North American Journal of Fisheries Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ujfm20

Discard Mortality of Trawl-Caught Lingcod in Relation to Tow Duration and Time on Deck

Steven J. Parker [a], Polly S. Rankin [a], Robert W. Hannah [a] & Carl B. Schreck [b]

[a] Oregon Department of Fish and Wildlife, Marine Resources Program, Hatfield Marine Science Center, Newport, Oregon, 97365, USA

[b] Oregon Cooperative Fish and Wildlife Research Unit, Biological Resources Division, U.S. Geological Survey, Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon, 97331, USA

Available online: 08 Jan 2011

To cite this article: Steven J. Parker, Polly S. Rankin, Robert W. Hannah & Carl B. Schreck (2003): Discard Mortality of Trawl-Caught Lingcod in Relation to Tow Duration and Time on Deck, North American Journal of Fisheries Management, 23:2, 530-542

To link to this article: http://dx.doi.org/10.1577/1548-8675(2003)023<0530:DMOTCL>2.0.CO;2

North American Journal of Fisheries Management 23:530–542, 2003

Discard Mortality of Trawl-Caught Lingcod in Relation to Tow Duration and Time on Deck

STEVEN J. PARKER,* POLLY S. RANKIN, AND ROBERT W. HANNAH

Oregon Department of Fish and Wildlife,
Marine Resources Program, Hatfield Marine Science Center,
Newport, Oregon 97365, USA

CARL B. SCHRECK

Oregon Cooperative Fish and Wildlife Research Unit,
Biological Resources Division, U.S. Geological Survey,
Department of Fisheries and Wildlife,
Oregon State University,
Corvallis, Oregon 97331, USA

Abstract.—The lingcod *Ophiodon elongatus* is a benthic marine fish commonly caught by groundfish trawlers and discarded due to low catch limits. Managers must account for the mortality of bycatch to assess population status accurately. Our objectives were to estimate the actual mortality of trawl-discarded lingcod (50–84 cm) and describe their physiological stress response to capture. We investigated three major factors of the trawling operation that may influence lingcod survival: tow duration, fish size, and the amount of time fish were on the deck of the vessel. Survival was monitored for 21 d and each surviving animal was then physically and physiologically evaluated. The results showed that regardless of the duration of the tow, lingcod survival was 100% for animals discarded immediately after the cod end was emptied on deck. All lingcod captured during a tow of average commercial duration demonstrated a maximal stress response, measured by plasma cortisol, glucose, and lactate concentrations. As expected, lingcod from an average duration tow showed decreased survival with increased time on deck, though still had 50% survival after 30 min. This study suggests that discard mortality of lingcod is determined mainly by on-deck sorting and can be minimized by releasing fish quickly upon capture. Accurate estimation of mortality rates for lingcod will depend on the documentation of normal fishing behavior and on-deck sorting procedures.

Declines in the abundance of many stocks of Pacific groundfish and the regulatory responses of federal and state management agencies have focused the attention of the fishing industry and stock assessment scientists on bycatch and discard mortality as one of the few areas where reductions in impact can occur (National Marine Fisheries Service 1999). Specifically, documentation of bycatch composition and estimates of the associated discard mortality are essential for estimating total mortality for accurate stock assessment models.

Lingcod *Ophiodon elongatus* have been heavily exploited by both commercial and recreational fisheries on the U.S. West Coast and in Alaska (North Pacific Fishery Management Council 1999; Pacific Fishery Management Council [PFMC] 1999). The Magnuson–Stevens Fishery Conservation and Management Act (Public Law 94–265) mandates documentation and minimization of fishery bycatch, discard, and discard mortality. In 1999 the PFMC declared lingcod as overfished and implemented a rebuilding plan for West Coast stocks. Currently, sublegal- and almost all legal-sized lingcod are discarded after capture because of size limits, low trip limits, or complete moratoriums on landings during certain periods of the year (PFMC 1999). Because lingcod are captured in ongoing mixed-species fisheries, it is expected that these management actions will result in increased discard rates compared with those in the recent past.

Lingcod do not possess swim bladders and are generally considered by both fishers and scientists to be resistant to barotrauma and handling trauma. One hooking mortality study that examined recreational fishing mortality in California found very low levels of mortality after fish were held in tanks for several weeks (Albin and Karpov 1998). Consequently, their postrelease survival is thought to be generally good in recreational fisheries (Jagielo 1995, 1999). However, the vast majority of lingcod discards occur in the commercial bottom trawl

* Corresponding author: steve.parker@oregonstate.edu
Received March 12, 2002; accepted August 23, 2002

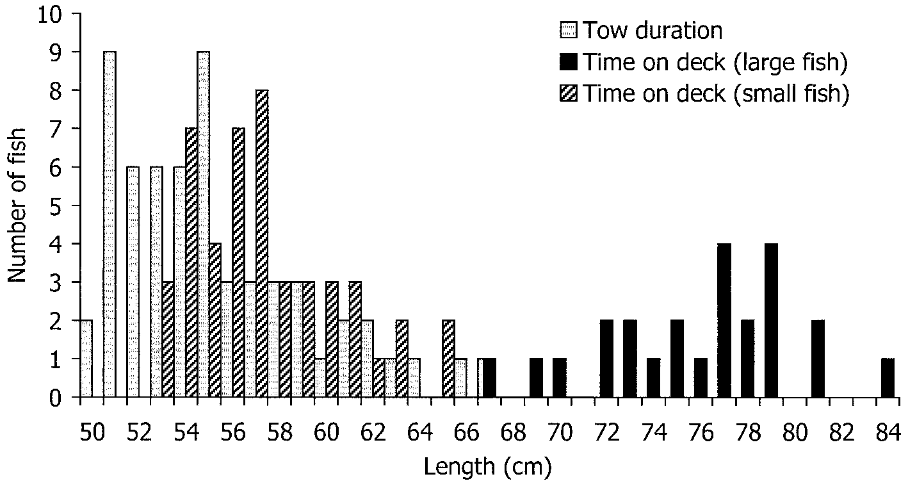

FIGURE 1.—Frequency distribution of fish length (cm) for lingcod used in three experiments: (1) tow duration (n = 63), (2) time on deck for large fish (n = 64), and (3) time on deck for small fish (n = 58).

fishery (PFMC 1999), and mortality rates for that gear type have never been estimated and so cannot be incorporated into stock assessment models (Jagielo et al. 1997, 2000). Discard mortality studies with other species have determined that the time spent on deck, fish length, total weight of catch, tow depth, and tow duration are significant factors in determining subsequent mortality (Neilson et al. 1989; Wassenburg and Hill 1993; Oddsson et al. 1994; Richards et al. 1995; Albin and Karpov 1998). In addition, the degree to which the capture process, time on deck, and handling method affects stress and postrelease survival is not known. Documenting the capture stress response and any recovery under different capture conditions through physiological measures would help to establish a useful link between capture as a stressor and mortality. This study was conducted to provide information concerning the physical factors that influence the mortality of lingcod discarded during normal operations of commercial bottom trawl fisheries off the West Coast. In addition, we describe the physiological stress response associated with trawl capture and subsequent recovery, and suggest handling and discard procedures that will minimize mortality in this important species.

Methods

Lingcod were caught using a chartered commercial bottom trawler off Newport, Oregon (44°45′N, 124°28′W). Trawling was conducted at a depth of 150 m and a normal speed of 1.2 m/s using a standard bottom trawl routinely fished off the West Coast. Briefly, the trawl was a four-seam, Western Atlantic 4A sole trawl (31.7-m footrope, 2.2-m headrope height, 4-mm polyethylene webbing, 114-mm stretch diamond mesh throughout, and alternating clusters of 20/12-cm rubber discs for the footrope). The cod end was double twine throughout, with 2-cm rope chafing gear on the bottom panel. Cod end circumference and length were 88 meshes and 50 meshes, respectively.

We conducted three separate experiments to isolate different physical aspects of capture on the resultant mortality rate; varying trawl duration, time on deck for large fish (legally retainable, 67–84 cm total length [TL]), and time on deck for small fish (sublegal size, 50–66 cm TL; Figure 1). Other potentially significant factors in subsequent discard mortality were held constant (e.g., depth and water temperature). All three experiments were conducted in similar weather conditions (partly cloudy, breezy [2.5–8.0 m/s], air temperature 11°C, surface water temperature 10°C, bottom water temperature 7.5°C), which subjected the lingcod to fairly constant effects of desiccation, warming, and transport. We chose to study mortality of lingcod that are always discarded because they are smaller than the minimum size limit imposed by fishery managers. However, they are large enough (>50 cm) that fishermen could find and identify them easily in an average-sized catch and so could discard them quickly if such is effective in reducing mortality.

Tow duration.—To determine if tow duration alone had a relationship with subsequent lingcod stress responses and mortality rates, we conducted four tows in the same general area. Following the

TABLE 1.—Summary of experimental design and treatment groups for three lingcod experiments. On-deck blood samples were taken from lingcod excess to the survival experiments. Survival of lingcod for each treatment group was determined after a 21-d holding period.

Experiment	Tow duration (min)	Time on deck (min)	Catch weight (kg)	Target length (cm)	Lingcod collected (*n*)	On-deck blood samples (*n*)	Survival (%)
Tow duration	35	0	167	51-66	17	10	94
	120	0	113	51–66	14	0	100
	180	0	244	51–66	16	3	100
	300	0	188	51–66	15	1	100
Time on deck (large fish)	180	7	4,840	67–84	16	4	81
		30		67–84	16	4	56
		40		67–84	16	4	13
		55		67–84	16	5	6
Time on deck (small fish)	180	0	569	51–66	16	6	100
		15		51–66	15	6	94
		30		51–66	14	0	50
		45		51–66	13	6	62

capture portion of the tow (35 min), we raised the net to the surface and processed the fish (35-min tow), or raised the net 20–30 m off the bottom and continued towing at the normal speed of 1.2 m/s for a total tow duration of either 120, 180, or 300 min. These tow durations represent the range of normal tow durations in fisheries where lingcod are captured; the 1995–1998 mean duration of lingcod tows was 2.8 h (Oregon Department of Fish and Wildlife, unpublished data). The height of the net off the bottom was monitored with a Simrad ITI (Seattle, Washington) headrope height sensor. This procedure resulted in a similar tow volume and species composition, speed, and temperature profile, varying only the time the fish were towed in the cod end (Table 1).

Upon retrieval for each tow duration treatment, the net was emptied on deck and we haphazardly collected lingcod between 51 and 66 cm TL (regardless of their condition) and placed them temporarily in onboard polyethylene tanks ($1.0 \times 1.0 \times 0.6$ m) filled with flow-through seawater. The target sample size was 16 fish, but samples were limited by the number captured in the tow (Table 1). To minimize fish density, only eight fish were placed in a tank, utilizing two tanks per treatment group. For the tow duration experiment we performed four treatments totaling 63 fish (Table 1).

To measure the stress response at capture associated with different tow durations, we collected blood samples from the caudal vasculature using a 3-mL Vacutainer (21-gauge needle) without anesthetic but within 5 min of the targeted sampling period. Blood was centrifuged at $4,000 \times g$ for 5 min and plasma was stored for later analysis at −80°C. Hematocrit was measured as a percentage of total blood volume. Plasma cortisol was measured by radioimmunoassay techniques (Redding et al. 1984). Lactate and glucose concentrations were determined using standard colorimetric methods (Passonneau 1974; Wedemeyer and Yasutake 1977). Ionic potassium and sodium were measured using ion-selective electrodes and a Nova Na/K analyzer.

Sample sizes for physiological stress measurements for each treatment group were variable because there was limited time in which to collect the blood samples to represent each treatment group. Also, collection of lingcod for the mortality portion of the experiment was the priority and only excess lingcod within the desired length range were sampled. All other catch were then sorted to species, counted, and weighed to determine a total catch weight and composition.

The shipboard tanks were equipped with air stones and fresh, degassed seawater (either chilled or pumped from depth), maintaining the tanks at a temperature found at or near the bottom (8–10°C). Tanks were cleaned by siphon periodically during transport to ensure high water quality. Any dead fish (with flared opercula, bleached gills, and rigid) were noted and removed. The lingcod were transported to the Hatfield Marine Science Center, Newport, Oregon (taking approximately 3 h), transferred in water to covered, outdoor polyethylene tanks (2 m diameter, 1 m depth, 3,140 L), and monitored for survival in flow-through (15 L/min), temperature-controlled (9–11°C), pathogen-free seawater (30–32‰ salinity) for 21 d. Ammonia levels were not detectable throughout the holding period. A holding period longer than the standard 4–5 d was chosen in an attempt to observe any delayed mortalities (Wassenburg and Hill 1993; Chopin and Arimoto 1995; Olla et al. 1997).

Lingcod were monitored daily to identify, remove, and examine any mortalities, and to maintain water quality by siphoning any debris. Fish were not fed during the experiment. Following the holding period, we performed an external physical evaluation and collected plasma samples as described above for physiological comparisons of recovery status among treatment groups. Fish were captured simultaneously by tank and a blood sample was collected to determine if the different treatment groups resulted in changes in the stress response of surviving fish. Each fish was then measured (cm, TL), and examined for injuries in the following categories and scored by severity: eyes, fins, gills, body musculature, skin, and parasites. The values for each fish were then summed to create an overall score of the condition of each fish. These data were summarized and analyzed as a health assessment index (HAI; Adams et al. 1993). Physiological and HAI responses were analyzed by analysis of variance (ANOVA).

Time on deck.—To estimate the effect that time spent on deck has on subsequent mortality, we conducted a single tow of 180 min (corresponding to the 180-min tow treatment group from the tow duration experiment). Upon retrieval, the net was emptied on the deck in a normal fashion, and the first 16 lingcod encountered within the appropriate slot size were collected and placed in tanks as described above. Because of the time required for net handling, the first sample was not taken until 7 min after the net left the water. The slot size for large fish was 67–84 cm and for small fish was 50–66 cm (Figure 1). Sixteen large fish were collected from a single tow after 7, 30, 40, and 55 min on deck (measured from the time the cod end left the water to the beginning of the collection period) for a total of 64 fish for the large fish experiment (Table 1). During the second time-on-deck experiment, small lingcod were collected from a single tow after 0, 15, 30, and 45 min on deck, though we were limited by available fish for the 30- and 45-min treatment groups (Table 1).

In each experiment, we collected plasma samples from additional lingcod within the target size range to measure and describe stress responses throughout the entire period spent on deck (Table 1). Transport, holding, examination, sample collection, and analysis were as described for the tow duration experiment except that for the small-fish, time-on-deck holding experiment, fish were anesthetized immediately in 200 mg/L tricane methanesulfonate (MS-222; Argent Chemical Laboratories, Redmond, Washington) prior to blood collection, and fish were held at 8°C, better matching the bottom temperature at capture.

Results

Tow Duration

The amount of time lingcod were towed in the trawl before being brought to the surface did not influence the subsequent mortality rate. Survival from the time fish were placed in shipboard tanks was at or near 100% for all tow duration groups (Table 1). These fish experienced similar total catch weights and conditions of capture, and were returned to water immediately after the trawl was emptied on deck. One fish from the 35-min tow was moribund at capture and died during transport. It was the only mortality during the entire experiment.

Physiological variables measured after a 21-d holding period indicate that the lingcod in all treatments were undergoing strong stress responses, as cortisol levels were high in all groups (Figure 2), but they were not different among treatment groups ($P = 0.543$). There were also no differences among treatments in plasma levels of lactate ($P = 0.354$), glucose ($P = 0.245$), hematocrit ($P = 0.304$), sodium ($P = 0.360$), or potassium ($P = 0.515$) levels following the holding period (Figure 2). Lingcod sampled immediately from a 35-min tow had low cortisol levels as it was detectable in only two of six fish sampled. After a 21-d holding period, cortisol levels in the 35-min tow treatment were elevated compared with the 35-min tow levels at capture ($P < 0.0001$, Figure 2). Lactate ($P < 0.0001$), hematocrit ($P < 0.0001$), potassium ($P < 0.0001$), and sodium ($P < 0.0001$) levels decreased during the holding period from the levels measured at capture.

Physical examination after 21 d showed all fish were generally in good condition. The main injuries noted were torn fin membranes and skin abrasions, injuries that probably resulted from the trawl mesh as they occurred in all treatment groups (Figure 3). There were no differences in the overall HAI scores or component categories among lingcod exposed to different tow durations ($P = 0.621$).

Time on Deck

The amount of time lingcod remained on deck during sorting was directly associated with increased mortality (Figure 4). However, the fish were extremely resilient to this stressor, with more than 50% surviving 21 d after being held on deck for more than 30 min. The majority of the mortality

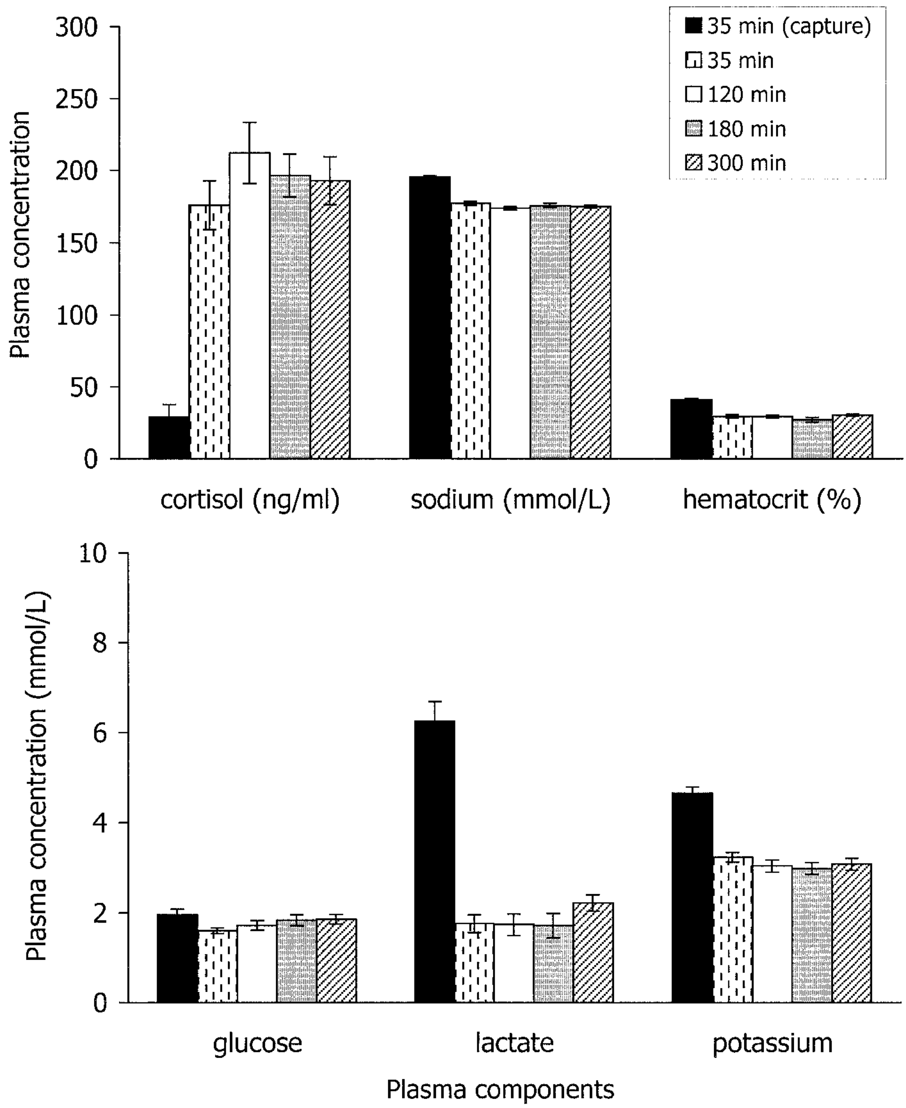

FIGURE 2.—Concentration of plasma components (cortisol [ng/mL], sodium, glucose, lactate, potassium [mmol/L], and hematocrit [%]) for lingcod grouped by tow duration. Samples taken on deck immediately after a 35-min tow are shown as ''capture.'' Other measurements are after a 21-d holding period. Values are mean ± SE.

occurred within the first week after capture, and only one fish died 2 weeks after capture (Figure 4).

Cortisol levels measured in plasma samples taken during the time-on-deck treatments at the time of capture were elevated compared with the levels measured in the 35-min tow (Figures 2, 5, and 6). There was no change in cortisol levels the longer fish remained on deck in either experiment (Figure 7), although some fish may have died by the end of the treatment period (1 h). Following a 21-d recovery period, plasma cortisol levels remained elevated in the large-fish experiment survivors ($P = 0.274$), though they decreased in survivors of the following experiment using smaller fish ($P < 0.0001$; Figure 6). Lactate, glucose, hematocrit, sodium, and potassium levels were all elevated at capture and decreased during the recovery period in both experiments ($P < 0.007$; Figures 5 and 6). There were no differences in cortisol, glucose, lactate, sodium, or hematocrit levels among treatment groups after the 21-d holding period in either time-on-deck experiment ($P > 0.05$; Figures 5 and 6). Potassium levels recovered to a lower level in the

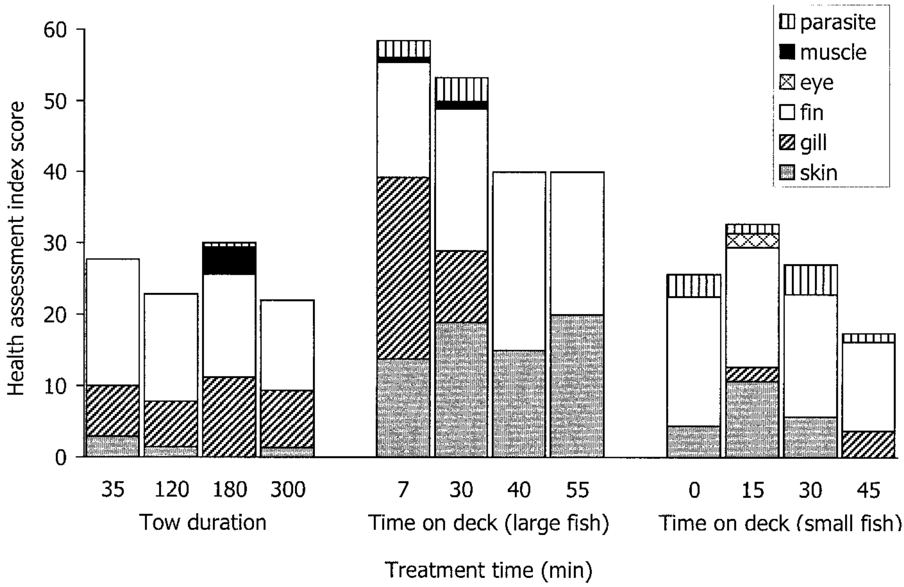

FIGURE 3.—Mean health assessment index (HAI) scores of lingcod for three experiments by treatment group after 21 d. Overall HAI score is the sum of the subcomponent scores.

45-min on-deck group than the 0-min on-deck group in the small fish experiment ($P = 0.024$; Figure 6).

Physical examination following the 21-d recovery again showed relatively minor injuries in surviving lingcod (Figure 3), although several fish died from deck exposure in both experiments. Overall HAI scores were statistically the same for all treatment groups within each experiment ($P > 0.225$). Subcategory comparisons showed a significant reduction in gill-related injuries in long deck exposures for the large-fish experiment ($P = 0.012$). In the small-fish experiment, the 45-min group had significantly lower scores than the 15-min treatment group for skin injuries ($P = 0.018$).

Although limited by low sample sizes, those surviving 30 min or more on deck showed only fin and skin injuries, while those spending less time on deck survived with fin and skin injuries in addition to parasite, muscle, and gill injuries (Figure 3). Parasites noted in the time-on-deck experiments were external copepods or branchiurans. Mortalities that occurred during the holding phase of the experiments showed various injuries related to the capture process such as crushing, lacerations, punctures, and abrasions which were not observed in surviving lingcod. Postmortem examinations noted necrotic muscle tissue, hemorrhaging in the ovaries, and bruised livers, though not all mortalities showed obvious causes of death. No significant disease symptoms were noted during postmortem examinations or during examinations after 21 d of surviving fish. This degree of physical trauma was not apparent in the small-fish experiment (Figure 3). No muscle injuries were noted in the small fish, but a single fish with a gill injury survived from the 45-min treatment group. In both time-on-deck experiments, few fish survived long durations on deck, resulting in low sample sizes for physiology and health assessments of survivors.

Discussion

Survival

Lingcod exposed to various tow durations ranging from 35 to 300 min in a commercial bottom trawl followed by the immediate transfer to seawater showed no mortality throughout a 21-d recovery period, demonstrating that the capture process itself (with total catch weight, fish size, and species composition held approximately constant) does not directly result in mortality of lingcod. This is contrary to findings with Pacific halibut *Hippoglossus stenolepis*, sole *Solea solea* (=*S. vulgaris*), plaice *Pleuronectes platessa*, and pollock *Pollachius virens*, where tow duration was determined to be a significant mortality factor (Van Beek et al. 1990; Oddsson et al. 1994; Richards et al. 1995; Ross and Hokenson 1997). However,

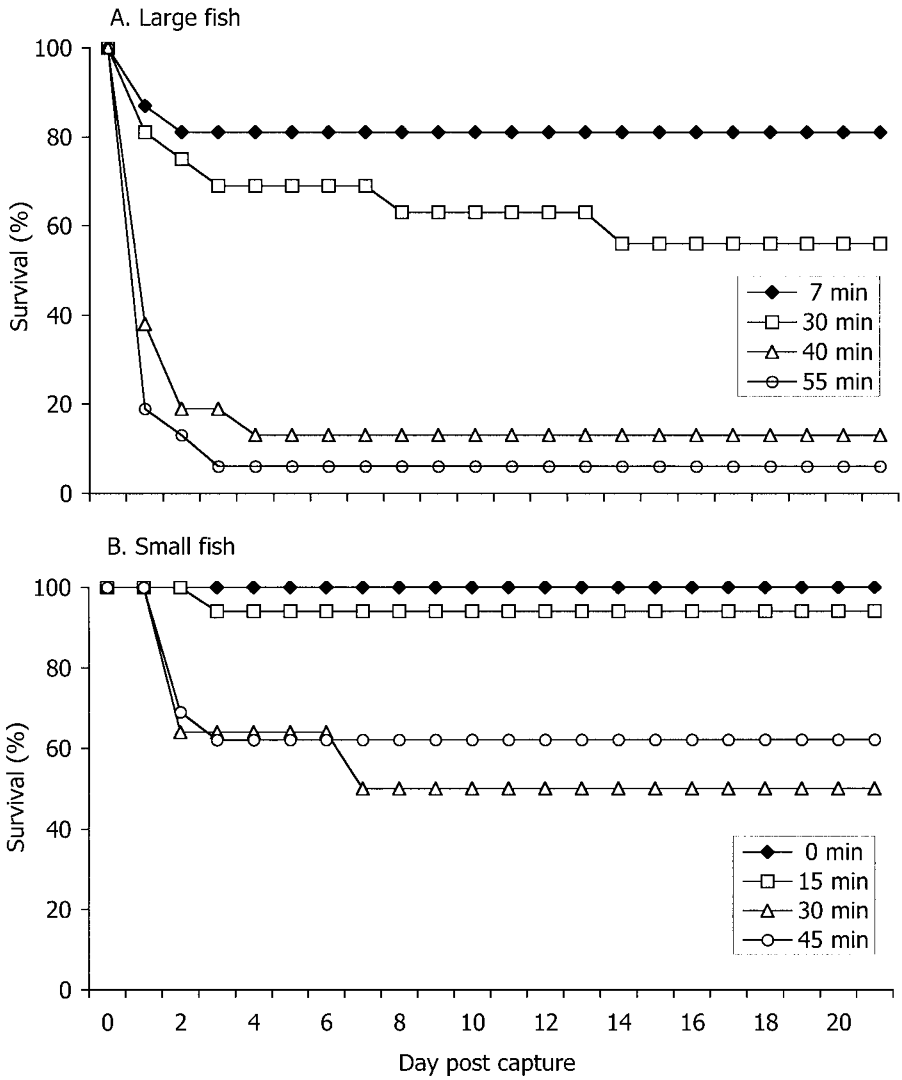

FIGURE 4.—Daily survival (%) of lingcod during a 21-d holding period for **(A)** large (67–84 cm) and **(B)** small (51–66 cm) fish for time-on-deck experiments.

these studies did not separate tow duration from other covarying effects such as total catch weight and deck processing time.

A major factor in the survival of discarded lingcod is the time spent on deck during the sorting process. Those returned to seawater immediately upon starting the sorting process showed 100% survival unless they were part of a large tow where crushing during net retrieval could be an additional factor. Survival decreased to near 50% only after 30 min or more on deck. Although the time to 50% mortality was similar between small (50–66 cm) and large (67–84 cm) lingcod, the large lingcod experienced higher mortality rates for almost all durations on deck (Figure 4). These higher mortality rates were likely due to the effect of total catch weight, which was an order of magnitude larger than the weight captured in the tow with small lingcod and has the potential to cause more injuries (Table 1). The weight of the catch will also influence the on-deck sorting time and lower the percentage of lingcod that could feasibly be discarded quickly after capture.

These experiments were limited in scope and replication, and the results of any particular treatment group must be interpreted in relation to the responses observed in other treatment groups and the sample sizes within each group. In addition,

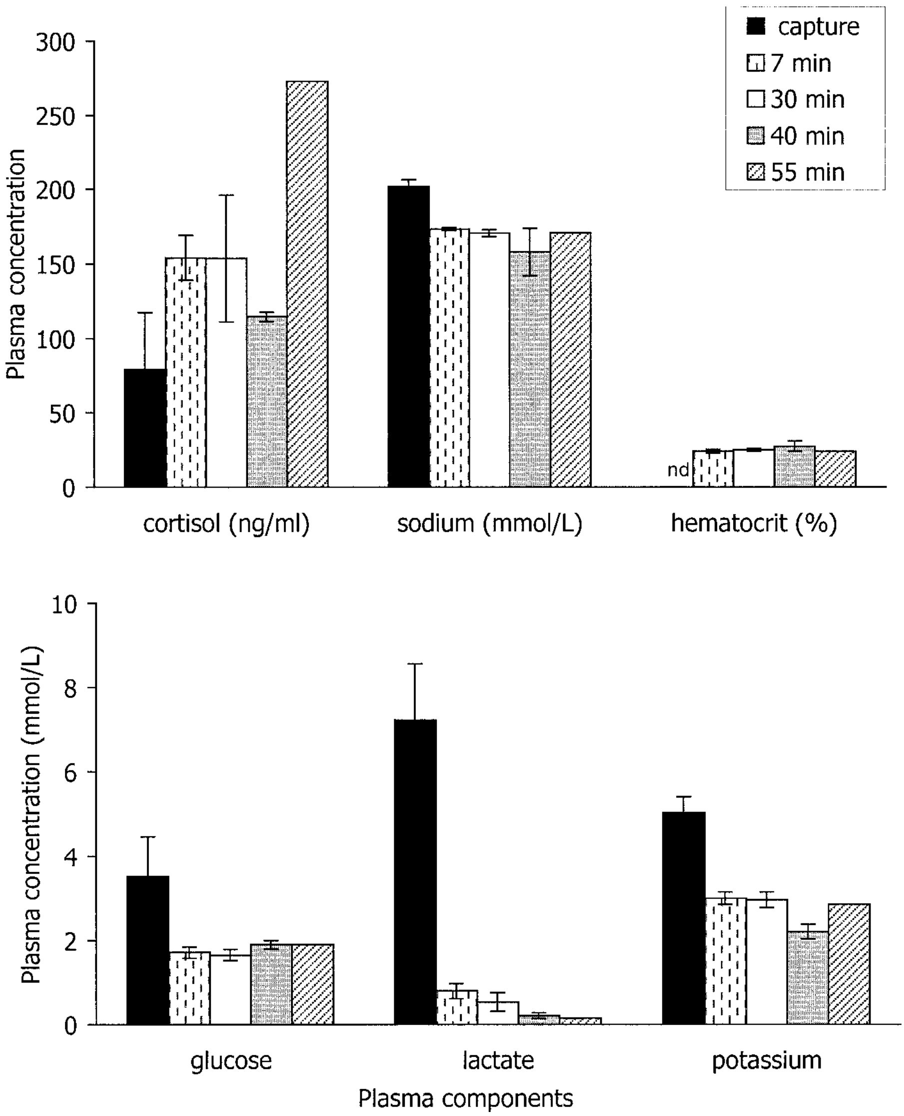

FIGURE 5.—Concentration of plasma components (cortisol [ng/mL], sodium, glucose, lactate, potassium [mmol/L], and hematocrit [%]) for large lingcod from the time-on-deck experiments. Samples taken on deck immediately after a 180-min tow are shown as ''capture.'' Other measurements are after a 21-d holding period. Values are mean ± SE; nd = samples not done.

other factors may limit the scope of conclusions (such as seasonal variability or variation in net design). Considering these constraints, these data represent the only estimates of lingcod discard mortality under actual trawl fishing conditions and address the major mortality factors of tow duration, time on deck, and fish size.

The mortality rates associated with processing times vary considerably among species (Richards et al. 1995; Ross and Hokenson 1997). Lingcod is one of the more resilient species studied. Our results match well with other studies using lingcod exposed to air in either hook and line fisheries (Jagielo 1995; Albin and Karpov 1998) or laboratory simulations (Davis and Olla 2002; Schreck, unpublished data). Discard mortality may be magnified under various combinations of factors such as air temperature, water temperature, and the weight of the catch. Davis and Olla (2002) showed smaller fish (<50 cm) to be more susceptible to thermal stress at 30 min in air because of their smaller mass, but did not have data for much larger

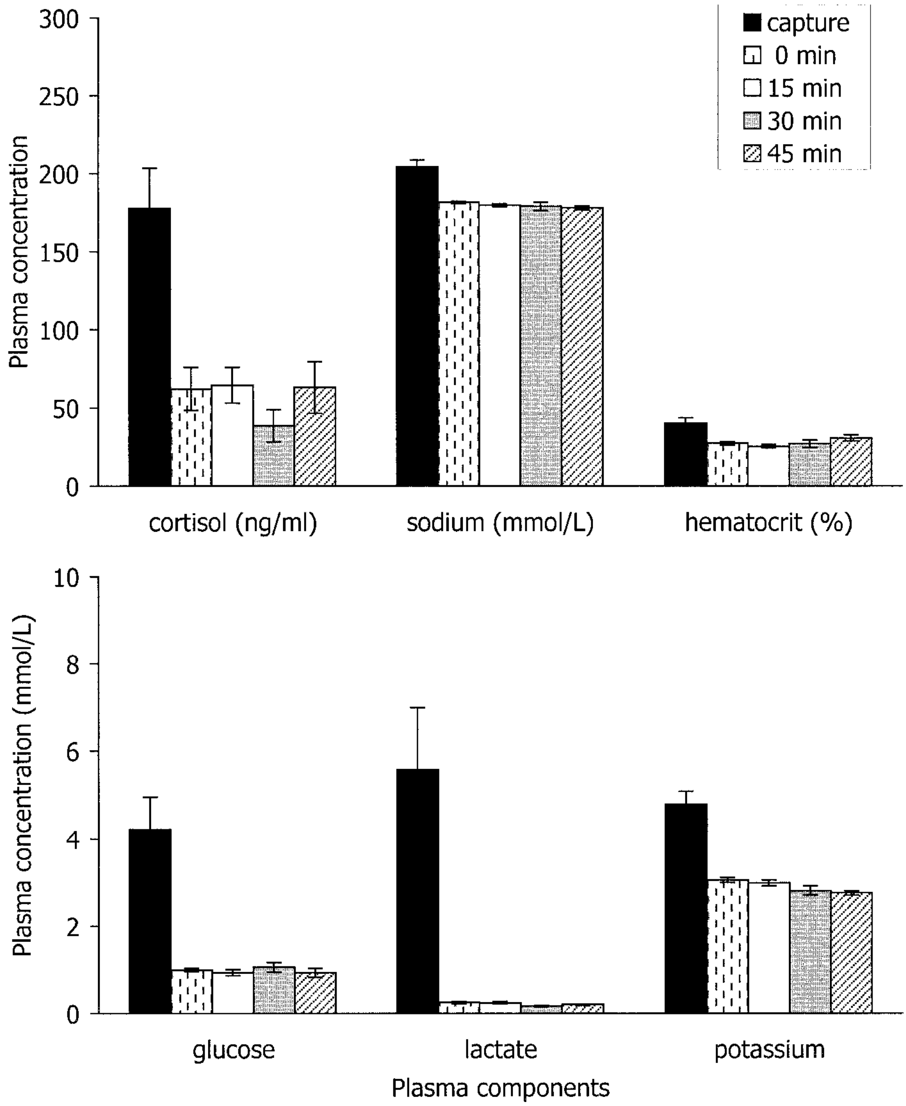

FIGURE 6.—Concentration of plasma components (cortisol [ng/mL], sodium, glucose, lactate, potassium [mmol/L], and hematocrit [%]) for small lingcod from the time-on-deck experiment. Samples taken on deck immediately after a 180-min tow are shown as ''capture.'' Other measurements are after a 21-d holding period. Values are mean ± SE.

fish. Our data suggest similar responses for fish 50–66 cm and 67–84 cm at 30 min on deck and, therefore, that the threshold for any increased susceptibility to thermal stress is likely below 50 cm as suggested by Davis and Olla (2002). In 2001, the legal size limit for lingcod on the West Coast was 61 cm (though it varies with regulation), so all the lingcod in their experiment and the ''small'' lingcod from our experiment would have been discarded. Smaller lingcod also likely suffer from the compounding problems of being too weak to create an airspace around their gills by flaring opercula while surrounded by other fish, and being too small in body height to raise their gills out of the puddle of hypoxic water and mucus to obtain oxygen while on the sorting deck of a trawler. Lastly, very small (<30 cm), thin lingcod are not as visible during sorting and are the some of the last individuals to be sorted.

To maximize survival of discarded lingcod, they should be released by hand immediately after emptying the cod end on deck. However, significant

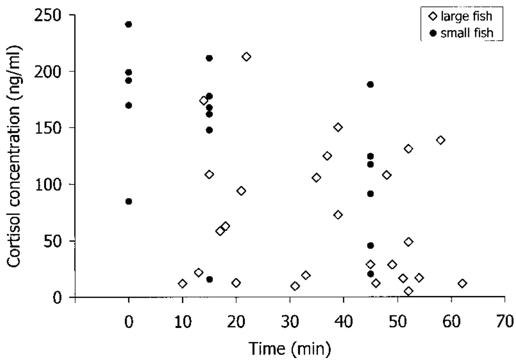

FIGURE 7.—Plasma cortisol concentrations (ng/mL) for individual lingcod during the on-deck period of the time-on-deck experiment. Fish from each experiment were from a single tow of 180-min duration.

mortality can occur within 20 min (Figure 4), so the trawl should not be reset prior to sorting and discarding lingcod. This recommendation is consistent with the recommendations of Davis and Olla (2002) for immediate discard along with processing at cool temperatures. Although the minimum retention size is 61 cm, low landing limits result in the discard of almost all lingcod encountered in commercial fisheries regardless of size during most of the year. Releasing the smallest lingcod quickly will be difficult to implement on trawlers since the total catch weight will impact the ability to find small lingcod, and will also decrease the period during which released fish will survive. Lingcod less than 50 cm are captured by bottom trawls with minimum legal-sized mesh (114 mm), so an increase in mesh size could reduce bycatch. However, the impact of increasing mesh size on the retention of other targeted species has not been modeled in light of new management restrictions (Perez-Comas et al. 1998). In addition, the mortality caused by passing through the trawl mesh is unknown for lingcod, but has been shown to be significant for other species (Chopin and Arimoto 1995; Suuronen et al. 1995, 1996; Ryer 2002).

Stress Response

Although lingcod survive in air after capture for relatively long periods, their stress response is maximal by the time they are brought onboard in the trawl from any trawl duration of more than 35 min (Figures 2, 5, and 6). However, we cannot know if cortisol or some other index of stress became more elevated at some later point during the 21-d holding period. Laboratory experiments with very small lingcod suggest this is unlikely because cortisol levels never exceeded 300 ng/mL and returned to baseline within 24 h during a simulated stress response experiment (Schreck, unpublished data). Cortisol, lactate, and glucose levels were always at their maximal observed levels when sampled at capture, regardless of the time in air. A graded response in cortisol was observed only if lingcod were sampled immediately after a short tow (35 min; Figure 2). Davis et al. (2001) showed cortisol levels did not reach maximal levels until 24 h poststress in sablefish *Anoplopoma fimbria* exposed to simulated towing. In our experiments, during all tows of normal commercial fishery duration, cortisol levels were observed to be at their highest by the time the net was brought on board (3 h). We found no additional increase in cortisol levels during the hour following exposure to air, and in some treatment groups, cortisol remained near these maximal levels even after the 21-d holding period. Although the overall response indicates capture in a trawl to be a maximal stressor as evident in plasma cortisol, lactate, and glucose responses, it does not predict subsequent mortality as has been suggested in other species (Morgan and Iwama 1997; Olla et al. 1998). However, different stressors may result in different stress responses and therefore would not necessarily show a direct relationship with subsequent mortality in every species (Barton and Iwama 1991; Davis et al. 2001).

The lack of a significant decrease in cortisol while lactate and glucose levels recovered during the holding period suggests that the holding conditions in the first two experiments were still somewhat stressful to the fish (speculatively due to light intensity and the frequency of cleaning disturbances). Simple confinement or changes in environmental conditions have been shown in numerous studies with other species to cause elevated cortisol levels (Barton and Iwama 1991; Pankhurst and Sharples 1992). A more complete stress recovery was observed after the tanks were cooled, covered with 1.5-mm black plastic, and disturbed only briefly every third day for cleaning; this suggests that at least part of the elevated cortisol response was due to holding conditions during the first two experiments (Figures 2, 5, and 6).

Resting cortisol levels in captive lingcod can be variable, as observed in other species, and may explain some of the variability observed among individuals in all three holding experiments (Barton and Iwama 1991; Olla et al. 1997). The recovery from stress in the third experiment (small fish) also indicates that the 21-d holding period without feeding was not a significant factor in the sustained stress response, since cortisol levels were similar to those measured in fed, captive lingcod (41.7 ± 14.3 ng/mL, $n = 3$; Michael Davis, National Marine Fisheries Service, personal communication). The long-term effects of stress from capture in a trawl have not been studied but may have effects on disease resistance through immunosupression, or on reproduction through shifts in energy metabolism and allocation (Barton and Iwama 1991; Pankhurst and van der Kraak 1997).

Cortisol levels measured for lingcod in this study are within the normal ranges for stressed and nonstressed levels reported for other fish species, though considerable variation exists among species and among stressors (see review by Barton and Iwama 1991). The normal and stressed plasma levels of lactate, glucose, sodium, and potassium found here are also within the ranges found in the studies of other species (Wedemeyer and Yasutake 1977; Waring et al. 1996; Morgan and Iwama 1997; Davis et al. 2001). Lactate and glucose levels indicated intense physical activity had occurred in all groups. Sodium and potassium concentrations, however, were stable among the treatments both at capture and after 21 d, indicating that no physical trauma or secondary stress response causing loss of osmotic balance had occurred. Although there was no difference in the lactate response of small and large fish to a 180-min tow (Figures 5 and 6), it is unclear why lingcod in the 180-min tow from the tow duration experiment had higher lactate levels than lingcod from the 180-min tows in the time-on-deck experiments (Figures 2, 5, and 6). Because lingcod are overtaken quickly by a bottom trawl, most of the physical activity resulting in increased lactate levels takes place during confinement in the cod end. This results in lingcod of all sizes being exhausted by the time the trawl is brought onboard.

Hyperglycemia is a short-term, secondary response to stress associated with energy metabolism and has been noted in most species studied (Waring et al. 1996). Both lactate and glucose returned to normal, low levels during holding, suggesting that the elevated cortisol levels were a long-term response to holding conditions and were not associated with short-term metabolic activity resulting from the experimental treatment.

Health Assessment Index

The physical evaluations of fish surviving after a 21-d recovery showed mostly skin and fin injuries. More serious injuries did exist in some groups but were only noted in postmortem examinations, indicating that in more strenuous treatment groups, those lingcod with more serious injuries died, whereas in less strenuous treatments, lingcod survived with more severe injuries (Figure 3). Many of the injuries were likely the result of crushing forces experienced during the capture process. These types of injuries were more prevalent in the time-on-deck experiment with large fish (where the lingcod were part of a very large catch consisting mainly of lingcod). In contrast, gill injuries were present in all groups of the tow duration experiment with no resultant mortalities, suggesting that the additional stress imposed by tow duration was not a significant stressor over a short capture period.

The health assessments showed that for lingcod, impacts from capture in a bottom trawl are additive, and that a combination of large catch weight and increased processing times quickly cause mortalities in those fish with the most serious injuries. The long-term fitness of these surviving but physically impacted and significantly stressed lingcod is unknown. Field studies that address the survival of very small lingcod (<40 cm) would be useful in assessing the overall impact of capture and discarding on lingcod fitness.

Given the robust qualities of lingcod, the fish are excellent candidates for reducing discard mortality through changes in handling and on-deck sorting procedures. Survival rates for species that suffer significant mortality from the capture process alone cannot be significantly improved by on-deck procedures. However, to improve discard mortality rates, changes are needed in fisher behavior, something which may prove difficult to accomplish. Even with economic incentives because of bycatch mortality caps and information on how to best improve discard mortality rates of Pacific halibut, estimated mortality rates in many Alaskan fisheries have not been reduced (Williams and Hare 2000).

In addition to maximizing survival of discarded fish, fishery managers are also concerned with accurate estimation of total discard mortality for many fisheries. Our study, along with others, has found that ultimate mortality is strongly related to fishing practices (such as how quickly or slowly a fish is returned to the water). Therefore, generating accurate estimates of discard mortality now depends on gathering some very novel data. It is clear that we need to know much more about how fish are processed under actual fishing conditions and how this ''average handling'' varies with tow volume, crew size, and other factors more related to fisher behavior than to fish physiology. This additional information could possibly be obtained from fishery observer programs or from directed studies that study fishing behavior and the process of commercial fishing. In other words, to estimate total discard mortality of lingcod and other resilient species, we need to study not only the fish, but the fishers as well.

Acknowledgments

We thank Ben Chestnut for his advice and skill in operating the F/V *Olympic*, Michael Davis for culture equipment and chilled seawater, and Ethan Clemons for maintaining the high-quality seawater system for the holding periods. Tim Miller-Morgan and John Kauffman provided the medical evaluations at the close of the holding experiments. We also thank the myriad samplers who assisted in the collection, transport, rearing, and handling efforts.

References

Adams, S. M., A. M. Brown, and R. W. Goede. 1993. A quantitative health assessment index for rapid evaluation of fish condition in the field. Transactions of the American Fisheries Society 122:63–73.

Albin, D., and K. A. Karpov. 1998. Mortality of lingcod, *Ophiodon elongatus*, related to capture by hook and line. U.S. National Marine Fisheries Service Marine Fisheries Review 60(3):29–34.

Barton, B. A., and G. K. Iwama. 1991. Physiological changes in fish from stress in aquaculture with emphasis on the response and effects of corticosteroids. Annual Review of Fish Diseases 1991:3–26.

Chopin, F. S., and T. Arimoto. 1995. The condition of fish escaping from fishing gears- a review. Fisheries Research 21:315–327.

Davis, M. W., and B. L. Olla. 2002. Mortality of lingcod towed in a net is related to fish length, seawater temperature and air exposure: a laboratory bycatch study. North American Journal of Fisheries Management 22:1095–1104.

Davis, M. W., B. L. Olla, and C. B. Schreck. 2001. Stress induced by hooking, net towing, elevated sea water temperature and air in sablefish: lack of concordance between mortality and physiological measures of stress. Journal of Fish Biology 58:1–15.

Jagielo, T., P. Adams, M. Peoples, S. Rosenfield, K. Silberberg, and T. Laidig. 1997. Assessment of lingcod. *In* Pacific Fishery Management Council. Appendix: status of the Pacific Coast groundfish fishery through 1997 and recommended biological catches for 1998: stock assessment and fishery evaluation. Pacific Fishery Management Council, Portland, Oregon.

Jagielo, T., D. Wilson-Vandenburg, J. Sneva, S. Rosenfield, and F. Wallace. 2000. Assessment of lingcod (*Ophiodon elongatus*) for the Pacific Fishery Management Council in 2000. Pacific Fishery Management Council, Portland, Oregon.

Jagielo, T. H. 1995. Abundance and survival of lingcod at Cape Flattery, Washington. Transactions of the American Fisheries Society 124:170–183.

Jagielo, T. H. 1999. Movement, mortality, and size selectivity of sport- and trawl-caught lingcod off Washington. Transactions of the American Fisheries Society 128:31–48.

Morgan, J. D., and G. K. Iwama. 1997. Measurements of stressed states in the field. Pages 247–268 *in* G. K. Iwama, A. D. Pickering, J. P. Sumpter, and C. B. Schreck, editors. Fish stress and health in aquaculture. Cambridge University Press, Cambridge, UK.

National Marine Fisheries Service. 1999. Research plan for west coast groundfish. National Marine Fisheries Service, Seattle.

Neilson, J. D., K. G. Waiwood, and S. J. Smith. 1989. Survival of Atlantic halibut (*Hippoglossus hippoglossus*) caught by longline and otter trawl gear. Canadian Journal of Fisheries and Aquatic Sciences 46:887–897.

North Pacific Fishery Management Council. 1999. Stock assessment and fishery evaluation report for the groundfish resources of the Bering Sea. Aleutian Islands regions. North Pacific Fishery Management Council, Anchorage, Alaska.

Oddsson, G., E. K. Pikitch, W. Dickhoff, and D. L. Erickson. 1994. Effects of towing, sorting and caging on physiological stress indicators and survival in trawl caught and discarded Pacific halibut (*Hippoglossus stenolepis*). Pages 437–442 *in* D. D. MacKinlay, editor. International Fish Physiology Symposium, Fish Physiology Association, Vancouver.

Olla, B. L., M. W. Davis, and C. B. Shreck. 1997. Effects of simulated trawling on sablefish and walleye pollock: the role of light intensity, net velocity and towing duration. Journal of Fish Biology 50:1181–1194.

Olla, B. L., M. W. Davis, and C. B. Schreck. 1998. Temperature magnified postcapture mortality in adult sablefish after simulated trawling. Journal of Fish Biology 53:743–751.

Pacific Fishery Management Council. 1999. Status of the Pacific coast groundfish fishery through 1999 and recommended biological catches for 2000: stock assessment and fishery evaluation. Pacific Fishery Management Council, Portland, Oregon.

Pankhurst, N. W., and D. F. Sharples. 1992. Effects of capture and confinement on plasma cortisol concentrations in the snapper, *Pagrus auratus*. Australian Journal of Marine and Freshwater Research 43: 345–356.

Pankhurst, N. W., and G. van der Kraak. 1997. Effects of stress on reproduction and growth of fish. Pages 73–93 *in* G. K. Iwama, A. D. Pickering, J. P. Sumpter, and C. B. Schreck, editors. Fish stress and health in aquaculture. Cambridge University Press, Cambridge, UK.

Passonneau, J. B. 1974. Fluorimetric method. Pages

1468–1472 *in* H. U. Bergmeyer, editor. Methods of enzymatic analysis. Academic Press, New York.

Perez-Comas, J. A., D. L. Erickson, and E. K. Pikitch. 1998. Cod-end mesh size selection for rockfish and flatfish of the U.S. West Coast. Fisheries Research 34:247–268.

Redding, J. M., C. B. Schreck, E. K. Birks, and R. D. Ewing. 1984. Cortisol and its effects on plasma thyroid hormone and electrolyte concentrations in fresh water and during seawater acclimation in yearling coho salmon, *Oncorhynchus kisutch*. General and Comparative Endocrinology 56:146–155.

Richards, L. J., J. Fargo, and J. T. Schnute. 1995. Factors influencing bycatch mortality of trawl-caught Pacific halibut. North American Journal of Fisheries Management 15:266–276.

Ross, M. R., and S. R. Hokenson. 1997. Short-term mortality of discarded finfish bycatch in the Gulf of Maine fishery for northern shrimp *Pandalus borealis*. North American Journal of Fisheries Management 17:902–909.

Ryer, C. 2002. Trawl stress and escapee vulnerability to predation in juvenile walleye pollock: Is there an unobserved bycatch of behaviorally impaired escapees? Marine Ecology Progress Series 232:269–279.

Suuronen, P., D. L. Erickson, and A. Orrensalo. 1996. Mortality of herring escaping from pelagic trawl codends. Fisheries Research 25:305–321.

Suuronen, P., T. Turunen, M. Kiviniemi, and J. Karjalainen. 1995. Survival of vendace (*Coregonus albula*) escaping from a trawl cod end. Canadian Journal of Fisheries and Aquatic Sciences 52:2527–2533.

Van Beek, F. A., P. I. Van Leeuwen, and A. D. Rijnsdorp. 1990. On the survival of plaice and sole discards in the otter-trawl and beam-trawl fisheries in the North Sea. Netherlands Journal of Sea Research 26: 151–160.

Waring, C. P., R. M. Stagg, and M. G. Poxton. 1996. Physiological responses to handling in the turbot. Journal of Fish Biology 48:161–173.

Wassenburg, T. J., and B. J. Hill. 1993. Selection of the appropriate duration of experiments to measure the survival of animals discarded from trawlers. Fisheries Research 17:343–352.

Wedemeyer, G. A., and W. T. Yasutake. 1977. Clinical methods for the assessment of the effects of environmental stress on fish health. U.S. Fish and Wildlife Service Technical Papers 89:1–18.

Williams, G. H., and S. R. Hare. 2000. Pacific halibut discard mortality rates in the 1990–1999 Alaskan groundfish fisheries, with recommendations for monitoring in 2001 and beyond. International Pacific Halibut Commission, Seattle.