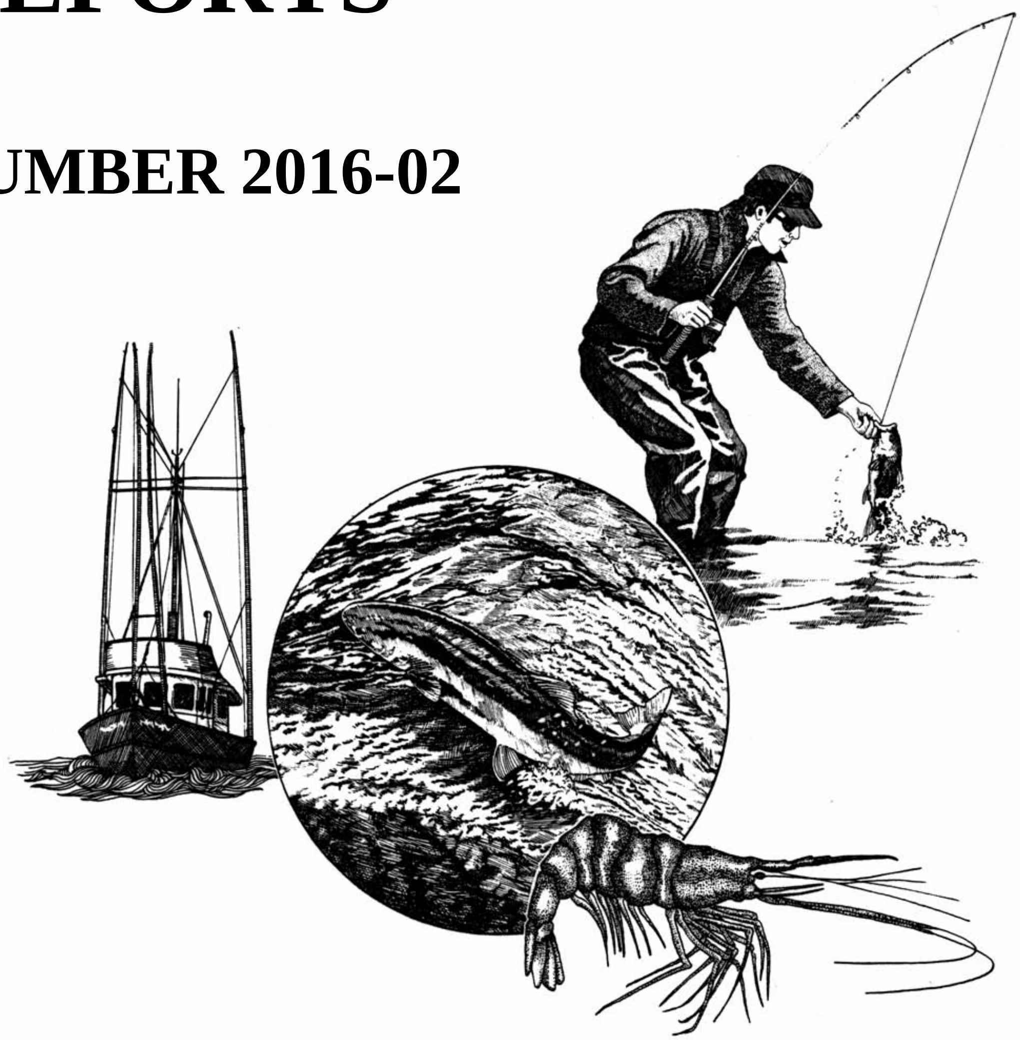
INFORMATION REPORTS

NUMBER 2016-02



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Oregon Department of Fish and Wildlife

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Modeling the effect of changing fishing effort and bycatch reduction technology on risk to eulachon (*Thaleichthys pacificus*) from bycatch mortality in the ocean shrimp (*Pandalus jordani*) trawl fishery

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February 2016

Introduction

This report describes methods and results from an updated fishery modeling effort directed at evaluating the population risk to eulachon (*Thaleichthys pacificus*) from bycatch mortality in the ocean shrimp trawl (*Pandalus jordani*) fishery. The eulachon is an anadromous smelt species inhabiting the Pacific coasts of the U.S. and Canada that has been listed as "threatened" under the U.S. Endangered Species Act (ESA, Gustafson et al. 2012). Specifically, the southern "distinct population segment" (SDPS) of eulachon has been determined to be both a species, as defined by the ESA, and at some risk of extinction over the next 100 years (Gustafson et al. 2012). The SDPS is comprised of river runs ranging from northern California to the Nass River in northern British Columbia (Gustafson et al. 2012). The determination that SDPS eulachon are "threatened" is based primarily on historically reduced in-river spawning runs that are also highly variable from year to year (Gustafson et al. 2012). Moreover, the factors causing the declines in the abundance of SDPS eulachon are not well understood. Bycatch in the ocean shrimp trawl fishery, climate change, changes in the abundance and distribution of predator populations, and changes in the timing of peak river flows due to dams and water diversions have all been identified as potential contributors (NMFS 2010). Although the status of eulachon has been determined mostly from in-river catches and spawning runs, eulachon are primarily a marine fish, spending most of their lives in the ocean (Hay and McCarter 2000).

The general lack of data on eulachon marine abundance poses a major problem for gauging the potential impact of marine fishing mortality on stock recovery, particularly in U.S waters where no systematic small-mesh trawl surveys are conducted. Eulachon are a small (< 300 mm TL), slender fish, not efficiently captured by groundfish bottom trawl gear or by the survey trawls used by the National Marine Fisheries Service to monitor U.S. west coast groundfish populations (codend liner of 38 mm stretch measure mesh, Keller et al. 2007). Fishing mortality of eulachon in U.S. marine waters is dominated by bycatch in the small-mesh trawl fishery for ocean shrimp (NWFSC 2009). Eulachon and other smelt species (Osmeridae) have historically represented a sizable component of the bycatch in this fishery (Hannah and Jones 2007). In recent years, bycatch of eulachon and other fish species in this fishery have been greatly reduced by the mandatory use of bycatch reduction devices (BRDs, Hannah and Jones 2007). As of 2012, vessels landing ocean shrimp into the states of Washington and Oregon have been required to use the most efficient BRDs currently available, rigid-grate BRDS with vertical bar spacing of 19.1 mm (Hannah and Jones 2012). Very recently, the addition of green LED lights to the footropes of ocean shrimp trawls has been shown to reduce eulachon byatch by an additional 91% (Hannah et al. 2015). This new technology also greatly reduces catches of small flatfish and juvenile rockfish and has been widely and rapidly adopted by most of the U.S. ocean shrimp fishing industry (ODFW, unpublished data), but is not currently required by regulation.

These modern improvements in shrimp trawl gear should help greatly in aiding the recovery of SDPS eulachon. However, without information on fishing mortality of eulachon it will be very difficult to evaluate risk quantitatively for this species, especially in U.S waters. In Canadian waters, annual small-mesh (12.7 mm stretch mesh codend liner, Pers. Comm. Ken Fong, Department of Fisheries and Oceans, Canada) trawl surveys are conducted and eulachon bycatch limits have been established based on an estimate of the sustainable level of fishing and the precautionary principle (Schweigert et al. 2012, DFO 2011).

In a prior study, I developed a model to generate preliminary estimates of the annual rate of fishing on SDPS eulachon resulting from the operation of the regional trawl fishery for ocean shrimp (Hannah 2014). The model was simpler, but conceptually similar to the approach used by Zhou and Griffiths (2008) to evaluate the sustainability of bycatch harvest rates on elasmobranch species in Australia's northern prawn fishery. These models evaluate risks from fishing based on the relationship between the spatial footprints of fishing and that of the non-target species (Zhou and Griffiths 2008, Stobutzki et al. 2002, Pope et al. 2000, Zhou et al. 2009, Zhou et al. 2011). They can also incorporate specific knowledge of the fishing gears involved, including estimates or assumptions about elemental efficiency and parameters such as size selectivity and post-discard mortality.

Results from the prior study indicated that risk to SDPS eulachon from continued operation of the shrimp fishery was low, providing regional trawl fishing effort did not increase greatly in the future. However, this conclusion relied heavily on the very large spatial extent of eulachon marine habitat considered, potentially allowing for more severe local effects on eulachon in U.S. waters. Here, I report on results from an updated and improved version of this model that differs from the prior study in three ways. First, the modeling approach is more geographically focused: it considers just U.S. coastal waters and associated shrimp trawl fishing effort. Second, the new model incorporates the effect of varying levels of mandatory bycatch reduction technology: no bycatch reduction technology used, high-efficiency BRDs only and BRDs used along with the new LED light technology, on footropes, for all fishing. Consideration of these different levels of technology allowed for evaluation of both future and historical risk to eulachon in U.S waters from bycatch mortality in the shrimp fishery. Lastly, a minor error in the earlier model equations was corrected.

In this study, my objectives were to:

1) Generate estimates of the rate of fishing on eulachon in U.S. waters at recent levels of shrimp trawl fishing effort (single-rig-equivalent h, sreh) and compare these to two estimates of the rate of fishing on eulachon that is considered sustainable, and,

2) Evaluate how the use of different bycatch reduction technologies influences the risk to SDPS eulachon in U.S waters from the ocean shrimp fishery, at historical, current and potential future levels of fishing effort.

It should be noted that the approach used in this study and the earlier effort (Hannah 2014) rely on a suite of simplifying assumptions to generate what can be considered, at best, approximate and preliminary estimates of the rate of fishing on eulachon. The actual fishing mortality experienced by SDPS eulachon each year will depend on a variety of factors that currently cannot be modeled, including particularly the annual relative spatial distribution of eulachon and shrimp trawling effort.

Methods

With several assumptions, the approximate annual exploitation rate of eulachon caught as bycatch in the shrimp trawl fishery can be estimated by the following equation,

$u = (A_{swept}/A_{eulachon}) \times p_{elemental} \times (1- (p_{excluded} \times (1-p_{latent})))$, where,

u = the annual exploitation rate, and,

A_{swept} = the spatial area (ha) swept by ocean shrimp trawls in a year (a function of fishing effort), and,

$A_{eulachon}$ = the spatial area of marine habitat of eulachon,

$p_{elemental}$ = the elemental efficiency of shrimp trawl nets for eulachon, or the proportion of all eulachon within the swept width of a shrimp trawl that are actually entrained into the net, with or without the modifying effect of LED lights on the fishing line, and,

$p_{excluded}$ = the proportion of eulachon that are excluded by modern rigid-grate BRDs after entrainment, and,

p_{latent} = the proportion of BRD-excluded eulachon that subsequently die as a result of their interaction with the trawl net.

The estimates of u can then be converted into an instantaneous annual rate of fishing (F) by iterative solution of:

$u = F/((F+M) \times (1-e^{-(F+M)}))$, where,

the annual rate of natural mortality, M, is assumed to be 0.51 following Schweigert et al. (2012).

Model assumptions

To employ the simple model detailed above to generate estimates of fishing mortality, a variety of simplifying assumptions were needed. First, it was necessary to assume that SDPS eulachon in U.S waters are evenly distributed across a typical spatial habitat range, and that their distribution does not vary consistently by depth or latitude, and, that outside of this area, there are no SDPS eulachon. This assumption is certainly not correct. However, eulachon distribution is highly variable from year to year, and likely expands and contracts with changes in population size (MacCall 1990, Hay et al. 1997, Levesque and Therriault 2011), which is also highly variable. There is little evidence to suggest any persistent spatial structure in the marine distribution of eulachon, except with regard to the range of depths across which they can be found, thus this simplifying assumption is a reasonable approximation. The highly variable annual distribution of ocean shrimp and associated trawling effort (Hannah 1995) also supports the use of this assumption.

For these model results to be reasonable, there also must be a general spatial correspondence between the distribution of eulachon and shrimp fishing effort, but no inherent and strong fine-scale spatial association between the two species. I tested both of these assumptions. To test for the general correspondence between shrimp trawl effort and eulachon distribution, I overlaid a polygon enclosing the available 2009-2014 Oregon shrimp trawl fishery haul start locations (based on large subsamples of fishery logbook data averaging 71% of all logbooks) with haul start locations recording the presence of eulachon in the National Marine Fisheries Service (NMFS) triennial trawl survey data from 1989-2001 and from the Northwest Fisheries Science Center annual trawl surveys from 2003-2012. This assumes that the fishery logbook data and data on presence of eulachon are representative of the relative spatial distributions. To test for a fine-scale spatial association between ocean shrimp and eulachon, I conducted a meta analysis of the available haul data from several recent shrimp trawl research projects (N=156, Hannah et al. 2011, Hannah and Jones 2013, Hannah et al. 2015). From these experiments I assembled all of the haul-by-haul data on eulachon and ocean shrimp catch resulting from hauls made with trawl nets utilizing rigid-grate BRDs with 19.1 mm bar spacing and no other net or footrope modifications. Typically, this was data from just the control net in experiments with double-rigged shrimp nets, but for one of the experiments that tested the effect on bycatch from reducing BRD bar spacing to 19.1 mm, I used data from just the treatment net (Hannah et al. 2011). Then, for each data set and species, I calculated a geometric mean anomaly of individual haul catches. This was necessary in order to combine data collected in different years, as both ocean shrimp and eulachon abundance vary greatly from year to year. I then used linear regression of the eulachon catch anomalies on those for ocean shrimp to evaluate evidence for a fine-scale spatial association. The residuals from this model were also tested for normality using the Shapiro-Wilk goodness of fit test in JMP® 6.0.

Additional assumptions required for this model are that the area swept by a typical pair of 27.4 m (footrope length) shrimp trawl nets is representative of the fleet average, and that shrimp trawl nets generally have constant catchability for eulachon across the season, across vessels and across a large range of total effort, (e.g. the proportion of the eulachon population captured by any single pass of a shrimp trawl in an area is independent of any prior shrimping effort in that area). This last assumption is conservative, in that interaction of individual units of fishing effort should act to reduce actual exploitation rates relative to model estimates.

I also assumed that annual Washington and California shrimp trawl fishery catch-per-unit-effort (CPUE) was equal to CPUE for Oregon vessels. This assumption is employed to estimate total annual U.S. ocean shrimp fishing effort based on annual landed catch by state and average CPUE calculated annually from Oregon logbook data. In addition, I assumed that the high-efficiency 19.1 mm BRDs required in Oregon and

Washington were used in all segments of the U.S fishery from 2011-2014. California has less restrictive BRD regulations, however, most California shrimpers are believed to use BRDs that are also legal in Oregon (Frimodig et al. 2009). The final assumption used was that the adoption of LED lights on trawl fishing lines to reduce bycatch will be universal across the three states at some point in the near future (Hannah et al. 2015) and that no LED lights were used in 2014. This is also not strictly correct because many Oregon vessels began using LED lights in the final 2 months (September-October) of the 7-month 2014 fishing season.

Sensitivity analysis

Given the broad simplifying assumptions required for this model and the uncertain nature of many of the parameter estimates employed, examination of model results across a range of parameters is justified. For each parameter estimate detailed below, I provide justification, as available, for the chosen values. I considered model output from these parameters as a “base case” scenario for estimating eulachon fishing mortality rates as a function of ocean shrimp trawl fishing effort. I also selected an alternative, less optimistic, value for several of the model parameters and also estimated fishing mortality rates for these combined “conservative” parameter values.

Parameter estimates - A_{swept}

Oregon ocean shrimp fishery logbook data, along with landed catch data from Washington and California (Eureka and Crescent City, CA only), were used to generate estimates of the total spatial area swept in a single season, as a function of fishing effort. Oregon shrimp trawl fishing effort is estimated annually from logbook data and standardized to single-rig equivalent hours (sreh, Table 1, PFMC 1981). With typical ocean shrimp trawl nets, one sreh has been calculated to sweep 5.93 ha of the grounds (Table 2, Hannah 1995). This parameter for area swept per sreh of trawling was considered one of the better known model parameters and was used for all model runs.

Table 1. Catch of ocean shrimp (t) north of Cape Mendocino, CA, by U.S. state, fishing effort (single-rig equivalent hours, sreh) for the Oregon shrimp fishery, and estimates of total U.S. fishing effort for this region, 2011-2014. The mean values for 2011-2014, including catch percentages by state, are also shown.

Year	Catch (t)			Effort (sreh) Oregon	Total estimated U.S. effort (sreh)
	Northern California	Oregon	Washington		
2011	3,345.3	21,915.3	4,088.2	33,276.0	44,562.9
2012	2,790.6	22,291.4	4,225.1	38,649.0	50,812.8
2013	3,842.5	21,603.7	6,183.1	32,723.1	47,908.9
2014	3,845.0	23,568.7	13,795.7	32,640.7	57,071.5
Mean	3,455.8	22,344.8	7,073.0	34,322.2	50,089.0
Percent	10.5%	68.0%	21.5%		

Table 2. Parameter values used to estimate annual rate of fishing on eulachon from shrimp trawling effort in the base and conservative models (see text).

Parameter	Base model	Conservative model
A_{swept}/sreh	5.93 ha	5.93 ha
$A_{eulachon}$	1,987,719 ha	1,590,175 ha
$P_{excluded}$	0.55	0.40
P_{latent}	0.00	0.50
$P_{elemental}$	0.50	0.75
$P_{elemental\ (with\ LED\ lights)}$	0.05	0.15

Marine spatial area occupied by eulachon ($A_{eulachon}$)

I used a geographic information system to make an estimate of the spatial area of eulachon marine habitat in U.S waters. I selected the spatial area between 73 and 183 m (40 and 100 fathoms) contours as a proxy for the spatial area inhabited by SDPS eulachon. The spatial distribution of hauls recording the presence of eulachon in the National Marine Fisheries Service (NMFS) triennial trawl survey data from 1989-2001 and from the Northwest Fisheries Science Center annual trawl surveys from 2003-2012 show that this area agrees fairly well with the survey haul locations that captured eulachon (Figure 1). Both NMFS surveys extend to much greater depths than 183 m, however, the triennial survey probably did not fully sample the shoreward extent of eulachon. Data from Toole et al. (2011) record eulachon catches at shallower depths than sampled by the NMFS survey, documenting eulachon as shallow as 50-79 m of depth. For the ocean area from Cape Mendocino north to the U.S. Canada border, the area between these two depth contours equaled 1,987,719 ha (Figure 1, Table 2). For a more conservative parameter value, I assumed that 20% of this area is not suitable habitat for eulachon (Table 2).

BRD exclusion rate ($p_{excluded}$)

The average eulachon exclusion efficiency of 19.1 mm rigid-grate BRDs was estimated based on ODFW field studies of BRD performance. State regulations in Washington and Oregon require all shrimp vessels to use rigid-grate BRDs with bar spacing no larger than 19.1 mm to maximize exclusion of eulachon (Hannah and Jones 2012). The only direct data on overall exclusion rates of eulachon for this type of BRD are the underwater video observations from Hannah and Jones (2012). In that study, 76% of the large eulachon (approximately 160-240 mm TL) escaped via the BRD, while only 25% of the smaller eulachon escaped. That finding is somewhat uncertain because, in that study, large and small eulachon were distinguished only visually from the video and misclassification was possible due to varying distance of the eulachon from the camera. In the 1995 BRD study by Hannah et al. (1996), 70% of the smelt (Osmeridae), as a mixed species group, by weight, escaped from a shrimp trawl equipped with a rigid-grate BRD with 25.4 mm bar spacing. That study did not differentiate smelt species, but encountered mostly larger smelt, and noted both whitebait smelt and eulachon in the catch (ODFW unpublished data). The length data from that study do not support a strong length-based sorting effect for eulachon encountering the 25.4 mm BRD. A later study comparing the efficiency of rigid-grate BRDs with 25.4 and 19.1 mm bar spacing showed a 16.6% reduction in eulachon catch weight with the 19.1 mm BRD, an effect that was also not modulated by eulachon length (Hannah et al. 2011). Considering these data, I chose 55% as an average exclusion rate for eulachon of all sizes encountering shrimp trawls equipped with rigid-grate BRDs with 19.1 mm bar spacing (Table 2). For a more conservative parameter, I also modeled a BRD exclusion rate for eulachon of just 40% (Table 2).

Latent mortality rate (p_{latent})

Hannah and Jones (2012) showed, using underwater video, that large eulachon were typically in very good condition as they escaped from a shrimp trawl via a BRD, with most fish retaining the ability to avoid contact with the grate and maintain an upright and forward-oriented swimming posture. Those data are consistent with the concept that for fish like eulachon, which are excluded efficiently by BRDs even though they are small enough to pass through the grid, the BRD acts as a behavioral sorting device. Fish that are exhausted and in poor condition pass back through the grid and into the codend, while those in the best condition exit the trawl net with minimal physical contact with the trawl components. Based on this limited information, I assumed that all excluded eulachon survive and all captured and discarded eulachon do not (p_{latent} = 0.0, Table 2). To incorporate a more conservative view of post-exclusion survival, I also modeled a latent mortality rate of 50% (p_{latent} = 0.5, Table 2).

Elemental trawl efficiency for eulachon ($p_{elemental}$)

The elemental efficiency of a trawl is defined as the proportion of fish that are within the swept area of the net that actually become entrained in the trawl (Winters and Wheeler 1985, Hannah 1995). This is a difficult parameter to estimate for most trawl fisheries and species. For ocean shrimp, elemental trawl efficiencies have previously been assumed to range somewhere between 0.25-0.75 (Hannah 1995). Data supporting elemental efficiency well below 1.0 for ocean shrimp include their vertical migration under low light conditions (Pearcy 1970) and catch studies and underwater video observations that show escapement of shrimp both under the fishing line and through the meshes of the body of the trawl (Hannah et al. 2003, Hannah and Jones 2003). Some of these factors should act to limit elemental efficiency of these trawl nets for eulachon as well. The groundline configuration and fishing line height of ocean shrimp trawls have been shown to greatly influence the bycatch of eulachon and other small demersal species (Hannah and Jones 2000, Hannah et al. 2011, Hannah and Jones 2013), suggesting substantial fish escapement between the groundline and elevated fishing line (35-70 cm above the seafloor, Hannah and Jones 2003) of shrimp trawls. Escapement of eulachon and other fish species between the elevated fishing line and trawl groundline have also been directly observed with underwater video (ODFW unpublished data). Although the vertical movements of eulachon are not well known, at least one study suggests eulachon are captured up to 40 m above the bottom and thus are sometimes unavailable to shrimp trawl nets (Emmett et al. 2004). Lacking any more definitive data on elemental efficiency of shrimp trawls for eulachon, I assumed a rate of 0.50 for elemental trawl efficiency as the "base model" scenario and modeled efficiency of 0.75 for the more conservative parameter set (Table 2).

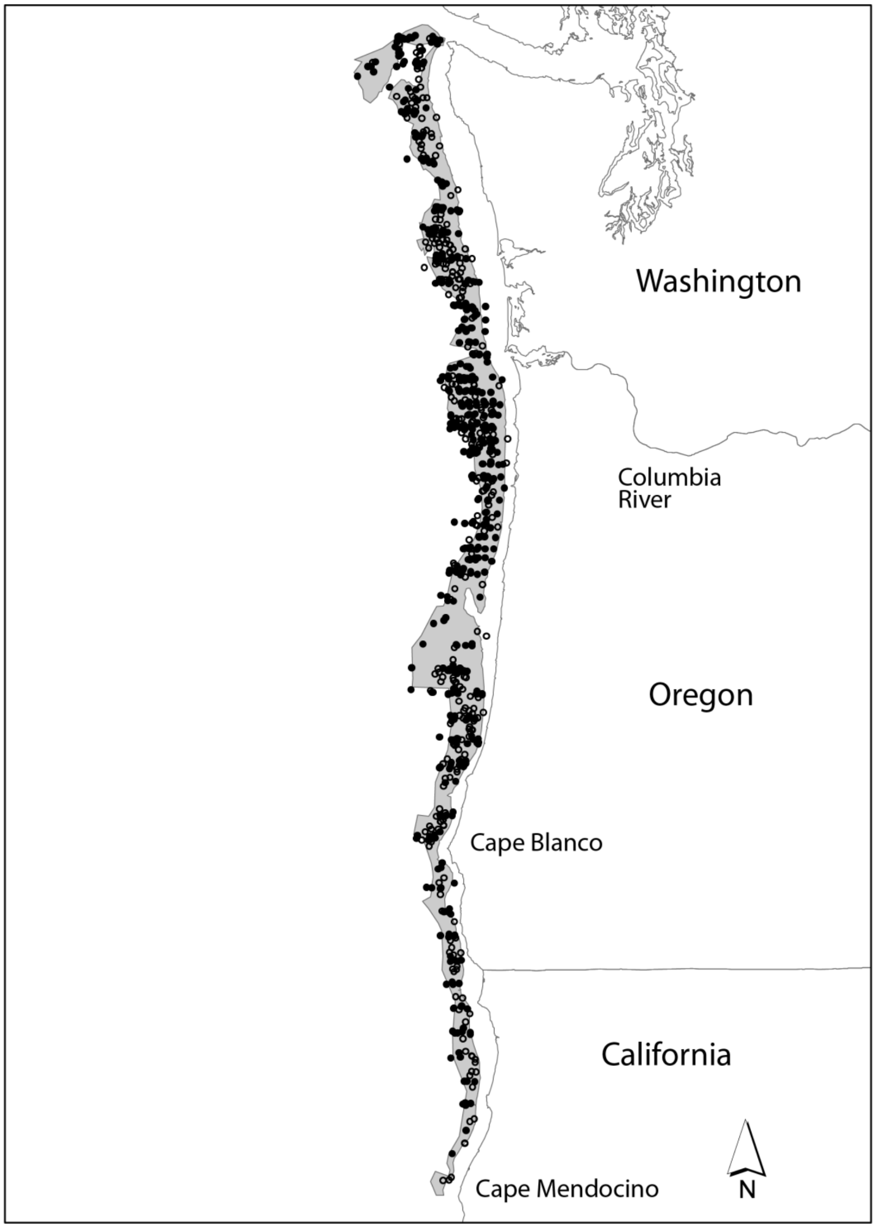

Figure 1. Comparison of the spatial area between the 73 and 183 m depth contours (40 and 100 fathoms, $A_{eulachon}$) and the locations of the 1989-2001 NMFS triennial trawl

survey (filled circles) and 2003-2012 NWFSC annual survey hauls (open circles) that captured eulachon.

The LED light technology that has just recently been widely adopted by U.S. west coast shrimp trawl vessels to reduce eulachon bycatch reduces elemental trawl efficiency for this species (Hannah et al. 2015). For base model runs incorporating LED lights, the assumed elemental efficiency value of 0.5 was therefore reduced by 90% to 0.05 (Table 2). For the more conservative scenario, I assumed that LED light technology would not perform up to research standards when actually implemented in the fishery, a common problem with bycatch reduction technology (Foster 2004, Richards and Hendrickson 2006). So for the conservative scenario I assumed that the LED lights would reduce elemental efficiency by just 80% at a fishery scale, which for the conservative scenario yields an elemental efficiency for eulachon of 0.75, reduced by 80% to equal 0.15 (Table 2).

Model output

Model runs were conducted for both parameter sets to estimate eulachon fishing mortality rates under a variety of conditions. To evaluate how the implementation of bycatch reduction technology alters eulachon fishing mortality and risk, the model was used to profile mortality across a wide range of regional fishing effort under 3 sets of conditions: no bycatch reduction technology in use, high efficiency BRDs only and the combination of high-efficiency BRDs and LED footrope lights on all trawl nets. These results were then evaluated for 3 scenarios: recent conditions in the fishery (effort levels from 2011-2014 and 19.1 mm codend BRDs used), historical conditions (wide range and much higher levels of effort and no bycatch reduction technologies in use) and future conditions considering potential increases in fishing effort and anticipating a coastwide requirement to use LED footrope lights for all fishing. To evaluate historical risks for eulachon from the fishery, the maximum level of regional fishing effort modeled was chosen to include average annual effort levels observed in 1986-89 (204,333 sreh). This time period was chosen because fishing effort estimates were available for all 3 states and total fishing effort was much higher than in recent years.

Evaluation of model results

The model-generated fishing mortality rates were compared with fishing mortality rates that are considered acceptable for other components of SDPS eulachon or considered acceptable based on life history theory. A Bayesian population model constructed for the Fraser river eulachon (Schweigert et al. 2012) suggested low stock productivity and a sustainable fishing rate of F = 0.10. Levels of harvest equal to natural mortality (F = M, Quinn and Deriso 1999) have also been suggested as sustainable, as well as harvest levels set below this threshold (F = 0.8 X M, Thompson 1993). Combining the latter formula with the life-history-based estimate of M from Schweigert et al. (2012) following Jensen (1996), suggests a sustainable F value of 0.408. Model results were compared with these two values (F=0.10, F=0.408) to evaluate risk to the U.S component of SDPS eulachon.

Results

Evaluation of model assumptions

Comparison of the polygon enclosing Oregon shrimp trawling effort from 2009-2014 with the haul-start locations where eulachon have been recorded in the two NMFS survey data sets (Figure 2) shows general spatial correspondence between the two data sets. Of the 816 survey haul locations that recorded eulachon, 61.4% lie within the polygons that approximately define the shrimp fishing grounds. There are also a few notable differences between the spatial distributions. Eulachon have been recorded by the trawl surveys in some areas where 2009-2014 Oregon shrimp trawl effort was not noted, including some locations off central Oregon, extreme northern Washington and in many areas shoreward of where shrimp trawling typically occurs (Figure 2). The linear regression of geometric mean catch anomalies of shrimp and eulachon from ODFW research hauls with 19.1 mm BRDs did not show evidence for a strong fine-scale spatial association between these two species (N=156, P > 0.134) The residuals from this model were normally distributed (P>0.05). Taken together, these results suggest that the spatial model developed here may be a reasonable first approximation of the interaction of the ocean shrimp trawl fishery with SDPS eulachon.

Eulachon risk in recent years

Estimated total fishing effort for the U.S. ocean shrimp fishery north of Cape Mendocino, California for 2011-2014 ranged from 44,563 to 57,072 sreh, with an average of 50,089 (Table 1). These levels of total fishing effort resulted in base model estimates of eulachon fishing mortality that ranged from 0.039-0.050 and averaged 0.044, with the assumption of no LED light technology in use but complete use of high-efficiency codend BRDs (Table 3). These are well below the range of 0.10-0.408 considered sustainable. At these levels of trawl effort, the base model indicates that a spatial area equal to only about 15% of the eulachon marine habitat was fished with shrimp trawls in recent years (Table 3). Using the more conservative parameter set, 2011-2014 eulachon fishing mortality ranged from 0.135-0.177 with an average of 0.153, with about 19% of the eulachon marine habitat trawled (Table 2) . These mortality rates are above the 0.10 standard for the Canadian fishery, but below the level of 0.408 suggested by life history theory.

Historical risk

Base-model eulachon fishing mortality rates profiled across fishing effort showed that without modern bycatch reduction technologies, the lower sustainable fishing mortality rate of 0.10 would be exceeded at an effort level similar to 2011-2014 levels, about 50,000 sreh (Figure 3). The base-model estimates also suggest that at the higher fishing effort levels recorded for 1986-89 (mean of 204,333 sreh), prior to the development of bycatch reduction technologies, eulachon fishing mortality rates likely exceeded the higher estimate of sustainable mortality of F= 0.408 (Figure 3). The mortality rate estimates from the conservative model parameter set (Figure 4) show sustainable rates being exceeded at much lower levels of fishing effort, about 100,000 sreh for the F=0.408 (Canadian F_{sust} in Figures 3 and 4) threshold.

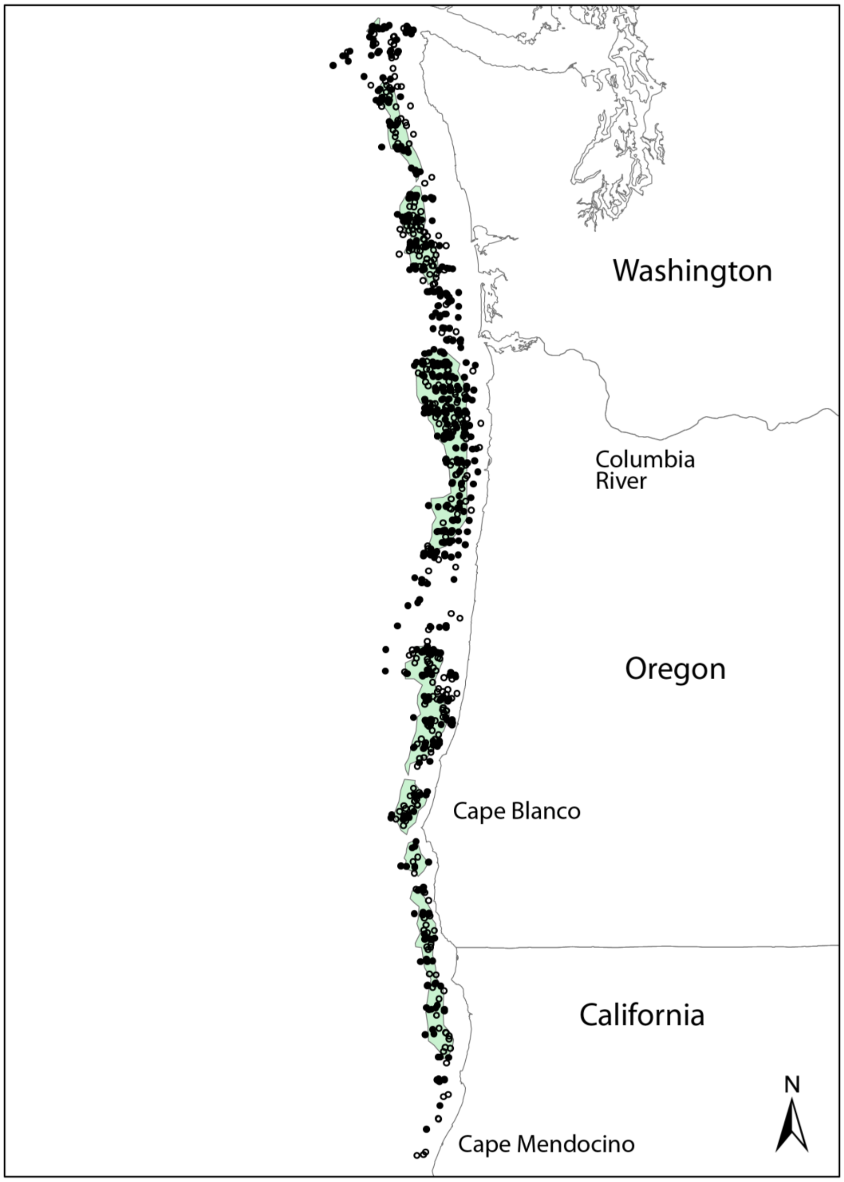

Figure 2. Spatial overlay of polygons enclosing the 2009-2014 ocean shrimp trawl fishery haul start locations (from Oregon fishery logbook data, see text) with the locations of the 1989-2001 NMFS triennial trawl survey (filled circles) and 2003-2012 NWFSC annual survey hauls (open circles) that captured eulachon.

Table 3. Model estimates of eulachon fishing mortality in the 2011-2014 U.S. ocean shrimp trawl fishery using the "base case" and "conservative" model parameters, assuming complete use of 19.1 mm codend BRDs and no use of LED lights on trawl footropes (see text).

Year	A_{swept} (ha)	Base model		Pessimistic model	
		Percent $A_{eulachon}$ swept	F	Percent $A_{eulachon}$ swept	F
2011	264,258	13.3	0.039	16.6	0.135
2012	301,320	15.2	0.044	18.9	0.156
2013	284,100	14.3	0.042	17.9	0.146
2014	338,434	17.0	0.050	21.3	0.177
Mean	297,028	14.9%	0.044	18.7	0.153

Future risk

Profiling across a range of effort levels using the base model parameters (Figure 3) showed that with current BRD requirements in place for the entire U.S fishery, fishing effort would need to increase to more than 120,000 sreh, before fishing mortality rates would rise above the lower threshold F of 0.10 (Figure 3). However, the conservative model parameter set generates a much lower threshold of just 40,000 sreh, below recent average effort levels (Figure 4, Table 1). With mandatory use of both codend BRDs and LED footrope lights, the base model generated very low estimated F values, well below the lower threshold value of F = 0.10, across all modeled levels of fishing effort up to 210,000 sreh (Figure 3). Even using the conservative parameter set, this combination of bycatch reduction technologies reduced estimated eulachon fishing mortality rates so greatly that the lower threshold of F=0.10 was only exceeded at 170,000 sreh and the upper mortality rate threshold of F=0.408 was not exceeded at any modeled effort level up to 210,000 sreh (Figure 4).

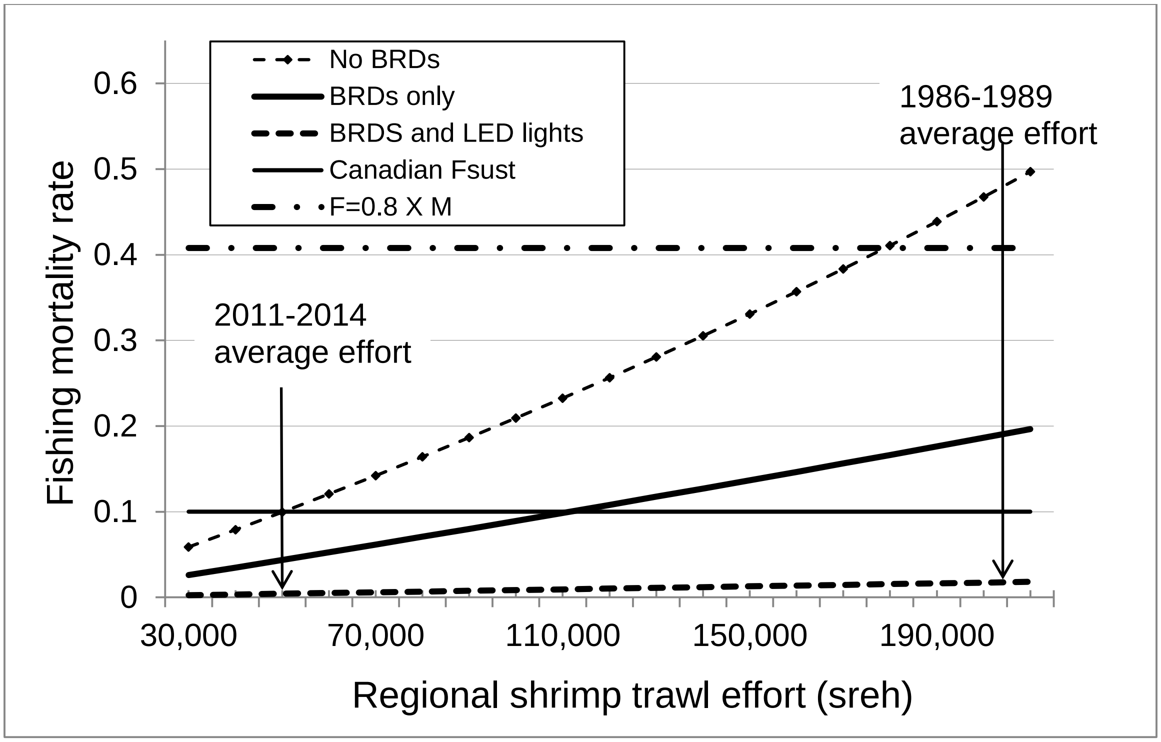

Figure 3. Model estimates of eulachon fishing mortality rate in the ocean shrimp trawl fishery across a range of regional U.S fishing effort (sreh) using the "base case" parameter set assuming 1) no use of bycatch reduction technology (no BRDs), 2) use of high efficiency 19.1 mm BRDs only and 3) use of 19.1 mm BRDs with LED lights also affixed to all trawl footropes. Also shown are a range of fishing mortality rates assumed to be sustainable for eulachon from 0.10 (solid horizontal line, Canadian F_{sust}) to 0.408 (dashed horizontal line, F=0.8 X M, see text).

Discussion

This modeling effort demonstrates that a spatial model, in combination with knowledge of how trawl gear and bycatch reduction technologies work, can sometimes be used to generate estimates of fishing mortality that can inform risk evaluations for a small, demersal bycatch species like eulachon. For eulachon, these estimates of fishing mortality are probably the best available data to assess fishing risk and fishery management measures, due to the near complete lack of the types of monitoring data for eulachon that are typically used in formal fish stock assessment models (Gustafson et al. 2012). However, the estimates of eulachon fishing mortality generated in this analysis must be considered very approximate. The actual rates of fishing mortality experienced by SDPS eulachon in the shrimp fishery in U.S. waters will depend on the relative fine-scale temporal and spatial distributions of eulachon and of shrimp trawling effort, as well as the real, unknown and certainly variable values for $p_{elemental}$, p_{latent} and $p_{exclude}$, as well as many other factors. However, the analysis presented here is a useful approximation that does suggest some conclusions with regard to risk for SDPS eulachon from continued operation of the ocean shrimp trawl fishery. Moreover, the model captures some of the major sources of uncertainty in assessing risk for eulachon, in that it incorporates the effects of increases in trawling effort as well as some level of uncertainty in $p_{elemental}$, p_{latent} and $p_{exclude}$. One additional source of uncertainty that is not addressed within the model is the possibility that a fine-scale spatial association between shrimp and eulachon exists, but was not detected by our limited regression analysis of research data. Fortunately, that question can potentially be addressed by the collection of additional field data.

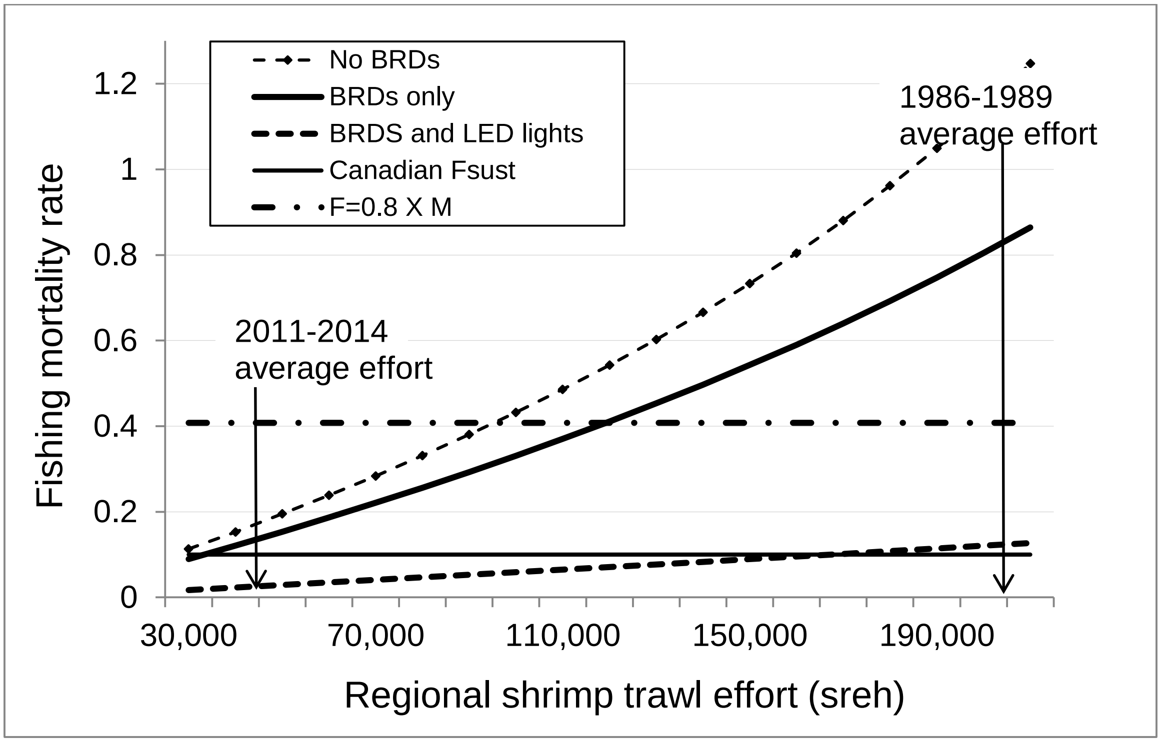

Figure 4. Model estimates of eulachon fishing mortality rate in the ocean shrimp trawl fishery across a range of regional U.S fishing effort (sreh) using the "conservative" parameter set assuming 1) no use of bycatch reduction technology (No BRDs), 2) use of high efficency 19.1 mm BRDs only and 3) use of 19.1 mm BRDs with LED lights also affixed to all trawl fishing lines. Also shown are a range of fishing mortality rates assumed to be sustainable for eulachon from 0.10 (Solid horizontal line, Canadian F_{sust}) to 0.408 (dashed horizontal line, F=0.8 X M, see text).

The model estimates of eulachon fishing mortality from historic higher levels of shrimp trawl effort without bycatch reduction technology in use suggest that bycatch in the shrimp fishery may have contributed to the initial declines in eulachon abundance that led to its listing as "threatened". However, model estimates of fishing mortality and sustainable fishing rates for eulachon both remain very uncertain. What seems clear though, is that the development of two complementary bycatch reduction technologies, high-efficiency codend BRDs and LED footrope lights (Hannah et al. 2011, 2015) can reduce risk to SDPS eulachon substantially without the need for management measures severely limiting trawl fishing effort. This assumes, however, that both bycatch reduction technologies can be implemented consistently and effectively across the entire fishery.

The results from this study suggest that requiring the use of LED lights on all ocean shrimp trawl footropes in use north of Cape Mendocino, California, along with modern, high-efficiency rigid-grate 19.1 mm BRDs, is the best way to maintain low risk for SDPS eulachon, across all anticipated changes in ocean shrimp trawling effort. Although the base model output suggests that at current levels of shrimp trawling effort, risk to eulachon is low (Figure 3), effort in the shrimp fishery is likely to increase. The recent low effort levels result from a combination of factors that are likely to change in future years. The number of vessels participating in the ocean shrimp fishery was reduced by a federal groundfish vessel buyback program implemented in 2003 that also removed a number of shrimp trawl vessels from active fishing. However, in 2011 the groundfish trawl fishery was converted to a “catch shares” program, which has facilitated industry consolidation, leading to some vessels increasing their active participation in the shrimp fishery. Also, recent catch-per-unit-effort in the fishery has been at an historical high due to several exceptionally large recruitment events (Hannah and Jones 2014). This has led to vessels very rapidly catching their limits and very short fishing trips. However, recruitment in ocean shrimp is environmentally driven (Hannah 2011) and is certain to decline at some point in the future. As recruitment declines towards average levels, more days of fishing will be needed to fill market orders and overall, fishing effort will likely increase.

The model results also suggest that requiring LED footrope lights, along with BRDs, for ocean shrimp trawling, reduces the risk to eulachon in a number of ways. Obviously, the LED light technology should greatly reduce fishing mortality on average (Figures 3 and 4). Also though, because the LED footrope lights act to reduce elemental trawl efficiency for eulachon, requiring their use also reduces the risk to eulachon from uncertainty about BRD exclusion rates ($p_{exclude}$) and post-exclusion mortality rates (p_{latent}). If LED footrope lights are reducing trawl entrainment of eulachon by 91%, as estimated in fishing gear experiments (Hannah et al. 2015), or even at a somewhat reduced rate in the actual fishery, then the precise rates at which they are excluded by codend BRDs or survive post-exclusion, become much less critical. This analysis supports the general contention that, when possible, it’s much better to keep bycatch species out of the trawl net entirely, than to exclude them after entrainment.

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