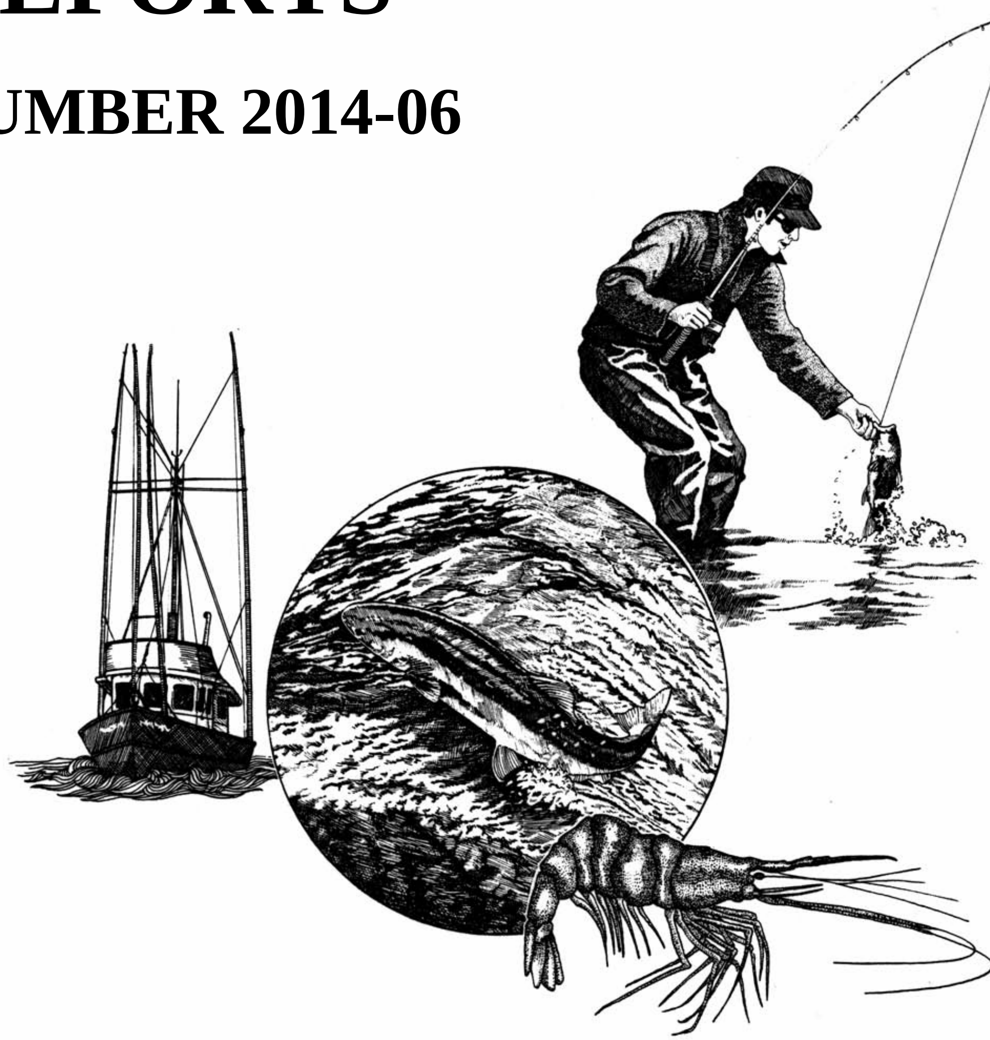
# INFORMATION REPORTS

## NUMBER 2014-06



# FISH DIVISION

## Oregon Department of Fish and Wildlife

Evaluating the population-level impact of the ocean shrimp (*Pandalus jordani*) trawl fishery on the southern distinct population segment of eulachon (*Thaleichthys pacificus)*

# Evaluating the population-level impact of the ocean shrimp (*Pandalus jordani*) trawl fishery on the southern distinct population segment of eulachon (*Thaleichthys pacificus*)

Robert W. Hannah

Oregon Department of Fish and Wildlife
Marine Resources Program
2040 SE Marine Science Drive
Newport, Oregon 97365, U.S.A.

May 2014

## Introduction

Eulachon (*Thaleichthys pacificus*), an anadromous smelt species inhabiting the Pacific coasts of the U.S. and Canada, is the first marine forage fish species to be 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 moderate risk of extinction over the next 100 years (Gustafson et al. 2012). The SDPS is comprised of eulachon spawning runs ranging from northern California to the Nass River in northern British Columbia (Gustafson et al. 2012). The factors causing the recent declines in the abundance of SDPS eulachon are not well understood, however, climate change, changes in the abundance and distribution of predator populations, bycatch in the ocean shrimp (*Pandalus jordani*) trawl fishery and changes in the timing of peak river flows due to dams and water diversions have been identified as potential contributors (NMFS 2010). Interpreting the significance of the recent declines in SDPS eulachon abundance is very challenging. Eulachon are primarily a marine fish, spending very little of their lives in fresh or brackish water (Hay and McCarter 2000). No estimates of the marine population size are available, and inferences about population trends are based on limited data on spawning run sizes from several larger river systems (Gustafson et al. 2012). There is also a lack of information on the magnitude of natural multidecadal variation in the abundance of SDPS eulachon, in comparison with the more extensive time series available for other Pacific forage fish species such as northern anchovy (*Engraulis mordax*), Pacific sardine (*Sardinops sagax*) and Japanese sardine (Chavez et al. 2003, Yasuda et al. 1999).

The extremely limited monitoring data for river runs of SDPS eulachon poses a major challenge for recovery planning also, especially for gauging the potential impact of mortality during the marine phase of the eulachon life cycle, such as bycatch in the ocean shrimp trawl fishery. Further complicating the issue is an unexplained major discrepancy between the perceived magnitude of river runs in comparison with the limited available indices of abundance in marine waters. In their review of SDPS eulachon stock status, Gustafson et al. (2012) note that eulachon biomass abundance indices in offshore surveys are "one to two orders of magnitude" larger than freshwater estimates of spawning biomass. Possible explanations for this discrepancy include high natural mortality of SDPS eulachon and confounding of multiple year classes in marine waters. However, it's also fair to say that although the sharp mid-1990's decline in SDPS eulachon is not in question, the species' current and historical population abundance is simply not well known.

The uncertainty in current SDPS eulachon population abundance is particularly problematic for management of the ocean shrimp trawl fishery, because eulachon and other smelt species (Osmeridae) have historically represented a sizable component of the fishery bycatch (NWFSC 2009, Hannah and Jones 2007). In the early years of this fishery, smelt bycatch was large enough at times to create catch sorting problems for vessel operators. This prompted the development of specialized devices, called "smelt belts" that used angled, rotating sandpaper belts to mechanically separate shrimp from smelt and other small finfish (Jones et al. 1996). In recent years, fish bycatch has been greatly reduced by the use of bycatch reduction devices (BRDs) in the U.S fishery (Hannah and Jones 2007) and also by BRDs and eulachon bycatch limits in waters off British Columbia (DFO 2011). More recently, vessels landing 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 just 19.1 mm (Hannah and Jones 2012).

These, and other improvements in shrimp trawl gear should help greatly in aiding the recovery of SDPS eulachon. However, without knowing more about the relationship between the magnitude of fishery bycatch and the population size of SDPS eulachon, it will be very difficult to evaluate the performance of shrimp fishery management in aiding, or at least in not impeding, the recovery of SDPS eulachon. Here, I report on a simple model that uses the available information on shrimp trawl gear and BRD performance, in combination with a GIS-based analysis of eulachon marine habitat, to develop a preliminary estimate of the annual rate of fishing on SDPS eulachon by the regional shrimp fishery. This model is 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. My purpose, in addition to generating this "first order estimate" of the rate of fishing, is to outline the parameters that, although perhaps poorly known today, are potentially important for understanding the fishery's SDPS-level impacts. An additional goal for developing this model is to illustrate how additional research may be helpful for improving our understanding of shrimp fishery impacts on SDPS eulachon.

## The model

With some simple assumptions about eulachon marine distribution, the approximate annual exploitation rate of eulachon in the shrimp trawl fishery can be estimated by the following equation,

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

$u$ = the annual exploitation rate, and,

$A_{swept}$ = the spatial area 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, and,

$p_{excluded}$ = the proportion of eulachon that are excluded by modern rigid-grate BRDs and survive.

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

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

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

**Model assumptions**

This model assumes that SDPS eulachon are evenly distributed across their typical spatial range in both depth and latitude, and, that outside of this depth and latitude range, there are no SDPS eulachon. This assumption is certainly not correct, however, as more information on the marine distribution of SDPS eulachon and their preferred habitat becomes available, it can be incorporated into a more complex version of this model that is spatially stratified. Such a model could also incorporate data on the spatial distribution of shrimp fishing effort, data that is presently available for Oregon vessels and that could become available in the future for the other shrimp fisheries in California, Washington and British Columbia (DFO 2011).

This model also assumes that shrimp trawl nets have roughly constant catchability for eulachon across a season and across a wide range of total effort levels, (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 is a conservative assumption because interaction of individual units of fishing effort would act to reduce, rather than increase, the catchability coefficient for eulachon, making our estimate of the exploitation rate an overestimate.

Use of this model also assumes that the high-efficiency BRDs required in Oregon and Washington are used in all segments of the fishery, although this is not the case. California has less restrictive BRD requirements, however, most California shrimpers are believed to use BRDs that are also legal in Oregon (Frimodig et al. 2009). In British Columbia (west coast of Vancouver Island), rigid-grate BRDs are mandated, but larger bar spacing, up to 44.5 mm, is allowed to prevent the loss of other larger, more valuable pandalid shrimp species like spot prawn (*Pandalus platyceros*, DFO 2011).

**Estimates of model parameters**

Due to large uncertainty in the model parameters, I utilized a range of parameter estimates and examined the resulting F values. The range of parameters chosen correspond roughly to a "base model" and "worst case" scenario in terms of $A_{eulachon}$, $p_{elemental}$ and $p_{excluded}$. $A_{swept}$ was considered to be better estimated because it is based on the expansion of fishery logbook data (Hannah 1995).

*Area swept by the shrimp trawl fishery ($A_{swept}$)*

Fishery logbook data from Oregon, along with catch data from Washington, California and British Columbia was used to generate a crude estimate of the total shrimp trawl grounds swept in a single season. Shrimp trawl fishing effort in Oregon is estimated annually from logbook data and then standardized to single-rig equivalent hours (sreh, Table 1). One sreh has been calculated to sweep 5.93 ha of the grounds (Hannah 1995). This suggests, for example, that 30,000 sreh by Oregon shrimp trawlers corresponds to a swept area on the grounds of 177,900 ha. Based on the assumption that fishing in Washington, California and the offshore areas of British Columbia has approximately equivalent catch-per-unit-effort for shrimp as fishing by Oregon vessels, this estimate of the area swept by Oregon boats was expanded based on shrimp landings data by state or Province, to yield a coastwide estimate of the area swept by the regional fishery (Table 1).

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

A geographic information system was used to make a preliminary estimate of the spatial area representing eulachon marine habitat. The depth distribution of eulachon from 1989-2001 NMFS triennial trawl survey data suggest that eulachon are typically found between 73 and 183 m depth (40-100 fathoms), somewhat shallower than the typical depth distribution of shrimp trawling (Figure 1). I simply used the spatial area between 91 and 183 m (50 and 100 fathoms) as a proxy for the spatial area of SDPS eulachon habitat. Data from the National Marine Fisheries Service triennial trawl surveys from 1989-2001 shows that this area agrees fairly well with the survey haul locations that captured eulachon (Figure 2), however it is notable that there are some large areas shoreward of the 91 m contour that yielded catches of eulachon. Also, the NMFS triennial survey probably does not fully sample the shoreward extent of eulachon. Data from Toole et al. (2011) record eulachon catches 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 1,535,234 ha (Figure 2). For waters off of British Columbia, (from border to border, which approximates the area up to the northern boundary for SDPS, the Nass River, BC), this totaled 2,521,434 ha (Figure 3) bringing the combined estimate for $A_{eulachon}$ up to 4,056,668 ha. This was considered the "base model" scenario. Since it's possible that portions of this area are never occupied by eulachon, or that eulachon could be concentrated specifically in areas that are also trawled for shrimp, I also modeled a "worst case" scenario, with $A_{eulachon}$ reduced by 20% to 3,245,334 ha.

*BRD exclusion rate ($p_{excluded}$)*

Estimates of the exclusion efficiency of rigid-grate BRDs for eulachon were calculated from 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 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). Based on 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. It should be noted that these estimates could be improved with some additional field work directly estimating exclusion rates in nets with and without a 19.1 mm BRD.

An additional important unanswered question regarding estimates of $p_{excluded}$ is the survival rate of eulachon that escape from shrimp trawls via BRDs. The data from Hannah and Jones (2012) showed that large eulachon were typically in very good condition as they escaped from a shrimp trawl, with most fish retaining an ability to avoid contact with the grate and maintain an upright and forward-oriented swimming posture. The data from that study are consistent with the concept that for fish like eulachon, which are excluded efficiently by BRDs even though they are small enough to pass aft through the deflecting grid, the BRD acts as a behavioral sorting device. Fish that are exhausted and in poor condition pass back into the codend, while those in the best condition exit the trawl net with minimal physical contact with the trawl components (Hannah and Jones 2012). The single other study of the post-exclusion survival of other small fishes is consistent with high post-exclusion survival rates. In that study, age 1 northern cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*) and whiting (*Merlangius merlangus*) had 100% post-exclusion survival (Soldal and Engås 1997). Soldal and Engås (1997) noted much higher mortality rates for some other species such as herring (*Clupea harengus*) and capelin (*Mallotus villosus*). However, the authors caution that the study was not designed for those species and the "results should therefore not be relied upon" (Soldal and Engås 1997). The authors do not provide a reason for this assertion, however, some primary concerns for these type of cage-survival studies would include an inadequate control for the effects of caging, or the lack of feeding during confinement, on specific species (Hannah et al. 2012). Supporting this contention is the fact that Soldal and Engås (1997) provide "control" survival data for cod, haddock and whiting, but none for herring or capelin (Appendix table 1A, Soldal and Engås 1997). Based on this review of available information, I assumed that all excluded eulachon survive and all captured and discarded eulachon do not, for the "base model" scenario. To incorporate a more pessimistic view of post-exclusion survival, I also modeled a post-exclusion mortality rate of 50%.

*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 very 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 trawl escapement of shrimp both under the footrope 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 shrimp 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 (Hannah et al. 2011, Hannah and Jones 2013), suggesting substantial 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). Changes in shrimp trawl footropes over the past 2 decades have also reduced the bycatch of small demersal fishes, consistent with reduced elemental efficiency for eulachon (Hannah and Jones 2000). 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 0.75 for the less optimistic view.

*Evaluation of model results*

The estimates of F generated here can be compared with exploitation or fishing rates that are considered acceptable for other fish stocks or other components of SDPS eulachon. A Bayesian population model constructed for the Fraser river eulachon (Schweigert et al. 2012) suggested low stock productivity and a sustainable harvest rate of just F= 0.10, which I compare with my model estimates. 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. Finally, the Oregon Coastal Natural (OCN) Evolutionarily Significant Unit (ESU) of coho salmon (*Oncorhyncus kisutch*) have been listed as "threatened" under the ESA, have a roughly similar life span to eulachon, but have lower fecundity, a much larger adult body size and probably a greater dependence on freshwater habitat quality (Nickelson and Lawson 1998). Unlike eulachon though, a vast amount of population data exist for OCN coho salmon, and they have been subjected to a thorough analysis of population viability (Nickelson and Lawson 1998). Although OCN coho salmon are still harvested in a variety of fisheries, current exploitation rates are not considered to be an ongoing threat to the recovery of the ESU (National Marine Fisheries Service 2011). OCN coho salmon also suffer from some of the same threats facing eulachon, including climate change, changes in predator populations and changes in freshwater flows from dams and water diversions (Stout et al. 2011). To try and determine if the fishing rates for eulachon in the regional shrimp fishery estimated here suggest a low or high level of concern for recovery of eulachon, I compared my model estimates of exploitation rate (*u*) with annual exploitation rates that are currently considered acceptable for OCN coho salmon, as specified in the Pacific Fishery Management Council's (PFMC) Preseason Report 1 for 2012 (PFMC 2012).

## Results

Model estimates of exploitation rate for eulachon impacted by the 2007-2011 shrimp fisheries ranged from 0.0085-0.017 for the base model and 0.0240-0.0479 for the "worst case" parameterization. The associated annual rates of fishing F ranged from 0.0109-0.0219 for the base model parameter choices and from 0.0311-0.0541 for the "worst case" parameter choices (Table 1). This range of F values was generated by total regional ocean shrimp trawl fishing effort estimates ranging from just under 26,000 sreh in 2009 to over 44,600 sreh in 2011 (Table 1). The average estimate of fishing rate for these years, corresponding to an average effort level of 38,555 sreh, was 0.0163 and 0.0466 for the base model and "worst case" parameter choices, respectively (Table 1).

These estimates are well below the F = 0.1 rate recommended as sustainable by Schweigert et al. (2012) and far below the values of F = 0.51 (F = M) or F = 0.408 (F = 0.8 x M) based on life history data. The annual exploitation rates that are considered to be acceptable for OCN coho of 0.08, under conditions of low parent brood escapement and a very low index of marine survival

(Table 2) are also considerably higher than even the “worst case” scenario estimates of *u* for eulachon in the shrimp fishery (0.0240-0.0479). Under better conditions of marine survival and parent brood strength, allowable exploitation rates for OCN coho range from 0.15-0.45, many times higher than the model estimates of exploitation rate generated here for eulachon.

**Discussion**

In interpreting the results from this brief modeling exercise, it’s important to consider a variety of factors that contributed to these low estimates of exploitation rate for eulachon, as well as factors that could increase fishery impacts on eulachon in the future. The primary factor to consider is that the low estimates of exploitation rate and annual rate of fishing on eulachon reflect the much smaller spatial scale of the shrimp fishery in relation to the marine habitat occupied by eulachon. Put simply, the shrimp trawl fishery does not operate on a spatial scale that is large enough to exert a top-down controlling effect on eulachon populations. Factors that do operate on a much larger spatial scale, such as variation in the ocean environment, or the abundance and distribution of major predator populations like Pacific hake, are more likely to be a strong influence.

Another important factor to consider is the history of ocean shrimp trawl fishing effort and its dominant role in driving eulachon exploitation rate estimates within this model. The ocean shrimp fishery developed in the 1950’s and 1960’s, but only reached modern levels of fishing effort in the late 1970’s, following the introduction of both double-rigged vessels and shrimp peeling machines (Zirges and Robinson 1980, Hannah and Jones 1991, Hannah 1993). Due to curtailment of some state logbook programs in 1992, a complete accounting of recent fishing effort for the regional fishery is not available (Hannah 1999). Examination of Oregon effort data, as a proxy for the regional fishery, shows that recent levels of fishing effort are well below half of the high levels seen in the early and late 1980’s and early 1990’s (Figure 4). Since the peak in 1980, the number of vessels participating in the fishery in U.S. waters has been reduced by a variety of state-run limited entry programs, as well as by a large federal groundfish vessel buyback program in 2003 (Jones and Hannah 1992, Frimodig et al. 2009). Trawling for ocean shrimp in British Columbia waters has also been reduced, by a combination of rules designed to constrain exploitation rates on both ocean shrimp and eulachon (DFO 2011). This large reduction in fishing effort has contributed to the low exploitation rates calculated here, indicating that preventing extreme growth in trawl fishing effort for shrimp is probably the surest means to maintain low fishery impact rates on SDPS eulachon (Figure 5). Using base model projections, regional shrimp trawl effort would need to increase by a factor of about 5 from current levels to reach the very conservative sustainable fishing rate of F = 0.1 (Figure 5). Even using the “worst case” model paramaterization, regional shrimp trawl fishing effort would need to more than double from present levels before this rate is approached. To realize a rate of fishing equivalent to F = 0.8 x M, shrimp trawl fishing effort would have to reach unprecedented levels (Figure 5).

The use of modern, high-efficiency BRDs by most trawl vessels in the regional fishery also contributes to the low exploitation rates estimated here. Because these devices are already so efficient and are fairly widespread, additional reduction in eulachon bycatch from improving codend BRDs, or making them mandatory in areas where they are not currently mandated, is likely to be modest.  Note however that the model developed here assumes that all shrimp trawling is conducted with high-efficiency BRDs.

A variety of field studies could be conducted to improve the accuracy of the parameters used as input for this GIS- and gear-based exploitation rate model for eulachon, or at least to increase or decrease confidence in the parameters and assumptions used.  The assumption that eulachon are evenly distributed across the seafloor area enclosed by the 91 and 183 m contours is certainly the weakest assumption of the model, but also one that may be very difficult or expensive to improve upon.  Studies could be conducted to identify species-habitat associations of eulachon that could be used to better identify the appropriate marine spatial area to use within this model. However, large variation in river runs of SDPS eulachon (Gustafson et al. 2012) shows that their population size varies widely between years. So, it's likely that the area of marine habitat they occupy expands and contracts greatly with increasing or decreasing population size (MacCall 1990).  The annual match or mismatch between the varying spatial distribution of eulachon and the quantity and spatial distribution of shrimp trawl effort, which is also highly variable (Hannah 1995, Hannah 2011), is what will drive actual exploitation rates for eulachon.  Only an annual survey, employing a small mesh trawl across the spatial area where eulachon are found, like the one conducted annually in a portion of British Columbia waters, could provide approximate estimates of SDPS eulachon marine population size.  These data, along with the observer data that is presently being collected to estimate shrimp fishery bycatch of eulachon (NWFSC 2009), could allow for a more accurate picture of fishery impacts on SDPS eulachon.

It also may be possible to conduct field studies to evaluate the model assumption of 50% elemental trawl efficiency for eulachon. Capture bags placed between the fishing line and groundline of a shrimp trawl could allow a comparison of the relative magnitude of eulachon escapement under the fishing line and the observed codend catch.  Similarly, it may be possible to evaluate mesh pass-through of eulachon in various portions of a shrimp trawl.  Although this approach would not measure the reduction in elemental efficiency from off-bottom movement of eulachon, it may indicate whether or not the assumption of 50% efficiency is grossly inaccurate.

The model presented here is extremely simple and admittedly very difficult to evaluate.  This is due to the paucity of data on eulachon marine population size and distribution.  Still, I believe it serves a useful purpose by delineating the spatial and gear-related processes that result in eulachon impacts in the shrimp fishery.  Without direct information on the marine population size of this highly variable forage fish, the annual estimates of eulachon bycatch in the shrimp fishery observer program (NWFSC 2009) are very difficult to interpret and could raise concerns about fishery impacts hampering stock recovery.  Do increasing bycatches suggest higher fishery exploitation rates or simply the recovery of SDPS eulachon?  In the absence of large increases in shrimp trawl effort, they probably indicate the latter.

## Conclusions

Modelling of the spatial extent of shrimp trawl fishing effort and eulachon marine habitat in combination with known and assumed aspects of shrimp trawl gear efficiency suggests that, at current effort levels, exploitation and fishing rates of eulachon in the shrimp trawl fishery are very low in relation to likely sustainable rates of impact.  Moreover, the much smaller spatial scale of the shrimp trawl fishery makes it unlikely that incidental fishery take could exert a top-down controlling influence on SDPS eulachon inriver run sizes. Regional shrimp trawling effort would need to increase many times over before bycatch of eulachon would be likely to impede the rebuilding of the SDPS eulachon population.

**References**

Chavez, F.P., J. Ryan, S.E. Lluch-Cota and M. Ñiquen C. 2003. From anchovies to sardines and back: multidecadal changes in the Pacific ocean. Science 299:217-221.

DFO (Department of Fisheries and Oceans). 2011. Pacific region integrated fisheries management plan, shrimp trawl, April 1, 2011 to March 31, 2012. Department of Fisheries and Oceans, British Columbia, Canada.

Emmett, R.L., R.D. Brodeur and P.M. Orton. 2004. The vertical distribution of juvenile salmon (*Oncorhynchus* spp.) and associated fishes in the Columbia River plume. Fisheries Oceanography 13(6):392-402.

Frimodig, A.J., M.C. Horeczko, M.W. Prall, T.J. Mason, B.C. Owens and S.P. Wertz. 2009. Review of the California trawl fishery for Pacific ocean shrimp *Pandalus jordani*, from 1992 to 2007. Marine Fisheries Review 71(2):1-14.

Gustafson, R.G., M.J. Ford, P.B. Adams, J.S. Drake, R.L. Emmett, K.L. Fresh, M. Rowse, E.A.K. Spangler, R.E. Spangler, D. J. Teel and M.T. Wilson. 2012. Conservation status of eulachon in the California Current. Fish and Fisheries 13:121-138.

Hannah, R.W. 1993. The influence of environmental variation and spawning stock levels on recruitment of ocean shrimp (*Pandalus jordani*). Canadian Journal of Fisheries and Aquatic Sciences 50(3):612-622.

Hannah, R.W. 1995. Variation in geographic stock area, catchability and natural mortality of ocean shrimp (*Pandalus jordani*): some new evidence for a trophic interaction with Pacific hake (*Merluccius productus*). Canadian Journal of Fisheries and Aquatic Sciences 52:1018-1029.

Hannah, R.W. 1999. A new method for indexing spawning stock and recruitment in ocean shrimp, *Pandalus jordani*, and preliminary evidence for a stock-recruitment relationship. Fishery Bulletin 97:482-494.

Hannah, R.W. 2011 Variation in the distribution of ocean shrimp (*Pandalus jordani*) recruits: links with coastal upwelling and climate change. Fisheries Oceanography 20(4):305-313.

Hannah, R.W. and S.A. Jones. 1991. Fishery induced changes in the population structure of pink shrimp (*Pandalus jordani*). Fishery Bulletin. U.S. 89:41-51.

Hannah, R.W. and S.A. Jones. 2000. Bycatch reduction in an ocean shrimp (*Pandalus jordani*) trawl from a simple modification to the trawl footrope. Journal of Northwest Atlantic Fisheries Science 27:227-234.

Hannah, R.W. and S.A. Jones. 2003. Measuring the height of the fishing line and its effect on shrimp catch and bycatch in an ocean shrimp *(Pandalus jordani*) trawl. Fisheries Research 60:427-438.

Hannah, R.W. and S. A. Jones. 2007. Effectiveness of bycatch reduction devices (BRDs) in the ocean shrimp (*Pandalus jordani*) trawl fishery. Fish. Res. 85:217-225.

Hannah, R.W. and S.A. Jones. 2012. Evaluating the behavioral impairment of escaping fish can help measure the effectiveness of bycatch reduction devices. Fisheries Research 131-133:39-44.

Hannah, R.W. and S.A. Jones. 2013. Tests of trawl footrope modifications to reduce the bycatch of eulachon (*Thaleichthys pacificus*) and other small demersal fishes in the ocean shrimp (*Pandalus jordani*) trawl fishery. Oregon Department of Fish and Wildlife, Information Rept. Ser., Fish. No. 2013-02. 17 p.

Hannah, R.W., S.A. Jones and V.J. Hoover. 1996. Evaluation of fish excluder technology to reduce finfish bycatch in the pink shrimp trawl fishery. Oregon Department of Fish and Wildlife, Information Rept. Ser., Fish. No. 96-4. 46 p.

Hannah, R.W., S.A. Jones and K.M. Matteson. 2003. Observations of fish and shrimp behavior in ocean shrimp (*Pandalus jordani*) trawls. Oregon Department of Fish and Wildlife, Information Rept. Ser., Fish. No. 2003-03. 28p.

Hannah, R.W., S.A. Jones, M.J.M. Lomelli and W.W. Wakefield. 2011. Trawl net modifications to reduce the bycatch of eulachon (*Thaleichthys pacificus*) in the ocean shrimp (*Pandalus jordani*) fishery. Fisheries Research 110:277-282.

Hannah, R. W., P. S. Rankin and M. T. O. Blume. 2012. Use of a novel cage system to measure postrecompression survival of Northeast Pacific rockfish. Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science 4:46-56.

Hay, D.E. and P.B. McCarter. 2000. Status of the eulachon (*Thaleichthys pacificus* in Canada. DFO Canadian Stock assessment Secretariat Research Document 2000-145.

Jensen, A.L. 1996. Beverton and Holt life history invariants result from optimal trade-off of reproduction and survival. Can. J. Fish. Aquat. Sci. 53:820-822.

Jones, S.A. and R.W. Hannah. 1992. The Oregon pink shrimp fishery:1985-1989. Oregon Dept. of Fish and Wildlife. Inf. Rept. #92-3. 17 p.

Jones, S.A., R.W. Hannah and J.T. Golden. 1996. A survey of trawl gear employed in the fishery for ocean shrimp *Pandalus jordani*. Oregon Department of Fish and Wildlife, Information Rept. Ser., Fish. No. 96-6. 23 p.

MacCall, A.D. 1990. Dynamic geography of marine fish populations. Washington Sea Grant Program. University of Washington Press, Seattle, WA.

NMFS (National Marine Fisheries Service). 2010. Endangered and Threatened Wildlife and Plants: Threatened Status for Southern Distinct Population Segment of Eulachon.

Federal Register (Docket No. 080229343–0039–03; March 18, 2010) 75(52), 13012-13024.

NMFS (National Marine Fisheries Service). 2011. Endangered and Threatened Species: Threatened Status for the Oregon Coast Coho Salmon Evolutionarily Significant Unit. Federal Register (Docket No. 110531311-1310-02) 76(118), 35755-35771.

Nickelson, T.E. and P. W. Lawson. 1998. Population viability of coho salmon, *Oncorhyncus kisutch*, in oregon coastal basins: application of a habitat-based life cycle model. Canadian Journal of Fisheries and Aquatic Sciences 55:2383-2392.

NWFSC (Northwest Fisheries Science Center). 2009. Data Report and Summary Analyses of the California and Oregon Pink Shrimp Trawl Fisheries. West Coast Groundfish Observer Program. NWFSC, 2725 Montlake Blvd E., Seattle, WA 98112.

PFMC (Pacific Fishery Management Council). 2012. Preseason Report 1, Stock Abundance Analysis and Environmental Assessment Part 1 for 2012 Ocean Salmon Fishery Regulations. PFMC, Portland, Oregon. 127 p.

Pearcy, W. G. 1970. Vertical migration of the ocean shrimp *Pandalus jordani*: a feeding and dispersal mechanism. California Fish and Game 56(2):125-129.

Quinn, T.J., and R.B Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.

Schweigert, J., Wood, C., Hay, D., M. McAllister, Boldt, J., McCarter,B., Therriault, T.W., and H. Brekke. 2012. Recovery Potential Assessment of Eulachon (*Thaleichthys pacificus*) in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/098. vii + 121 p.

Soldal, A. V. and A. Engås. 1997. Survival of young gadoids excluded from a shrimp trawl by a rigid deflecting grid. ICES Journal of Marine Science 54:117-124.

Stout, H.A., P.W. Lawson, D.L. Bottom, T.D. Cooney, M.J. Ford, C.E. Jordan, R.G. Kope, L.M. Kruzic, G.R. Pess, G.H. Reeves, M.D. Scheuerell, T.C. Wainwright, R.S. Waples, E. Ward, L.A. Weitkamp, J.G. Williams, and T.H. Williams. 2012. Scientific conclusions of the status review for Oregon coast coho salmon (*Oncorhynchus kisutch*). U.S. Department of Commerce, NOAA Tech. Memo. NMFS-NWFSC-118, 242 p.

Thompson, G.G. 1993. A proposal for a threshold stock size and maximum fishing mortality rate. Canadian Journal of Fisheries and Aquatic Sciences 120:303–320.

Toole, C.L., R.D. Brodeur, C. J. Donohoe and D.F, Markle. 2011. Seasonal and interannual variability in the community strudture of small demersal fishes off the central oregon coast. Marine Ecology Progress Series 428:201-217.

Winters, G.H. and J.P. Wheeler. 1985. Interaction between stock area, stock abundance and catchability coefficient. Canadian Journal of Fisheries and Aquatic Sciences 42:989-998.

Yasuda, I., H. Sugisaki, Y. Watanabe, S. Minobe and Y. Oozeki. 1999. Interdecadal variations in Japanese sardine and ocean/climate. Fisheries Oceanography 8(1):18-24.

Zhou, S. and S.P. Griffiths. 2008. Sustainability Assessment for Fishing Effects (SAFE): a new quantitative ecological risk assessment method and its application to elasmobranch bycatch in an Australian trawl fishery. Fisheries Research 91:56-68.

Zirges, M. H. and J. G. Robinson. 1980. The Oregon pink shrimp fishery, management history and research activities. Oregon Department of Fish and Wildlife, Information Report Series, Fish No. 80-1.

Table 1. Regional catch of ocean shrimp (t), by U.S. state or Canadian province, fishing effort (single-rig equivalent hours, sreh) for the Oregon shrimp fishery, and estimates of total regional effort (sreh), trawl area swept ($A_{swept}$, ha) and rate of fishing (F) for the regional fishery under "best case" and "worst case" parameter assumptions (see text), 2007-2011. British Columbia data is for offshore areas on the west coast of Vancouver Island and Queen Charlotte Sound (excludes inside fishery areas) and includes some catch of other shrimp species. 2007-2011 average for catch, percent of total catch, effort, area swept and exploitation rate are also shown.

| Year | Catch (t) | | | | Effort (sreh) Oregon | Total estimated regional effort (sreh) | Estimate of $A_{swept}$ (ha) | Annual rate of fishing | |
|---|---|---|---|---|---|---|---|---|---|
| | California | Oregon | Washington | British Columbia | | | | Best case | Worst case |
| 2007 | 288.9 | 9,108.4 | 1,517.4 | 111.3 | 33,883.8 | 41,017.4 | 243,233 | 0.0174 | 0.0495 |
| 2008 | 945.5 | 11,575.7 | 2,843.1 | 56.5 | 38,849.1 | 51,753.6 | 306,899 | 0.0219 | 0.0629 |
| 2009 | 1,183.5 | 10,042.5 | 3,179.9 | 57.8 | 18,011.0 | 25,940.3 | 153,826 | 0.0109 | 0.0311 |
| 2010 | 1,770.8 | 14,271.3 | 4,295.6 | 11.8 | 20,615.0 | 29,395.0 | 174,312 | 0.0124 | 0.0353 |
| 2011 | 3,345.3 | 21,915.3 | 4,088.2 | 69.0 | 33,276.1 | 44,667.9 | 264,881 | 0.0189 | 0.0541 |
| Mean | 1,506.8 | 13,382.6 | 3,184.8 | 61.3 | 28,927.0 | 38,554.8 | 228,630 | 0.0163 | 0.0466 |
| Percent | 8.3% | 73.8% | 17.6% | 0.3% | | | | | |

Table 2. Maximum allowable exploitation rates for Oregon Coastal Natural coho salmon under a variety of marine survival conditions and parent brood sizes. Data are from Table A-3 in the Pacific Fishery Management Council Preseason Report 1 (PFMC 2012)

| Parent brood status | Marine survival index | | | |
|---|---|---|---|---|
| | Very low | Low | Medium | High |
| High | 0.08 | 0.15 | 0.30 | 0.45 |
| Medium | 0.08 | 0.15 | 0.20 | 0.38 |
| Low | 0.08 | 0.15 | 0.15 | 0.25 |
| Very low | 0.08 | 0.11 | 0.11 | 0.11 |
| Critical | 0.0-0.08 | 0.0-0.08 | 0.0-0.08 | 0.0-0.08 |

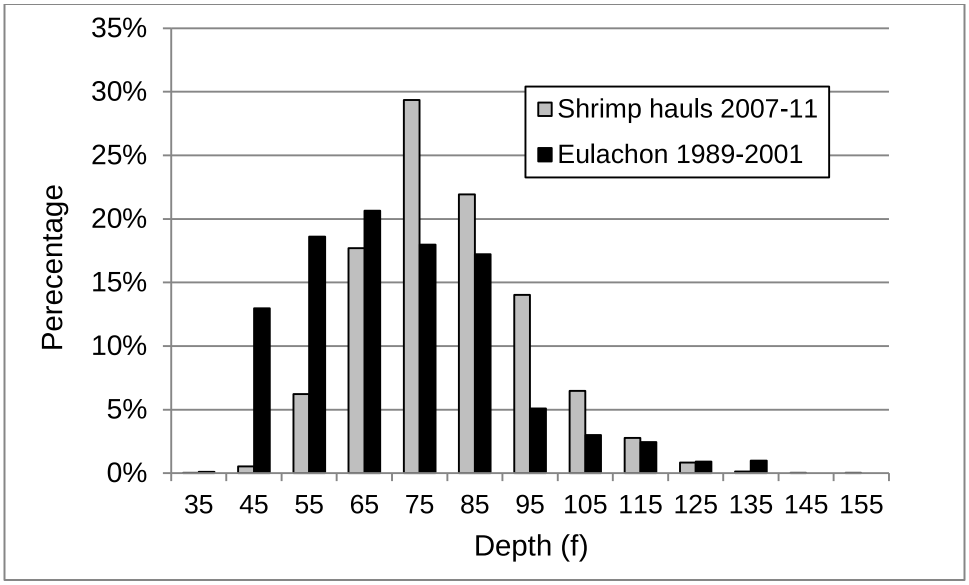



Figure 1. Average depth distribution of Oregon shrimp trawl effort (2007-2011 average) in comparison with the average depth distribution of eulachon catches in the National Marine Fisheries Service triennial trawl surveys from 1989-2001.

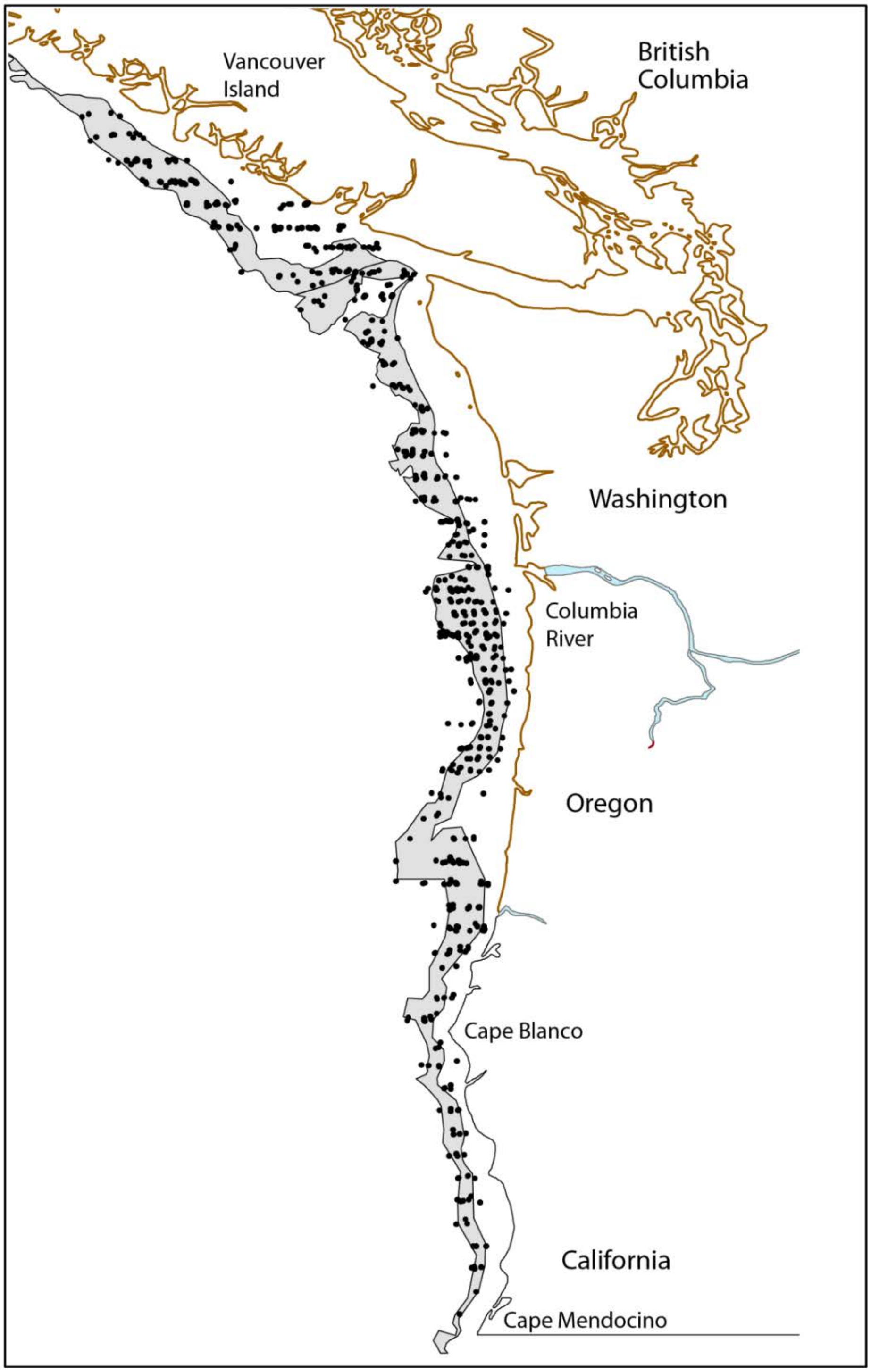



Figure 2. Comparison of the spatial area between the 91 and 183 m depth contours (50 and 100 fathoms) and the location of the 1989-2001 triennial trawl survey hauls that captured eulachon.


Figure 3.  Map showing the spatial area between the 91 and 183 m depth contours (50 and 100 fathoms) from Cape Mendocino, California up to the Nass River, British Columbia.

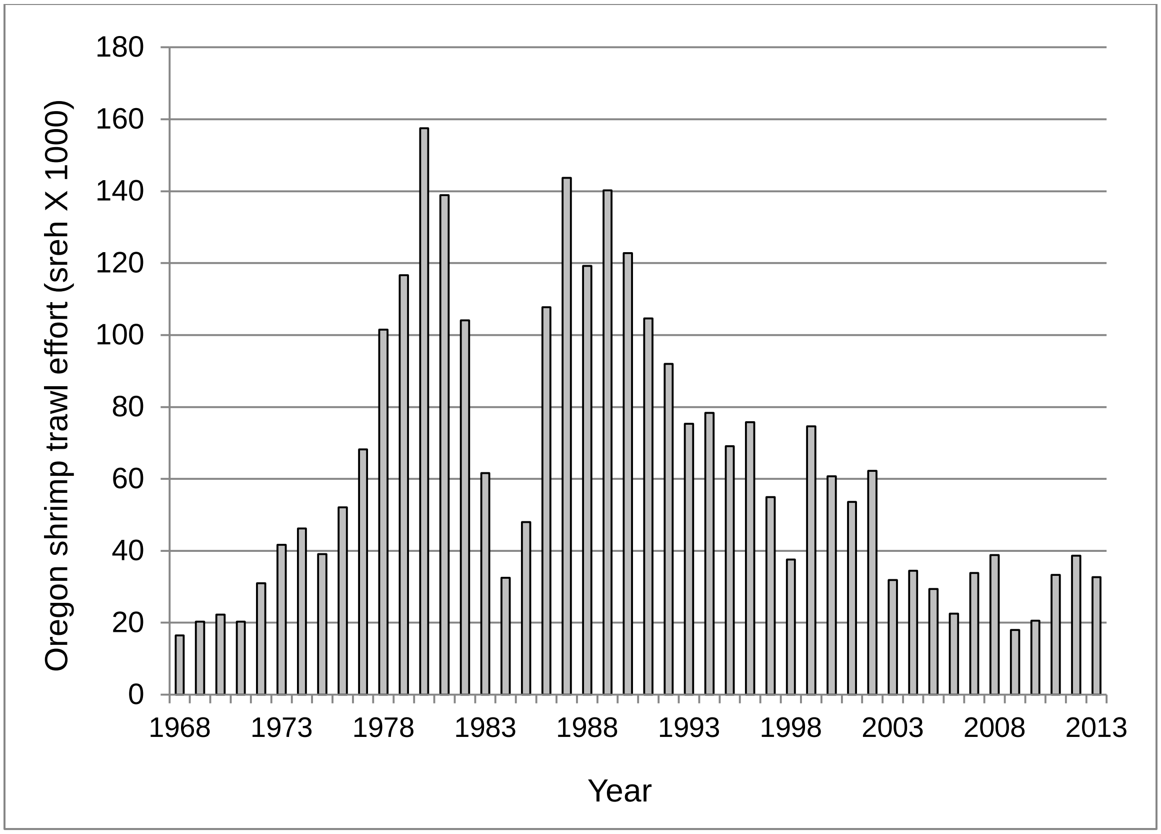



Figure 4. Oregon trawl fishing effort for ocean shrimp in thousands of single-rig-equivalent hours (sreh), 1968-2013.

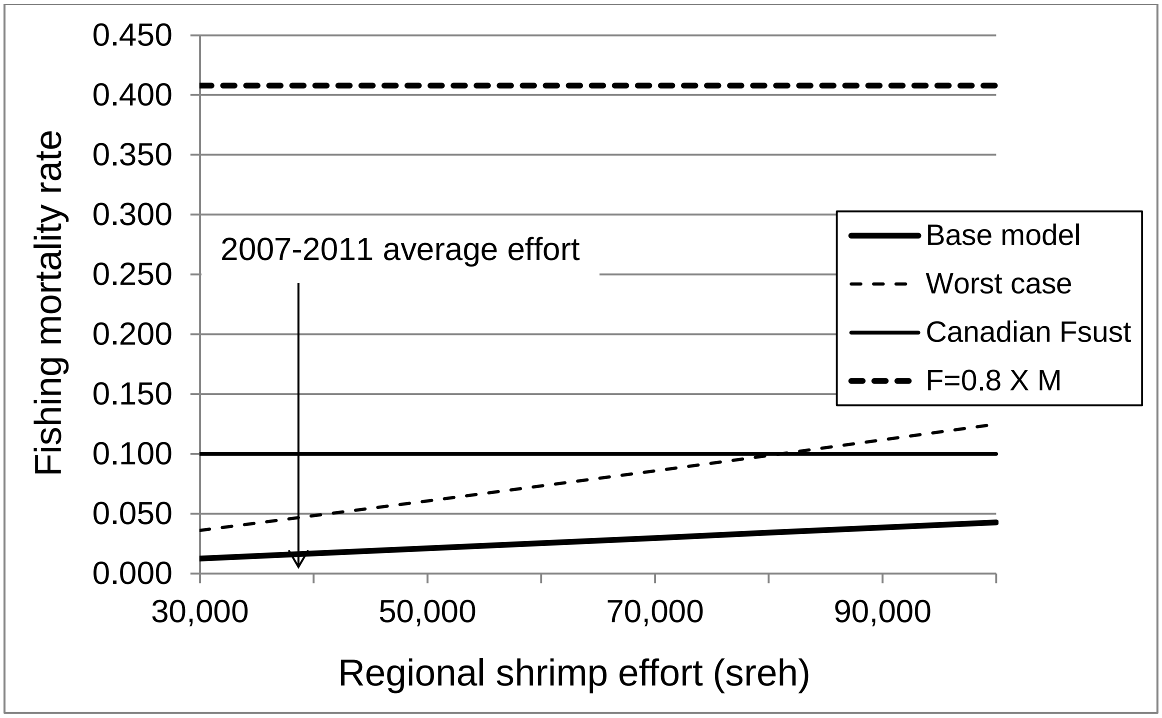



Figure 5. Graph of model estimates of F, annual fishing mortality rate of eulachon as a function of regional total shrimp trawl fishing effort (sreh), under "base model" and "worst case" assumptions regarding model parameters (see text), in comparison with a level of fishing mortality, F = 0.10, which has been suggested as sustainable for Fraser River eulachon (Schweigert et al. 2012) and an estimate of sustainable F based on life history information (F = 0.8 X M, Thompson 1993).

OREGON
Fish & Wildlife

**4034 Fairview Industrial Drive SE**

**Salem, Oregon 97302**