for foraging Steller sea lions, it is first necessary to determine the level of change in local abundance that may be attributable to fisheries.

There are several aspects of Pacific cod life history in the eastern Bering Sea that make it difficult to use fishery data and the Leslie depletion method to estimate local area biomass. The most important may be that the population in the area fished may not be closed over the time period analyzed. Pacific cod spawn north of Unimak Island in late winter but apparently arrive in groups and, after spawning, leave the area and spread out on the eastern Bering Sea shelf to feed during the remainder of the year (Shimada and Kimura, 1994; Thompson and Dorn, 2002). Seasonal emigration from and immigration into spawning areas in critical habitat, modeled with a combination of fishery and survey data by NMFS scientists[10] (Fig. 2), provide a baseline

[10] NMFS. 2000. Estimation of monthly Pacific cod biomass inside Steller sea lion critical habitat. *In* Biological opinion questions, NMFS-AKC analytical team. Unpubl. manuscript, 112 p. Alaska Fisheries Science Center, 7600 Sand Point Way NE, Seattle WA 98115.

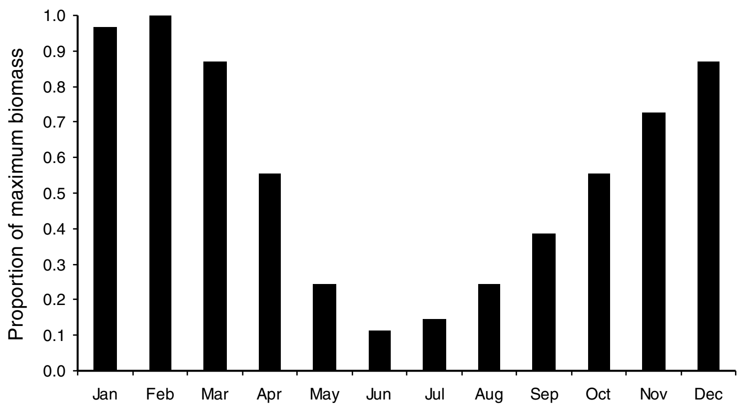

Figure 2

Proportion of maximum (in February) biomass of Pacific cod (*Gadus macrocephalus*) within Steller sea lion (*Eumetopias jubatus*) critical habitat in the eastern Bering Sea by month (see Footnote 10 in the general text).

against which possible changes related to local fisheries can be compared. The model results indicate that the highest biomass in critical habitat (largely on the shelf north of Unimak Island) occurs in February, declines to about 10% of the peak in June, and then slowly rebuilds through the summer and fall. Changes in the behavior of Pacific cod immediately prior to or after spawning, such as the formation of dense aggregations or the temporary cessation of feeding, would affect catchability by both trawl and fixed gears. However, abrupt changes in catchability due to the formation of aggregations should be evident within the time series of catch and effort data, and changes in feeding habits would not affect the catchability by trawl gear.

Methods

Bottom trawl survey

Stations sampled during the bottom trawl survey were selected by using a stratified random scheme. Two strata were defined: one with a high and another with a low degree of sampling effort, based on the expected distribution and abundance of Pacific cod from fishery information. In the nearshore or high sampling-effort stratum (7765 km^2), 38 stations were sampled, whereas 19 stations were sampled in the larger (12,112 km^2), offshore low sampling-effort stratum (Fig. 1). All survey tows were conducted during daylight hours from 16 February to 1 March 2001 aboard the FV *Northwest Explorer* and the FV *Ocean Harvester*. The 49-m FV *Northwest Explorer* was equipped with two 1800-hp engines, and the 33-m FV *Ocean Harvester* had a single 1250-hp engine. Both vessels were house-forward trawlers that had stern ramps, multiple net storage reels, and paired hydraulic trawl winches with 1280–2190 m of 2.54-cm diameter steel cable. Each vessel carried a full complement of navigation and fishing electronics, including global positioning systems (GPS), video position plotters, radars, and depth sounders.

A Poly-Nor'eastern high-opening bottom trawl rigged with roller gear was used to sample the groundfish community at each selected location. The trawl net was constructed of 12.7-cm stretched-mesh polyethylene web and had a 3.2-cm stretched-mesh nylon liner in the codend. Accessory gear for the Nor'eastern trawl included three 54.9 m, 1.6 cm diameter galvanized wire rope bridles, and 1.8 × 2.7 m steel V-doors weighing approximately 850 kg each.

Biomass (B) estimates for each stratum surveyed were computed by multiplying the average CPUE (in units of kg/km^2) for all hauls (n) in a stratum by its area (A). Haul CPUE was calculated as the weight of cod caught (kg) divided by the area swept (a), which was the length of the tow multiplied by the average net width determined by sonic mensuration equipment:

$$B = \frac{\sum^{n} \frac{kg}{a}}{n} \times A.$$

Confidence bounds on stratum biomass estimates were computed from the standard deviation of the haul CPUEs. For haul CPUEs we assumed a catchability[11] of 1 for Pacific cod (all cod within the area swept by

[11] Note that catchability within the survey biomass estimation procedure has a different literal definition than in the Leslie equation.

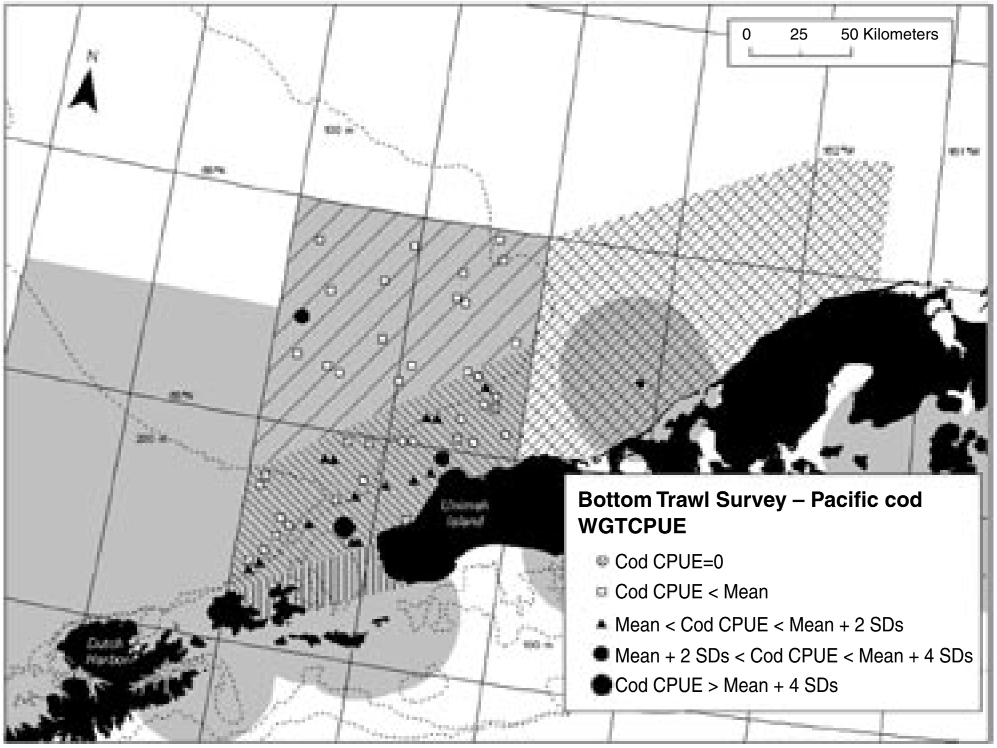

Figure 3

Catch per unit of effort (CPUE=kg/km^2) of Pacific cod (*Gadus macrocephalus*) during the February–March 2001 bottom trawl survey of the southeastern Bering Sea. “Wgtcpue” refers to the CPUE of Pacific cod from individual hauls (Table 2). Area shading is the same as that in Figure 1.

the net are captured) and that it is constant over the course of the survey. This assumption is also made in the Leslie analyses of fishery data. In addition, each haul is assumed to be a random, normally distributed estimate of the density of cod within the stratum. Therefore, the average of the haul CPUEs of cod was assumed to be an unbiased estimate of the true density of cod, allowing linear extrapolation from the CPUE within the area swept to a biomass estimate for each stratum.

Analysis of fishery data

Fishery observers record a wide variety of information about each haul taken by a fishing vessel, including retrieval location, depth, date and time of catch, and total catch weight (all referred to hereafter as “haul data”). In addition, the catch of a randomly chosen subset of hauls was sampled to determine the species composition of the haul and the length distribution of the target species (see Nelson et al. 1981 and NMFS[12] for observer sampling methods). Observer data were queried for any hauls with any gear in which Pacific cod were caught in the eastern Bering Sea and Aleutian Islands region in 2001. The geographic distribution of the observed Pacific cod catch was used to estimate the distribution of the actual catch of Pacific cod from January–April 2001 in four areas of the southeastern Bering Sea (Fig. 1): the high and low sampling-effort areas surveyed in February–March 2001, and two areas outside of the area surveyed—one to the east, and one to the south. To account for Pacific cod catches in both unsampled hauls and on unobserved vessels, the observed catch of cod was multiplied by the ratio of total-to-observed catch by processing sector and gear type (Table 1). For this procedure, the catch of the unobserved portion of the fleet is assumed to be similar to the observed portion. Ratios of total-to-observed catch by sector and gear ranged from 1.02 to 33.94, but for the majority of the catch, the ratios were less than 2 (Table 1).

A simple Leslie analysis of fishery catch and effort data was conducted on data collected by observers onboard vessels targeting groundfish. For the basic Leslie model (Ricker, 1975; Hilborn and Walters, 1992; Gunderson, 1993) a deterministic linear relationship between CPUE and cumulative catch is assumed:

$$\frac{C_t}{f_t} = qB_0 - qK_t,$$

[12] NMFS. 1996. Manual for biologists aboard domestic groundfish vessels, 431 p. U.S. Dep. Commer., NOAA, NMFS, Alaska Fisheries Science Center, 7600 Sand Point Way, NE, Seattle, WA 98115.

Table 1

Observed and total estimates of total catches of Pacific cod by processor and gear type in the Bering Sea-Aleutians Island region in 2001, and the ratio of Total ÷ Observed catches. CP=catcher processor; CV=catcher vessel.

		Processor type		
Gear	Catches and ratio	CP	CV	Other
Trawl	Total (t)	29,398	21,354	734
	Observed (t)	19,316	8590	720
	Ratio	1.52	2.49	1.02
Hook and line	Total (t)	96,238	637	11,331
	Observed (t)	52,920	19	11,109
	Ratio	1.82	33.94	1.12
Pot	Total (t)		16,506	478
	Observed (t)		4741	469
	Ratio		3.48	1.02

where C_t = catch in time period t;
f_t = effort in t;
q = catchability;[11]
B_0 = underlying (or initial) biomass; and
K_t = cumulative catch through t.

Current catch, effort, and cumulative catch are required by the model, whereas catchability and initial biomass are estimated from it. The catch and effort time series used in these analyses were 1) daily aggregates of observed cod catch in metric tons (t) and effort by vessels targeting cod by area (i.e., the high sampling-effort [HSE] area, the low sampling-effort area [LSE], the area east [AE] and the area south [AS] of the survey area), and 2) daily cumulative catch of cod by area for all vessels. CPUE metrics were defined for each gear: 1) trawl as the catch of cod (t) per hour of observed trawling per day; 2) pot as the catch of cod (t) per 20 pots observed per day; and 3) hook and line as the catch of cod (t) per 1000 hooks observed per day. These metrics were chosen so that the CPUE for each gear would be in approximately the same range to permit being plotted together on the same axis. Changing the unit-of-effort definition (number of pots or hooks fished, for instance) has no effect on the significance of the results. Hauls for which cod was the target species were defined as those in which the catch of cod was at least 20% of the total groundfish catch; target levels of 40% and 60% were also explored for trawl fisheries. Catch and effort from these hauls alone, in which cod was the target species, were used for CPUE calculations, whereas cumulative catch was derived from the total catch of cod from all vessels regardless of their target species.

The relationship between trawl vessel length and CPUE was investigated but was not included in the Leslie analyses. It was expected that CPUE would be directly related to vessel length. With increasing vessel length, horsepower would increase as would the vessel's ability to use larger nets. Vessel length (a surrogate variable for horsepower) could be a significant covariate in the relationship between CPUE and cumulative catch.

Results

Bottom trawl survey

Mean CPUE (kg/km^2) of Pacific cod in the smaller HSE survey stratum was almost three times higher than in the larger LSE stratum, resulting in mean biomass estimates of 31,312 t and 17,720 t of Pacific cod, respectively (Table 2 and Fig. 3). The highest recorded CPUE of cod was recorded for a haul on the northeast side of Unimak Pass (Fig. 3). Hauls with CPUEs above the mean were distributed throughout the HSE stratum in depths less than 200 m. Only one of the 18 hauls in the LSE stratum had a CPUE larger than the mean. For the HSE stratum, the 95% confidence interval on the mean biomass estimate was 19,284–43,339 t.

Fishery data

Total catch of Pacific cod Approximately 30,500 t of Pacific cod were caught in the four areas of the southeastern Bering Sea from 1 January to 30 April 2001 (Table 3 and Fig. 4). Almost 60% of this total catch was collected in the HSE survey stratum, whereas 25% and 12% of the total catch were collected in the AE and AS of the survey area, respectively; only 4% was collected in the LSE survey stratum. Based on the distribution of the observed catch of cod by gear, approximately half of the total catch was collected by trawls, a third by hook and line (=longline), and 14% by pots.

The distribution of cod catch by area primarily reflects the distribution of the fishery targeting Pacific cod (Fig. 4). Of the 5813 t of cod that was observed caught by the cod trawl fleet (with at least 20% of each haul composed of cod), 86% was caught in the HSE stratum in over 4600 hours of observed trawling. Most of the remainder (13% or 781 t) was caught east (AE) of the survey area, primarily between the HSE stratum and the 20 nautical mile (nmi) radius trawl exclusion zone encompassing sea lion critical habitat around Sea Lion Rocks and Amak Island (Figs. 1 and 4). There was little trawl effort targeting Pacific cod in the LSE stratum (only 10 observed hours of trawling) or south (17 hours observed) of the survey area. The cod pot fleet worked primarily south of the survey area (57% of their catch) and in the HSE stratum (31%) in areas where conflicts with trawl gear would be minimized. The cod longline fleet worked in both the HSE stratum and to the east of the survey area, and had only trace amounts of catch in the other areas (Table 3).

Percentage of Pacific cod in the haul The distribution of the percentage of cod in the total catch of each haul

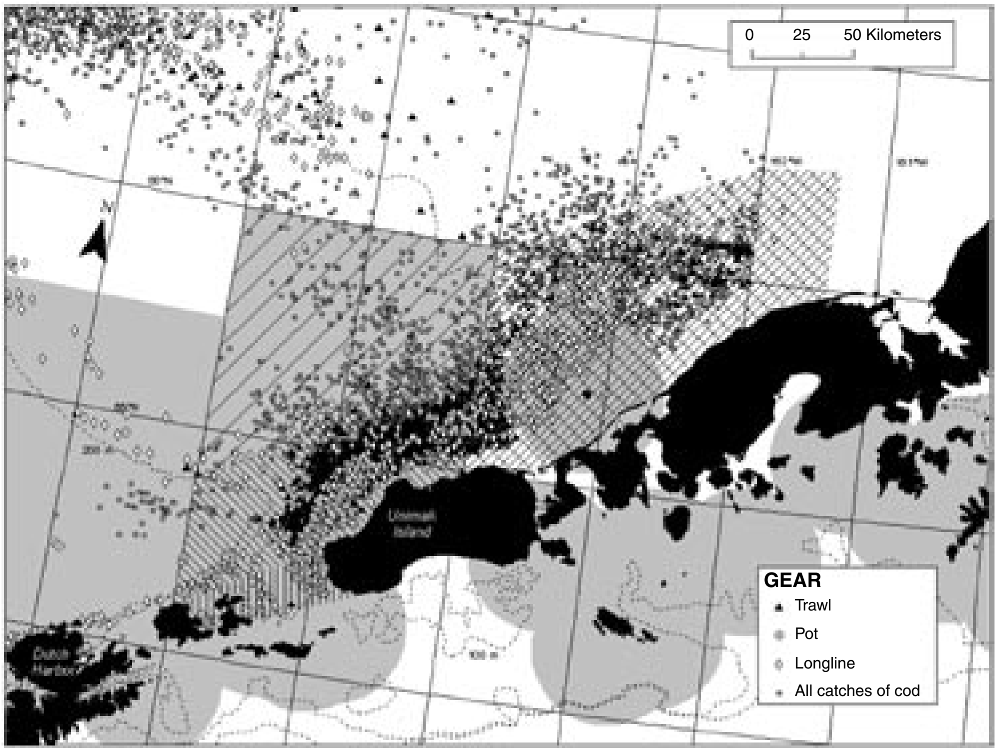

Figure 4

Locations of groundfish fishery catches of Pacific cod (*Gadus macrocephalus*) in the southeastern Bering Sea, January–April 2001. The cod target fishery is separated by gear type (trawl=at least 20% of the haul by weight was cod). “All catches of cod” refers to bycatch in trawl fisheries targeting other species. Area shading is the same as that seen in Figure 1.

Table 2

Results (catch and biomass of Pacific cod) and haul data from the bottom trawl survey of the southeastern Bering Sea conducted in February–March 2001. Low and high sampling-effort strata are shown in Figure 1. (CPUE=catch per unit of effort; CI=confidence interval).

	Survey stratum		
	Low sampling effort	High sampling effort	Total
Number of hauls	19	38	57
Number of hauls with cod	19	37	56
Mean CPUE (kg cod/km^2)	1463	4032	3176
Range in CPUE	65–12,681	0–21,299	0–21,299
Standard deviation of CPUE	2776	4676	4292
Area of stratum (km^2)	12,112	7765	19,877
Area of stratum sampled (km^2)	0.472	0.927	1.399
% of stratum area sampled	0.004%	0.012%	0.007%
Biomass (t)	17,720	31,312	49,032
95% CI on biomass (t)	1513–33,928	19,284–43,339	20,796–77,267

indicates that the vast majority of the fleet using pots or longline gear were targeting Pacific cod. The total catch of 350 of 351 observed hauls of pots and 777 of 797 observed hauls of longlines was composed of at least 60% cod (Table 4). Therefore, use of a 20% threshold to identify the cod fleet for the longline and pot vessels was unnecessary. For the trawl fleet, however, more than half the observed hauls had less than 10% cod, and

63% had less than 20% cod. These trawl vessels were targeting fish species other than Pacific cod, such as rock sole, and caught some cod (as bycatch) in the process. The distribution of hauls that had greater than 20% cod (by 10% bins) was relatively flat, varying only from 4% to 7% between bins and having no clear threshold or breakpoint. Use of a low threshold proportion of cod (such as 20%) would likely include some hauls in which

Table 3

Catch and effort statistics for Pacific cod fisheries in the southeastern Bering sea by strata (Fig. 1) in January–April 2001. Statistics include total catch estimates (in metric tons (t); all gear and fisheries), observed catch by all fisheries (by gear type), and observed catch and effort by fisheries targeting Pacific cod (by gear type). Three levels of Pacific cod catches from trawl gear are listed and are based on the minimum proportion of cod in each haul.

	Strata				
	East of sampling area	High sampling effort	Low sampling effort	South of sampling area	Total
Catch					
Total catch	7691	17,875	1,200	3724	30,491
Observed catch—all fisheries					
Trawl	1628	5737	324	32	7720
Pot	85	655	152	1198	2091
Longline	2493	2001	45	116	4654
Total	4205	8393	521	1345	14,465
Observed catch—Pacific cod fisheries					
Trawl (20% cod in each haul)	781	4993	7	32	5813
Trawl (40% cod in each haul)		4119			
Trawl (60% cod in each haul)		3364			
Pot	85	655	152	1198	2090
Longline	2493	2001	45	116	4654
Effort					
Trawl (hours; 20% cod in each haul)	677	4644	10	17	5348
Trawl (hours; 40% cod in each haul)		3768			
Trawl (hours; 60% cod in each haul)		2903			
Pot (number of pots)	1857	10,130	1119	14,816	27,922
Longline (no. of hooks)	4,220,051	3,265,606	88,880	165,585	7,740,122

Table 4

Frequency distribution of the percentage of cod in each haul by gear for the groundfish fishery in the four areas of the eastern Bering Sea (Fig. 1) in January–April 2001

	Trawl		Longline		Pot	
% cod	No. of hauls	% of total	No. of hauls	% of total	No. of hauls	% of total
<10%	1810	52	0	0	0	0
10–20%	371	11	1	0	0	0
20–30%	237	7	2	0	1	0
30–40%	169	5	1	0	0	0
40–50%	126	4	5	1	0	0
50–60%	126	4	11	1	0	0
60–70%	151	4	40	5	2	1
70–80%	166	5	120	15	4	1
80–90%	181	5	334	42	37	11
90–100%	161	5	283	36	307	87
Total	3498		797		351	

other species were targeted. On the other hand, the use of a high threshold (such as 60%) might exclude hauls where Pacific cod was the target species. Therefore, a range of trawl target definitions from 20% to 60% was used. The cod trawl fleet distribution shown in Figure 4 was defined by the 20% threshold. If the 40% or 60% thresholds are used, most of the cod trawl effort shown in the HSE area remains, whereas some of the effort in the eastern portions of the AE of the survey area is not coded as the effort of a cod-target fishery.

Distribution of Pacific cod catch Cod catches accumulated differently in the three primary areas fished (Fig. 5). In the HSE area, cod catches rose steadily from 1 January through early April, and totaled approximately 13,000 t. There was a brief increase in the rate of cod catch in mid-April, but by approximately 20 April, the cod fishery in the HSE area had essentially finished with a catch total of 17,875 t. In the AE of the survey area, cod catches accumulated steadily from 1 January through 2 March, and totaled 6340 t. There was a brief increase in catch rates for 6 days from 25 through 30 March, after which the cod fishery in the AE of the survey area was finished with a catch total of 7691 t. In the AS of the survey area, there was little cod fishing effort prior to 22 February, and it lasted only through 27 March, by which time almost 3500 t had been caught; catches through 30 April from the AS of the survey area totaled 3724 t. There was very little cod fishery effort in the LSE area (Table 3), and only 1200 t of cod were caught (principally as bycatch in other fisheries) through 30 April 2001.

The longline fleet began fishing for Pacific cod in both the HSE area and AE of the survey area on 1 January (Fig. 5). In the HSE area, daily average longline CPUE (t cod per 1000 hooks per day) remained relatively low and steady, ranging from 0.3–0.7 through January. The longline fleet left the HSE area for approximately two weeks, resuming effort again on 13 February and continuing through 6 March. Longline CPUEs were generally higher in late February than they were in January, ranging from approximately 0.7 to 1.2. The longline fleet again returned to the HSE area on 19–24 March, but daily average CPUEs were <0.5. There was sporadic longline fishing for cod in the HSE area through April, and CPUEs ranged from 0.3 to 1.0. In the AE of the survey area, the longline fleet fished continuously from 1 January through 2 March, and daily average CPUE declined from a range of 0.7–1.0 on 1–7 January to a range of 0.3–0.5 on 24 February–2 March.

The trawl fishery for cod began on 20 January in both the HSE area and AE of the survey area (Fig. 5). In the HSE area, trawl CPUE (t cod per hour trawled per day) increased from a range of 0.7–1.4 on 20–27 January to a range of 1.3–2.5 on 6–15 February. From 16 February–1 March, trawl CPUEs were slightly lower, ranging from 0.8 to 2.0, after which they declined further, ranging only from 0.5 to 1.3 from 2–24 March. On 26 March, the average CPUE increased substantially to over 12 but quickly declined to less than 1.0 by 1 April. This was followed by another short-lived increase in CPUE on 11 April, after which daily average CPUEs remained below 1.0 through April. In the AE of the survey area, CPUEs were highly variable (between 0.4 and 2.3) and there was little observable trend between 20 January and early March. On 25 March, however, average CPUE increased to over 4 and ranged between 0.4 and 3.9 through 2 April, after which there was only sporadic effort and daily average CPUEs were less than 1.

The pot fishery for cod began on 22 February south of the survey area and on 24 February in the HSE area (Fig. 5). In the AS of the survey, pot CPUE (t cod per 20 pots per day) decreased from a range of 0.3–1.0 from 22 February–1 March, to a range of 0.2–0.5 on 8–17 March. However, on 18 March, pot CPUE increased to 1.1, and remained between 0.5 and 0.8 through 22 March, after which it quickly declined to very low levels. In the HSE area, pot CPUE ranged between 0.7 and 1.7 from 24 February to 23 March. However, on 24–25 March, CPUE was greater than 2. Pot cod fishing occurred on only three more days through the end of April in the HSE area: on 27 March, 6 April, and 12 April. Although daily average CPUEs on the last two days were the highest recorded in the pot fishery in 2001, observed catches on these days totaled only 4 and 5 t of cod, respectively.

Leslie depletion analyses Leslie depletion analyses were conducted on four sets of Pacific cod fishery data collected in the HSE area and on two sets of data collected in the AE of the survey area (Table 5). In the HSE area, longline fishery data collected prior to 13 February and trawl fishery data collected prior to 6 February were excluded from the analyses because CPUE data indicated that fish were immigrating into the area in January in preparation for spawning (Fig. 5). It is unlikely that the increase in CPUE was due to a change in catchability because the increase was evident whether bait was used (pots and longlines) or not (trawls). Data indicating an increase in the abundance of cod north of Unimak Island in January and a peak in February were in agreement with a generalized model of cod abundance in Steller sea lion critical habitat in the eastern Bering Sea (Fig. 2) and seasonal cod movements from tagging data (Shimada and Kimura, 1994). The time series was truncated at 24 March because of the evidence within the fisheries data (increase in CPUE) that another group of cod had immigrated to the HSE area and AE of the survey area in late March or that catchability had increased substantially (Fig. 5). In addition, daily average CPUEs from hauls that had at least 20%, 40%, and 60% Pacific cod by weight were regressed against cumulative catch to see what effect the target definition might have on the regression results.

All Leslie regressions with longline or trawl fishery data from the HSE area were highly significant ($P<0.000001$; Table 5 and Fig. 6). Coefficients of determination (r^2) for the longline and the trawl-20% data were both greater than 0.6. Regression coefficients

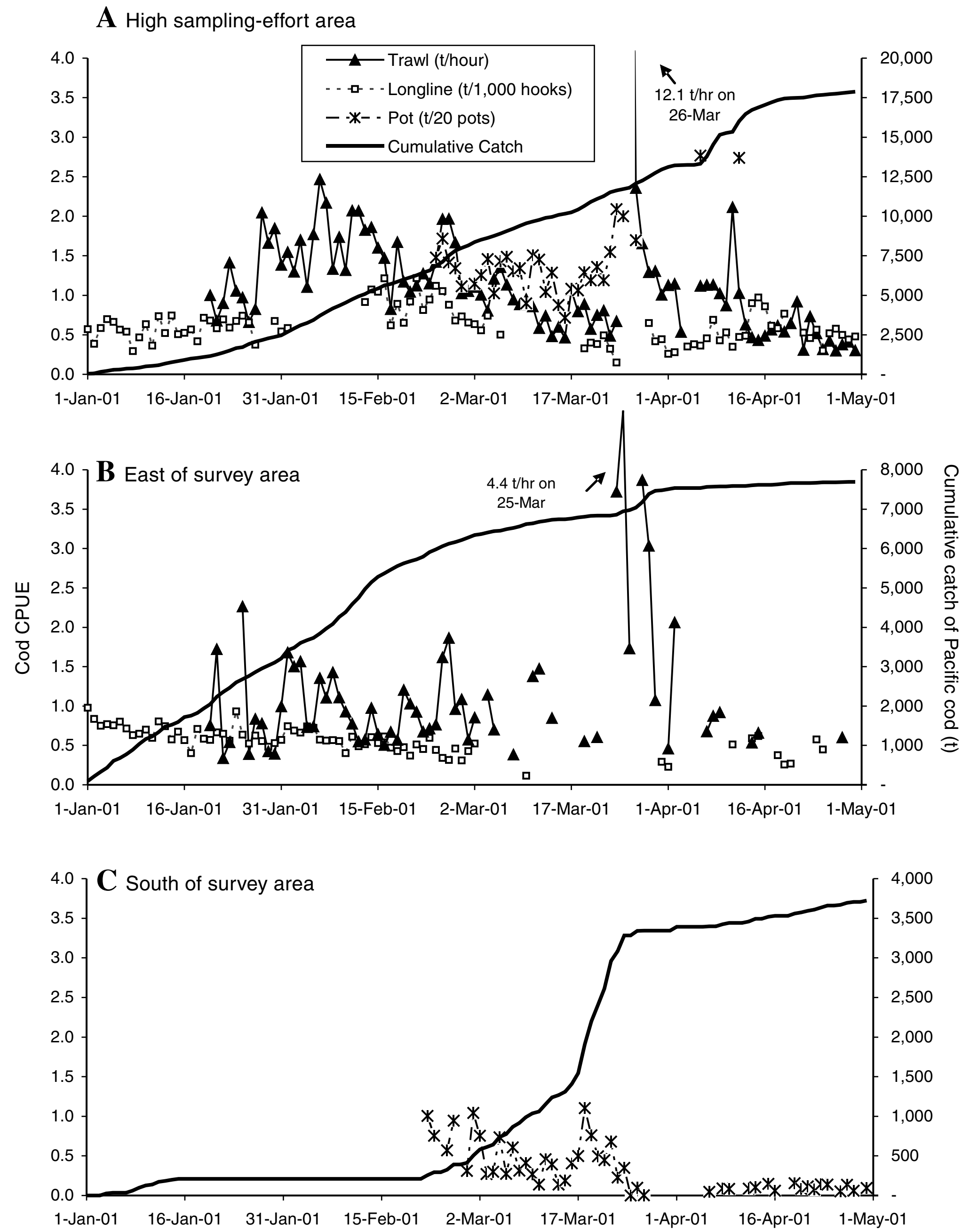

Figure 5

Daily average catch per unit effort (CPUE on left *y*-axis) for the observed Pacific cod (*Gadus macrocephalus*) fishery by gear (see legend for units) and area (Fig. 1) from 1 January–30 April 2001 in the southeastern Bering Sea. Estimated cumulative catch (t) of cod by all gear types by area is also shown (right *y*-axis).

(slopes) in all cases were negative and significantly different from zero. Collectively, these results strongly indicate that cod fishery CPUE was negatively correlated with cumulative catch. Initial biomass estimates (B_0) from the four regressions were similar and ranged between 14,119 and 14,806 t, with 95% confidence intervals ranging from approximately 9000 to 25,000 t. Use of different fishery catch levels (20%, 40%, 60% cod in each haul) had little effect on the initial biomass estimate but changed the estimate of q, which increased directly with the threshold proportion of cod in each haul (Table 5 and Fig. 7).

Table 5

Results of Leslie depletion analyses on cod trawl and longline fishery data collected in the (**A**) high sampling-effort (HSE) survey area and (**B**) east of the survey area (Fig. 2). Dates when data were collected are listed, along with the regression parameters (q=slope and y-intercept=qB_0) and statistics (P=probability that slope is not significantly different from 0, r=Pearson correlation coefficient, and 95% confidence interval (CI) on B_0). For the trawl fishery in the HSE area, three different levels catch for the target fishery were used (20%, 40%, or 60% of the total catch per haul was cod). Cumulative catches in each area are defined as the catch from 1 January through the end of the period analyzed.

A High sampling-effort survey area

	Gear			
	Longline 13 Feb–24 Mar	Trawl 20% 6 Feb–24 Mar	Trawl 40% 6 Feb–24 Mar	Trawl 60% 6 Feb–24 Mar
Cumulative catch (t)	11,631	11,631	11,631	11,631
B_0 (t)	14,251	14,806	14,119	14,410
95% CI on B_0 (t)	9608–22,195	10,549–21,570	9526–21,942	8989–24,860
q	0.000115	0.000172	0.000207	0.000212
y-intercept	1.6395	2.5442	2.9246	3.0573
P	<0.000001	<0.000001	<0.000001	<0.000001
No. of days (n)	27	47	46	46
r^2	0.712	0.635	0.577	0.479

B East of survey area

	Gear	
	Longline 1 Jan–2 Mar	Trawl 20% 20 Jan–21 Mar
Cumulative catch (t)	6340	6837
B_0 (t)	14,671	
95% CI on B_0 (t)	10,934–20,936	
q	0.000053	
y-intercept	0.7707	
P	<0.000001	0.65
No. of days (n)	61	49
r^2	0.515	0.004

Although a portion of the AE of the sampling area is also critical habitat, the majority of it is not. Cod are thought to move from the areas east and south of the survey area to aggregate within critical habitat, particularly north of Unimak Island, for spawning (Shimada and Kimura, 1994; Thompson and Dorn, 2002). Leslie analyses were conducted on longline data collected from 1 January to 2 March in the AE of the survey area, and on trawl data collected from 20 January to 21 March. The longline data yielded a highly significant negative relationship between CPUE and cumulative catch (P<0.000001), whereas the trawl data did not (P=0.65; Table 5 and Fig. 6).

Trawl fishery CPUE in the HSE area was not correlated with daily average vessel length for the period 20 January–30 April 2001 (P=0.16; r^2=0.02; Fig. 8). The data from the analysis period 6 February–24 March are highlighted in Figure 8. Although there was a significant linear relationship between vessel length and CPUE for this shorter period (P=0.004), the correlation coefficient was low (r^2=0.16), indicating that daily average CPUE and vessel length were poorly correlated.

Discussion

The bottom trawl survey point estimate of cod biomass in the HSE area (31,312 t) is approximately twice the values derived from analyses of fishery data (approximately 14,500 t). This is in part because the fishery worked almost exclusively within the eastern two-thirds of the HSE area. Restratifying the HSE survey yields biomass estimates of 23,329 t for the eastern two-thirds used by the fishery and 7983 t for the western portion. The fishery-derived biomass estimates for the eastern portion of the HSE survey area are within the 95% confidence bounds on the survey estimate (12,846–33,812 t).

In addition, the survey biomass estimate for the eastern two-thirds of the HSE area is within or close to the upper 95% confidence bounds of the Leslie analyses of trawl and longline Pacific cod fishery data (Table 5).

One possible explanation for the lower fishery-derived estimates in the eastern portion of the HSE area is that emigration of fish after spawning contributed to the low CPUEs observed near the end of the fishery time series. If this emigration occurred, however, it went largely undetected in the neighboring areas. Emigration over the course of the fishery would decrease CPUEs faster than what would be attributable to fisheries alone, which would, in turn, decrease the estimate of initial biomass.

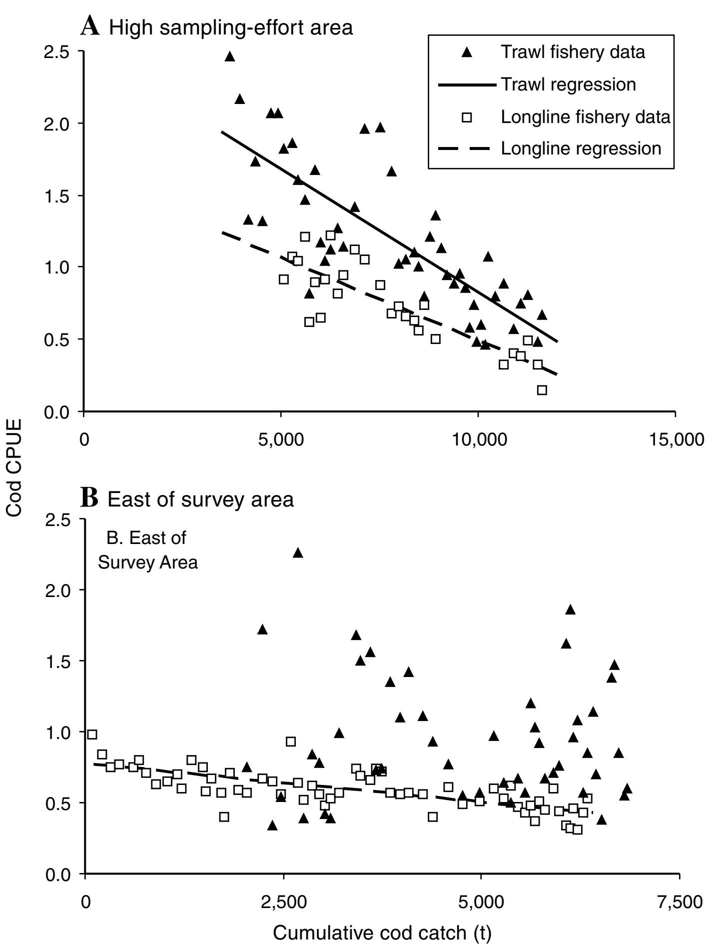

Figure 6

Daily average catch per unit of effort (CPUE) of Pacific cod (*Gadus macrocephalus*) by the observed Pacific cod fishery by gear type plotted against the estimated cumulative catch of cod by the groundfish fishery in the high sampling-effort area (**A**) and in the area east of the survey area (**B**; Fig. 1). For the trawl fishery (at least 20% of the haul catch was cod), CPUE = t/h; for the longline fishery, CPUE = t/1000 hooks. Lines are shown for those regressions whose slope was significantly different from 0 (P<0.05; Table 5).

Plots of fishery CPUEs of Pacific cod were very similar for all gears used in each area. This finding indicates that these time series are useful as indices of relative cod abundance. Similarly, inferences can be made through analyses of fishery CPUE data regarding fish movement from area to area (or lack thereof) to a possible cause in the observed declines in CPUE (or local abundance). For instance, the lack of fishery CPUE increases in areas to the north, east, and south of the HSE survey area in March indicates that emigration was not a significant factor in the CPUE decline observed in both the longline and trawl fishery CPUE data from early February through 24 March. In fact, in the AE of the survey area through 2 March, longline CPUE declined, indicating that either fish left this area (to the north) or were reduced in abundance by fishing and were not replenished. Although the time series from the AS of the survey area is short, there is no indication that cod moved there in early March. There is also no evidence that cod moved north to the LSE survey area because the longline or pot fleets targeting cod did not move there, nor did the proportion of cod in trawl hauls increase (otherwise they would have been labeled as a cod-target fishery). It is possible that cod emigrating from the HSE area were so dispersed or their catchabilities were much lower than those for residents in other areas that their presence went undetected, but there is no evidence to suggest that either of these were any more likely than the more simple assumption that changes in CPUE within the fished area represented real changes in local abundance even after accounting for some level of emigration. If cod immigration exceeded emigration for the HSE area during early March as CPUEs were declining, then fishery-derived estimates of initial biomass calculated in our study are biased high.

Pot fishery CPUE data in the AS of the sampling area and in the HSE area indicated that there was an influx of Pacific cod from the south in mid-March. This was evident from the increase in pot fishery CPUE on 18 March in the AS of the survey area and beginning on 24 March in the HSE area. Cod may have moved into nearshore sections of the HSE area where they would be more vulnerable to pot gear than to trawlers. However, on 25–26 March, trawl CPUE on the border of the HSE area and the AE of the survey area increased substantially, indicating that these fish had moved offshore to areas worked by trawlers, or that they became highly aggregated (perhaps just prior to spawning). The late-March “pulse” of Pacific cod biomass was probably smaller than the

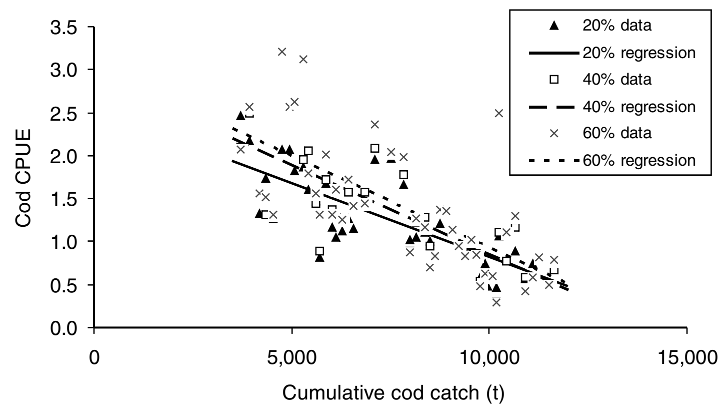

Figure 7

Catch per unit of effort (CPUE; t/h) of Pacific cod (*Gadus macrocephalus*) by the cod trawl fishery in the high sampling-effort area plotted against cumulative catch of cod in the same area by all groundfish fisheries. Three different levels of the cod fishery catch are used (20%, 40%, or 60% cod in each haul).

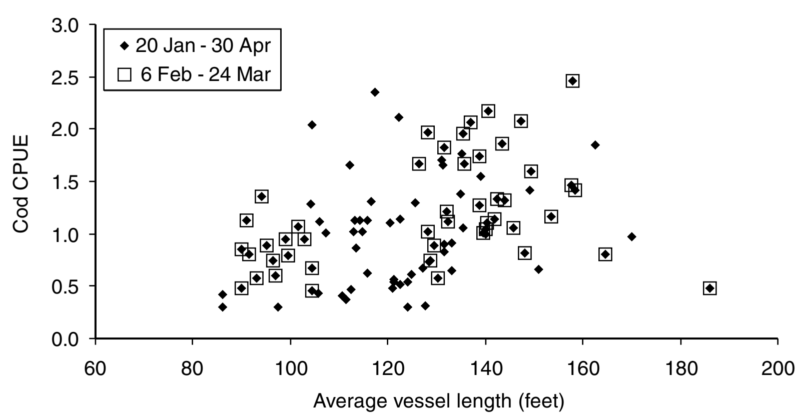

Figure 8

Daily average Pacific cod (*Gadus macrocephalus*) catch per unit of effort (CPUE; t/h) plotted against daily average vessel length for the trawl cod fishery in the high sampling-effort area in two time periods: 20 January–30 April 2001, and 6 February–24 March 2001.

initial influx that peaked in early February because it sustained the fishery for only 1–2 weeks, and resulted in cod catches of only approximately 7500 t from all four areas.

In the stock assessment for Pacific cod in the eastern Bering Sea and Aleutian Islands (BSAI; Thompson and Dorn, 2002), the estimate of age 3+ biomass in 2001 was approximately 1.284 million t, whereas the female spawning biomass was approximately 359,000 t. Doubling the latter to account for male spawner biomass, the survey and fishery data discussed in the present study indicate that only 4% of the adult spawning and 3% of the age 3+ biomass was in the HSE area, and only about 7% and 4%, respectively, in the entire area surveyed. The area north of Unimak Island is thought to be one of the principal spawning grounds for Pacific cod in the eastern Bering Sea (Shimada and Kimura, 1994; Thompson and Dorn, 2002). The results reported in the present study may indicate that either 1) this is not one of the principal spawning grounds for Pacific cod in the eastern Bering Sea and most spawning occurs elsewhere, 2) the stock assessment estimates are too high, or 3) Pacific cod aggregated in the area after the survey occurred.

Biomass estimates from the assessment are approximately twice those derived directly from bottom trawl

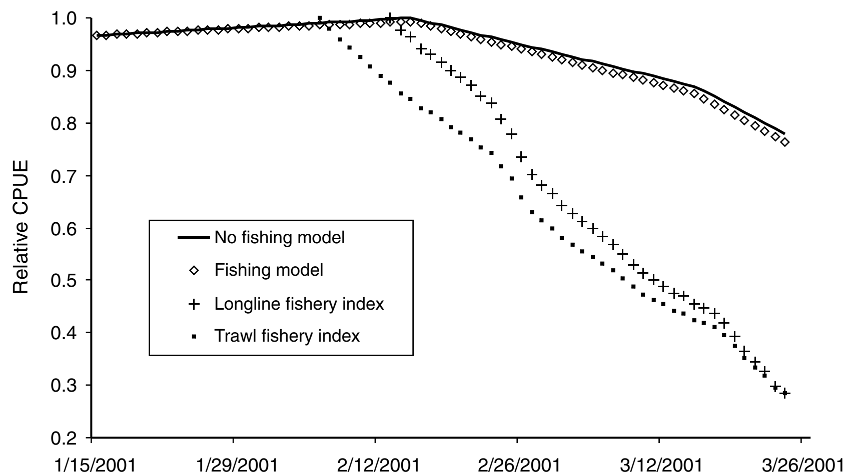

Figure 9

Comparison of relative abundance of Pacific cod (*Gadus macrocephalus*) in portions of Steller sea lion (*Eumetopias jubatus*) critical habitat from 15 January–24 March 2001 based on 1) no fishing model: the proportion of the maximum biomass (on 15 February) in critical habitat each day; 2) the fishing model: subtracting catch per day from 15 January–24 March 2001 in high and low sampling-effort areas from the no fishing model (total of 12,800 t); 3) longline fishery catch-per-unit-of-effort (CPUE) index of abundance from the high sampling-effort area, 13 February to 24 March (assigned a value of 1 on 13 February); and 4) trawl fishery (20% threshold) CPUE index of abundance from the high sampling-effort area, 6 February to 24 March (assigned a value of 1 on 6 February).

surveys of the entire Bering Sea shelf conducted in summer (Thompson and Dorn, 2002). This difference stems from highly domed-shaped selectivity-at-length schedules for the summer surveys and most fishery catches of cod (Thompson and Dorn, 2002). As a consequence, the model "assumes" that fewer cod are caught in proportion to their actual abundance at lengths greater than 45 cm for the survey catch and 80 cm for the fishery catch. However, it is unclear how large cod avoid capture during surveys or by longline, pot, and trawl fishery gear as implied by the dome-shaped selectivity-at-length schedules.

A seasonal model of Pacific cod movement patterns into and out of Steller sea lion critical habitat (Fig. 2) indicates that relative Pacific cod biomass inside critical habitat is highest in February, then drops 13% in March and 44% by April. If these values are assigned to the middle of each month and daily values are extrapolated linearly, the relative change from 15 February through 24 March is 23% (Fig. 9). Fishery indices of abundance in the HSE area in January and February are consistent with this seasonal pattern, with both trawl and longline CPUEs increasing from January to February. According to Figure 2 and the 2001 age 3+ biomass estimate (Thompson and Dorn, 2002), catches through 24 March within the entire survey area (12,806 t) represented only 1% of the BSAI stock and should have reduced the relative biomass of cod within critical habitat by only an additional 2%. Thus, the total reduction in relative cod biomass within critical habitat from mid-February through late March after accounting for fishing and emigration should have been 25% (Fig. 9). Longline and trawl fishery CPUE data in the HSE area provide an independent estimate of relative cod biomass. Both indices indicate that the reduction in relative cod biomass within the HSE survey area through 24 March was 71–46% greater than that predicted by the model.

Catches and biomass estimates of Pacific cod for different time periods and areas can be used to compute harvest indices (catch divided by observed biomass). For instance, the harvest index within the entire survey area (based on the catch from 1 January through 24 March and the survey biomass estimate) was 26% (12,806 or÷49,032). If the focus is narrowed to only the HSE survey area through 24 March, the harvest index was 37% (11,631 or÷31,312). However, both the fish and the fishery were concentrated within the HSE area. The eastern two-thirds of the HSE survey area had survey and fishery-derived biomass estimates of 23,418 t and ~14,500 t, respectively. With the area of fishery effort more precisely defined, local harvest indices increase even further, ranging from 50% (11,631 or÷23,329) to 80% (11,631 or÷14,500).

The annual harvest rate of BSAI cod in 2001 was estimated to be approximately 11% (Thompson and Dorn, 2002). The total catch of cod in the BSAI through 24 March represented only 44% of the total catch of Pacific cod in 2001. Therefore, the harvest rate through 24 March should only have been 44% of 11%, or about 5%. The local harvest indices estimated in the present study, which ranged from 26% to 80%, were five to 16 times greater than that on the BSAI Pacific cod stock as a whole in 2001. Much of the area used by the fishery is designated as critical habitat for the endangered Steller sea lion, primarily because of the prey resources available within it. In addition, the fisheries occurred in the winter and early spring, when sea lions are most likely to consume Pacific cod (Sinclair and Zeppelin, 2002). It is not known how or if cod fishery catches in this area affect Steller sea lion foraging success. One objective of the Pacific cod fishery management regulations is to minimize the competitive interactions between locally intense fisheries and Steller sea lions. The suite of groundfish fishery regulations enacted in 2001 and 2002 work together to avoid adverse modification of critical habitat under the ESA. However, based on the observations during 2001 discussed in the present study, regulations for the eastern Bering Sea Pacific cod fishery should be reviewed to ensure that they meet these management objectives.

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