Modeling nearshore fish habitats using Alaska as a regional case study

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ABSTRACT

Nearshore areas represent important habitats for many species, at least for part of their life cycle. Therefore, modeling and mapping nearshore habitats is essential for natural resource management and conservation, such as determining potential impacts to marine populations and their habitats from human activities and identifying conservation measures. Although fish survey and habitat data are uncommon for nearshore areas, two regional databases, the Nearshore Fish Atlas of Alaska (NFA) and *ShoreZone*, provide a rare opportunity to evaluate nearshore habitats for Alaska's shallow, nearshore fish assemblages. In the present study, we used the NFA and *ShoreZone* databases in a practical approach to model and map Alaska nearshore fish habitats. Specifically, we fitted generalized additive models (GAMs) to NFA and *ShoreZone* data to map the spatial patterns of probability of encounter and density of Pacific cod (*Gadus macrocephalus*) early juveniles in the northern southeastern Alaska (NSEA) area and walleye pollock (*Gadus chalcogrammus*) early juveniles in Prince William Sound (PWS). The density of Pacific cod early juveniles was found to be high in all of the western part of the NSEA area, particularly around Port Alexander. The density hotspots of walleye pollock early juveniles were found to be located in the northern and southernmost parts of PWS. Data inventories and modeling and mapping Alaska nearshore fish habitats provide valuable information to manage marine resources and human activities (e.g., to identify the main nursery areas of commercially important species along the Alaska coastline), and allow for other important ecological and ecosystem issues to be addressed (e.g., producing marine protected area planning scenarios to protect forage fishes used by large marine predators). The NFA and *ShoreZone* are valuable resources, and our efforts to leverage them to model and map nearshore fish habitats establishes a reference for similar efforts throughout Alaska's regions and beyond.

1. Introduction

The nearshore marine environment, including coastal and inshore areas of the continental shelf, provides important habitat for many marine species during at least part of their life history. Therefore, understanding the spatial extent and ecological importance of nearshore habitats for marine species allows natural resource managers to protect and restore habitats to ensure the sustainable use of natural resources. In the United States (U.S.), the Magnuson-Stevens Fishery Conservation and Management Act (MSA) requires that the National Marine Fisheries Service (NMFS) and regional fishery management councils describe and map essential fish habitat (EFH) – habitats that are necessary to fish and shellfish species throughout their life history – and recommend actions to conserve these areas from adverse human impacts[1]. NMFS may provide conservation recommendations such as gear modifications or restrictions and time and area closures in the case of fishing activities and alternative site selection and timing of work in the case of non-fishing activities (Limpinsel et al., 2017). EFH regulations provide an approach to organize the information necessary to describe and identify EFH, where designations rely at a minimum on distribution data (i.e., EFH Level 1 information). Whenever possible, designations are based on more detailed population-level information, including habitat-related densities or abundance (Level 2), survival, growth and reproduction within habitats (Level 3), and production rates by habitat (Level 4). EFH designations are periodically reviewed and updated by the regional fishery management councils to ensure that the best available scientific information is used to describe and identify EFH (NMFS National Standard 2 Scientific Information[2]).

Alaska is the largest U.S. state, with an intricate coastline composed of many bays, fjords and islands, extending a distance greater than the coastlines of all the other U.S. states combined (Shalowitz, 1964). Alaska spans five large marine ecosystems, including the Gulf

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[2] 50 CFR 600.315

of Alaska (GOA), Aleutian Islands, Bering Sea, and Chukchi and Beaufort seas of the U.S. Arctic region (Fig. 1a). Coastal areas of Alaska host a diverse array of shallow, nearshore habitats including eelgrass (*Zostera marina*) and kelp beds, sand beaches, and exposed or sheltered rocky shores (Dean et al., 2000; Johnson et al., 2012; Pirtle et al., 2012), which are affected by human activities that take place nearshore or in upland terrestrial locations. Human activities that affect Alaska nearshore habitats include, among others, urban development, oil and gas exploration and extraction, mining, timber harvest, municipal and industrial waste, and vessel traffic from a variety of industries (Harris et al., 2008; Johnson et al., 2012; Limpinsel et al., 2017).

Alaska nearshore areas provide habitat for numerous fish species. In Alaska, like in other marine regions, many fish and shellfish species undertake ontogenetic habitat shifts, whereby individuals migrate offshore into deeper waters as they grow, to meet the ecological demands of survival, growth, or reproduction. Thus, Alaska nearshore habitats serve as the nursery areas (i.e., the distribution areas of the early juvenile life stage) for many ecologically and economically important demersal fish and shellfish species with offshore life stages that are targeted by fisheries. These include commercially important gadoids (e.g., Pacific cod *Gadus macrocephalus*; walleye pollock *Gadus chalcogrammus*; Abookire et al., 2001; Laurel et al., 2009), flatfishes (Norcross et al., 1999; Hurst, 2016), sablefish (*Anoplopoma fimbria*; Courtney and Rutecki, 2011), and red king crab (*Paralithodes camtschaticus*; Loher and Armstrong, 2000).

The early juvenile stages of demersal fish populations have long been identified as being vulnerable to human impacts in nearshore areas (Beck et al., 2003; Lellis-Dibble et al., 2008; Johnson et al., 2012). However, species of Pacific salmon, and forage fishes such as Pacific herring (*Clupea pallasii*), Pacific sand lance (*Ammodytes personatus*), capelin (*Mallotus villosus*), and eulachon (*Thaleichthys pacificus*) are at least as vulnerable as the early juvenile stages of demersal fishes to disturbances in nearshore areas, as they use nearshore areas for feeding and shelter as juveniles as well as spawning as adults (Pahlke, 1985; Robards et al., 1999; Cooney, 2007; Harris et al., 2008; Johnson et al., 2008; Miller et al., 2016). The consequences of human impacts on nearshore areas for forage fish are concerning not only for forage fish populations, but also for the many fish, seabird, and marine mammal predator populations that prey upon them (Springer and Speckman, 1997; Mundy and Hollowed, 2005). Thus, there is a critical need to model and map Alaska nearshore areas because of their importance as habitat for numerous marine species of economic and ecological importance.

In the present study, we develop and demonstrate a practical approach to model and map Alaska nearshore fish habitats that rely on binomial and delta-Gamma generalized additive models (GAMs), fish survey data collected by multiple gear types, and very fine-scale habitat information. Our modeling approach leverages the information provided by two large databases for Alaska: a large fish survey database called the "NMFS Nearshore Fish Atlas of Alaska database" (hereafter referred to as the "Nearshore Fish Atlas" or the "NFA"; NMFS, 2020a); and a large habitat database called *ShoreZone* (Cook et al., 2017; NMFS, 2020b). Although our approach was designed for Alaska nearshore areas, it could easily be applied to other marine regions where survey and habitat databases are available. Our modeling approach was ddeveloped specifically to be simple enough to be employed and adapted by fisheries scientists and resource managers for a variety of purposes. There are two key steps to our approach: (1) constructing a strip of coastline consisting of ~10 m coastline segments for the study area to be able to generate predictions from fitted GAMs, which is referred to as a "predictive coastline"; and (2) using the fitted and validated GAMs and the predictive coastline to predict spatial patterns of probability of encounter and density at the very fine spatial scales at which localized ecological processes operate for life stages of demersal fishes in the nearshore areas. In the following, we first provide brief overviews of the study areas, the NFA and *ShoreZone*. We then detail our modeling approach, before demonstrating it for Pacific cod early juveniles of the northern southeastern Alaska (NSEA) area and walleye pollock early juveniles of Prince William Sound (PWS) (Figs. 1b-c). Next, we discuss how the information generated by our approach will support natural resource management in Alaska, and we highlight some avenues for future ecological and modeling research.

2. Material and methods

2.1. Study areas

In the present study, we focus on two nearshore areas of the GOA: the northern southeastern Alaska (NSEA) area in the case of Pacific cod (Fig. 1b) and Prince William Sound (PWS) in the case of walleye pollock (Fig. 1c). The NSEA area covers southeastern Alaska from about 56 to 59 degrees latitude, with the exclusion of inside waters around Juneau and outside waters near Yakutat. We constructed predictive coastlines (strips of coastline consisting of ~10 m coastline segments that are needed to generate predictions from fitted GAMs) for the NSEA area and PWS. The number of ~10 m segments totaled 929,998 in the NSEA area (Fig. 1b) and 573,716 in PWS (Fig. 1c). These predictive coastlines were used to generate very fine-scale maps of probability of encounter and density from GAM predictions (see Subsection 2.4).

2.2. Nearshore Fish Atlas (NFA)

The NFA is a centralized, relational database of nearshore fish surveys curated by NMFS' Auke Bay Laboratories (ABL) in Juneau, Alaska, which stores a relatively unique, large amount of fish survey data for Alaska nearshore areas (NMFS, 2020a). The 2020 version of the NFA employed in the present study includes fish survey data collected using multiple gear types including beach seine, trawl, purse seine, gillnet, jig, fyke net and minnow trap (Appendix A1). In October 2019, the NFA included fish catch data from a total of 1,848 unique stations sampled between 1995 and 2018; beach seine was employed to sample the great majority of these stations (1,220), followed by trawl (304). Beach seine and trawl surveys were carried out in the nearshore areas of all Alaska regions (i.e., the U.S. Arctic, Bering Sea, Aleutian Islands and GOA; Fig. 1a) using a variety of sampling designs. Beach seine surveys were conducted in vegetated (i.e., eelgrass and kelp) and unvegetated (i.e., bedrock and sand) habitats within 20 m of shore and less than 5 m deep, while trawl surveys were carried out further from shore and deeper (e.g., to a depth of 15 m and a distance up to 2.5 km from shore in the U.S. Arctic). Some of the stations sampled by beach seine, trawl and gillnet surveys were visited several times over the period 1995-2018, resulting in an overall total of 5,643 stations-years. In October 2019, the NFA had 109,078 data entries, the great majority of which were within the GOA (85,827). Fish captures are identified to species or genus levels in the NFA, and the length of most of the fish has been recorded to the nearest millimeter. More details about the NFA can be found in Appendix A1.

In the NSEA area, data were collected at a total of 365 unique sampling stations between 1998 and 2013 by surveys that used beach seine, purse seine, trawl or jig (Appendix A1). The majority of these unique stations (225) were sampled by beach seine using random sampling schemes. Some of the stations were visited several times over the period 1998-2013, resulting in an overall total of 391 stations-years in the NSEA area (Appendix A1).

In PWS, data were collected at a total of 177 unique sampling stations between 1999 and 2015 by surveys that employed beach seine, trawl, jig, purse seine, or gillnet (Appendix A1). Some of the stations sampled by beach seine were visited several times over the period 1999-2015, resulting in an overall total of 201 stations-years in PWS. The majority of the stations were sampled by beach seine (99 stations) or trawl (59) using random sampling schemes (Appendix A1).

2.3. ShoreZone

Habitat information developed specifically for coastal areas of Alaska, such as physical wave exposure and coverage of kelps and eelgrass, is available for almost the entire coastline of Alaska from a large database called *ShoreZone* (Cook et al., 2017). *ShoreZone* has a longer history than the NFA, and some of the main reasons for its development in Alaska was to facilitate oil spill response in remote coastal areas, similar to applications in British Columbia, Canada (Renner and Harper, 1993), as well as nearshore habitat modeling, although this latter objective has been largely unfulfilled (Cook et al., 2017). *ShoreZone* is a habitat mapping and classification system, which currently provides detailed biophysical information for small coastline segments (10s to 100s of m long) for almost all of the west and Arctic coasts of North America (Cook et al., 2017). *ShoreZone* data for the nearshore areas of Alaska can be accessed via a user-friendly online query system (NMFS, 2020b). More details about the *ShoreZone* can be found in Appendix A2.

For the present study, we extracted *ShoreZone* information for the NSEA area and PWS, which we associated with the survey data and segments of the predictive coastline for each area (Fig. 2 and Appendices A3 and A4). We needed to redefine the levels of coastal type and physical wave exposure to be able to fit GAMs, because some of the original levels of these two factors that were found in the predictive coastlines for the NSEA area and PWS were not found in the datasets for Pacific cod early juveniles and walleye pollock early juveniles (Appendices A3 and A4).

2.4. Nearshore fish habitat modeling

2.4.1. Modeling approach

To model nearshore fish habitats, we employed an approach relying on binomial and delta-Gamma GAMs (Hastie and Tibshirani, 1990; Wood, 2017). Binomial GAMs were fitted to encounter/non-encounter data from the NFA and habitat information from *ShoreZone* and were used to predict spatial patterns of probability of encounter in the nearshore areas. Delta-Gamma GAMs resulted from the product of logit-linked binomial GAMs and log-linked Gamma GAMs. Gamma GAMs were first fitted to non-zero catches-per-unit-effort (CPUEs; in numbers per m sampled) from the NFA and habitat information from *ShoreZone* in order to predict non-zero fish densities (in numbers per m of coastline). Next, the probabilities of encounter predicted by the binomial GAMs and the non-zero densities predicted by the Gamma GAMs were multiplied together to form the delta-Gamma GAMs used to predict spatial patterns of density in numbers per m of coastline (Lo et al., 1992; Grüss et al., 2014, 2019b). Delta-Gamma GAMs, rather than simple Gamma GAMs, were used to predict spatial density patterns in nearshore areas because the proportion of zero-valued data is high for the great majority of the species and life stages encountered in nearshore areas (Johnson et al., 2012). However, for those species that are encountered in every sampling event (e.g., crescent gunnel in some nearshore areas of Alaska), delta-Gamma GAMs could easily be replaced with simple Gamma GAMs by skipping the development of binomial GAMs. This implicitly assumes that zero-probabilities are constant across space, but is sometimes necessary when there are insufficient data to estimate an alternative model for zero-probabilities. Note that we employ the terms “encounters” and “probability of encounter” rather than the terms “presence” and “probability of presence” in the present study, because fish surveys do not necessarily detect all the fish that are present at a given location (Monk, 2014; Harford et al., 2016).

All binomial and Gamma GAMs initially included a tensor product smooth (Wood et al., 2013) fitted to eastings and northings (i.e., longitude and latitude expressed in UTM coordinates), one or more fixed effect habitat factors (e.g., physical wave exposure and eelgrass) that were chosen based on the literature, and, possibly, the fixed effect of year and the fixed effect of gear. When the GAMs relied on survey data collected with different gears (e.g., beach seine and trawl), it was necessary to include a gear factor in GAMs (as a fixed effect), as different gears can have different impacts on fish catchability (e.g., by covering different depth ranges along the coastline). Gear is then a “nuisance variable”, that is a variable that is not of immediate interest for the analysis but must be accounted for even when it is correlated to some degree with some of the habitat covariates included in the GAMs (Farmer and Karnauskas, 2013; Grüss et al., 2018a, 2018c, 2020; Grüss and Thorson, 2019). This approach implicitly assumes that gears sample the same underlying densities, and are not preferentially deployed in separate habitats. Future research could explore extensions of the models that further partition nearshore habitats, or estimate habitat-specific catchabilities for one or both gears, but we do not explore the topic further here. When some sampling stations were visited several times over the study period or when the GAMs relied on survey data collected with different gears over overlapping years, it was also necessary to include the nuisance effect of year in GAMs (as a fixed effect factor).

The tensor product smooth fitted to eastings and northings, $te(X, Y)$, represents the fixed effect of geographic position as well as unexplained variation in each variable (probability of encounter and non-zero CPUE; Swartzman et al., 1992; Denis et al., 2002; Politou et al., 2008). The estimated value of the tensor product smooth $te(X, Y)$ was used at every sampled location or ~10 m coastline segment, where both were restricted to a one-dimensional strip of nearshore habitat for every island or mainland coastline in all GAMs. The tensor product smooth $te(X, Y)$ was included in GAMs to account for spatial autocorrelation (spatial structure) in model residuals; ignoring spatial autocorrelation will generally result in permissive (biased low) estimates of standard errors for other covariates (Dormann et al., 2007) and less precise estimates of local densities (Brodie et al., 2020). We note the growing literature on developing methods to define autocorrelation along structured habitats such as stream networks (Ver Hoef et al., 2006; Hocking et al., 2018) and estuaries (Bakka et al., 2019), as well as other customized spatial domains (Wood et al., 2008) and forms of non-stationarity (Fuglstad et al., 2015). In the present study, we employed a simple tensor product smooth $te(X, Y)$ defined over a set of one-dimensional coastlines to approximate the net effect of unmeasured intrinsic (e.g., movement) and extrinsic (e.g., nutrient provisioning) processes that will cause densities to be correlated for locations that are nearby in terms of eastings and northings, as well as processes that are correlated based on coastline distances. For example, larval advection will often result in similar supply of pre-settlement juveniles for locations on opposite sides of an estuarine channel, and upwelling processes will similarly result in plankton densities that are correlated as a function of Euclidean (rather than coastline) distance.

Binomial and Gamma GAMs were all developed with R package “mgcv” (Wood, 2017). The initial (full) binomial and Gamma GAMs were of the following form (Wood, 2017):

$$g(\eta) = te(X, Y) + factor(f1) + \cdots + factor(fn) + factor(year) + factor(gear) \quad (1)$$

where η is either the probability of encounter when given binomial response data, or positive density when given non-zero CPUE data; g is the link function between η and each term on the right side of the equation (logit in the case of the binomial GAM, and log in the case of the Gamma GAM); $factor(f1) + \cdots + factor(fn)$ are fixed-effect habitat factors that are relevant for the species/life stage under consideration; and the nuisance effects of gear and/or year were included only if warranted (e.g., when the GAMs relied on survey data collected with different gears over overlapping years). The binomial and Gamma GAMs were re-fitted with only the significant fixed effect habitat factors, until the final binomial and Gamma GAMs included only significant fixed-effect habitat factors (Koubbi et al., 2006; Weber and McClatchie, 2010; Grüss et al., 2018a, 2019a). All the final binomial and Gamma GAMs included the tensor product smooth $te(X, Y)$, as well as the effects of year and/or gear if the inclusion of these nuisance effects was warranted.

The fitted binomial and delta-Gamma GAMs were validated using the method adopted in Grüss et al. (2014), Weijerman et al. (2019), Bolser et al. (2020) and Egerton et al. (2021). This validation method employs the datasets internal to GAM development where observed and predicted values can be compared. From the datasets of observed and predicted values, 1,000 bootstrap datasets were generated by resampling with replacement within the range of observed and predicted values. Then, in the case of binomial GAMs, two criteria were utilized to validate model predictions: (1) the area under the receiver operating curve (AUC), which helps gauge the ability of binomial GAMs to appropriately discriminate between non-encounters and encounters (Hanley and McNeil, 1982); and (2) the adjusted R^2 value, which is a measure of the proportion of the deviance in the data explained by binomial GAMs (Legendre and Legendre, 1998). The AUC and median adjusted R^2 of the binomial GAMs were calculated using the bootstrap datasets, and a given binomial GAM was deemed reasonable if its mean AUC is greater than 0.7 (Hanley and McNeil, 1982; Swets, 1988; Pearce and Ferrier, 2000) and its median adjusted R^2 was greater than 0.1 (Legendre and Legendre, 1998; Grüss et al., 2016; Bolser et al., 2020). In the case of delta-Gamma GAMs, the bootstrap datasets were used to assess whether Spearman's correlation coefficients (Spearman's ρ's) between the densities predicted by delta-Gamma GAMs and those observed in datasets were significantly different from zero (Grüss et al., 2014; Weijerman et al., 2019; Dove et al., 2019; Egerton et al., 2021). The validation method employed in this study is useful when there are too few data to permit the "leave group out" cross validation procedure, which requires datasets to be split into "test" and "validation" datasets. For the great majority of the fish populations and life stages inhabiting Alaska nearshore areas, it is not possible to implement the leave group out cross validation procedure, as the limited number of data points for these fish populations and life stages prevents the different levels of some habitat factors to be present in both all test datasets and all validation datasets.

After the binomial and delta-Gamma GAMs were fitted and validated, they were used to predict spatial patterns of probability of encounter and density over an entire nearshore area, as continuous maps are most useful for EFH applications. This step necessitated the construction of a predictive coastline for the nearshore area of interest (Figs. 1b-c) and the generation of habitat information (e.g., physical wave exposure and eelgrass) for that predictive coastline (Fig. 2). To make predictions for each segment of the predictive coastline produced for the nearshore area of interest, if the year factor was included in the GAMs, it was set to its most frequent level from the modeled dataset; and if the gear factor was also included in the GAMs, it was also set to its most frequent level from the modeled dataset (Punt et al., 2000; Ono et al., 2015; Grüss et al., 2018a, 2019a, 2020). We could have fitted generalized additive mixed models (GAMMs; Lin and Zhang, 1999) including year and gear as random factors rather than GAMs. However, GAMMs are computationally intensive and are often likely not to converge when working with small datasets involving few factor levels like many of the fish datasets available for Alaska nearshore areas (Zuur et al., 2014; Roberts et al., 2016). Hence, we opted for the simpler and more practical GAMs for modeling and mapping Alaska nearshore fish habitats.

2.4.2. Application to Pacific cod early juveniles of the NSEA area

We applied our nearshore habitat modeling approach to Pacific cod early juveniles (≤15 cm TL) of the NSEA area. A few Pacific cod were captured in the NSEA area with trawl and purse seine, but only beach seine survey data were used for this application (Fig. 3). Pacific cod early juveniles were encountered at 58 of 397 stations-years sampled by beach seine over the period 1998-2013 (Appendix A3); all life stages combined, Pacific cod were encountered at 65 of the stations-years sampled by beach seine between 1998 and 2013. Pacific cod early juveniles were encountered by beach seine in the NSEA area in all years of the period 1998-2013, except 2002 and 2011 (Appendix A3).

Because some stations in the NSEA area were sampled several times by beach seine over the period 1998-2013, the binomial and Gamma GAMs developed for Pacific cod early juveniles included the fixed effect of year. These GAMs did not include the fixed effect of gear because all survey data were from the same gear (beach seine). The literature suggested the inclusion of the following fixed effect habitat factors in the initial (full) GAMs of Pacific cod early juveniles: coastal type, wave exposure, eelgrass, rockweed, and soft brown kelps (Table 1).

2.4.3. Application to walleye pollock early juveniles of PWS

We also applied our nearshore habitat modeling approach to walleye pollock early juveniles (≤14 cm TL) of PWS. Survey data collected over the period 1999-2015 were used (Fig. 4). Although purse seine and jig surveys collected a few walleye pollock in PWS, we employed only beach seine and trawl data for this application. Walleye pollock (all life stages combined, measured and unmeasured) was encountered at 21 of the 99 stations-years sampled by beach seine over the period 1999-2015; walleye pollock early juveniles were also encountered at 21 of these stations-years (Appendix A4). Moreover, walleye pollock (all life stages combined, measured and unmeasured) was encountered at 54 of the 58 stations-years sampled by trawl surveys over the period 1999-2015; walleye pollock early juveniles were encountered at 50 of these stations-years (Appendix A4). Walleye pollock early juveniles were not encountered by beach seine or trawl in PWS in many years of the period 1999-2015, particularly prior to 2006 (Appendix A4).

Because the GAMs for walleye pollock early juveniles of PWS relied on survey data collected with different gears over overlapping years, these GAMs included the fixed effects of gear and year. The literature suggested the inclusion of the following fixed effect habitat factors in the initial (full) GAMs of walleye pollock early juveniles: coastal type, wave exposure, eelgrass, rockweed, and soft brown kelps (Table 1).

3. Results

3.1. Application to Pacific cod early juveniles of the NSEA area

The final binomial GAM of Pacific cod early juveniles of the NSEA area included the effect of year, the tensor product smooth between eastings and northings, and the eelgrass factor. Coastal type, wave exposure, rockweed, and soft brown kelps were all found to have a non-significant effect on the probability of encounter of Pacific cod early juveniles. This model explained 39.1% of the deviance in the encounter/non-encounter data. The median AUC of the final binomial GAM equaled 0.90 (CI: 0.86-0.95), and its median adjusted R^2 was 0.36 (CI: 0.25-0.49). Therefore, the final binomial GAM of Pacific cod early juveniles of the NSEA area passed the validation test.

The percentage of encounters of Pacific cod early juveniles in the NSEA area was higher at stations where eelgrass was present than at stations where eelgrass was absent (Table 2). Moreover, we found that the percentage of encounters of Pacific cod early juveniles is slightly lower at stations where eelgrass beds are continuous than at stations where eelgrass beds are patchy (Table 2).

The binomial GAM predicted that the western part of Chichagof Island and all the northwestern part of Baranof Island are hotspots of probability of encounter for Pacific cod early juveniles (Fig. 5a). The probability of encounter of Pacific cod early juveniles was also predicted to be relatively high in the southeastern part of Baranof Island (Port Alexander area; Fig. 5a).

The final Gamma GAM of Pacific cod early juveniles of the NSEA area included the effect of year, the tensor product smooth between eastings and northings, the wave exposure factor, and the rockweed factor. Coastal type, eelgrass, and soft brown kelps were all found to have a non-significant effect on the non-zero density of Pacific cod early juveniles. The final Gamma GAM of Pacific cod early juveniles explained 49.8% of the deviance in the positive CPUE data. The median Spearman's ρ of the final delta-Gamma GAM of Pacific cod early juveniles equaled 0.39 (CI: 0.31-0.49) and was found to be significantly different from zero. Therefore, the final delta-Gamma GAM of Pacific cod early juveniles of the NSEA area passed the validation test.

The Gamma GAM predicted that Pacific cod early juvenile non-zero CPUE was lowest at the locations of the NSEA area that are very protected from wave exposure (Fig. 6a). Pacific cod early juvenile non-zero CPUE was also predicted to be higher at exposed and protected locations than at semi-protected locations. The non-zero CPUEs of Pacific cod early juveniles at exposed and protected locations were similar (Fig. 6a). Moreover, the Gamma GAM predicted that the non-zero CPUE of Pacific cod early juveniles was lowest at the locations where rockweed beds are continuous (Fig. 6b). Pacific cod early juvenile non-zero CPUE was also predicted to be lower at the locations where rockweed beds are patchy than at the locations where rockweed is absent (Fig. 6b).

The Gamma GAM predicted that (1) the highest densities of Pacific cod early juveniles are found in the Port Alexander area; and (2) the density of Pacific cod early juveniles is also high in Glacier Bay National Park and Preserve and all of the "Southeast Northern Outside" (SENO) area, as well as in bays and inlets along the northeastern part of Chichagof Island (Fig. A5). The spatial density patterns predicted by the delta-Gamma GAM, which were obtained by multiplying the spatial predictions from the binomial GAM by the spatial predictions from the Gamma GAM, reflected the spatial patterns predicted by the Gamma GAM, except that delta-Gamma GAM predicted that the density of Pacific cod early juveniles is not high in the western part of Glacier Bay National Park and Preserve (Figs. 5b and 7).

3.2. Application to walleye pollock early juveniles of PWS

The final binomial GAM of walleye pollock early juveniles of PWS included the effects of year and gear, the tensor product smooth between eastings and northings, and the eelgrass factor. Coastal type, wave exposure, rockweed, and soft brown kelps were all found to have a non-significant effect on the probability of encounter of walleye pollock early juveniles. The final binomial GAM of walleye pollock early juveniles explained 51.7% of the deviance in the encounter/non-encounter data. The median AUC of the final binomial GAM equaled 0.92 (CI: 0.89-0.97), and its median adjusted R^2 was 0.51 (CI: 0.38-0.64). Therefore, the final binomial GAM of walleye pollock early juveniles of PWS passed the validation test.

The percentage of encounters of walleye pollock early juveniles in PWS was higher at the locations where eelgrass was present than at the locations where eelgrass was absent (Table 3). Moreover, the percentage of encounters of walleye pollock early juveniles in PWS was higher where eelgrass beds were patchy than where eelgrass beds were continuous (Table 3).

The binomial GAM predicted that the probability of encounter of walleye pollock early juveniles is highest in the northern part of PWS between the Whittier area and the

Valdez area (Fig. 8a). The probability of encounter of walleye pollock early juveniles was also predicted to be relatively high in the southernmost areas of PWS, and lowest in the southeastern part of PWS (south of Tatitlek; Fig. 8a).

The final Gamma GAM of walleye pollock early juveniles of PWS included the effects of year and gear, the tensor product smooth between eastings and northings, and the wave exposure factor. Coastal type, eelgrass, rockweed, and soft brown kelps were all found to have a non-significant effect on the positive density of walleye pollock early juveniles. The final Gamma GAM of walleye pollock early juveniles explained 91.7% of the deviance in the non-zero CPUE data. The model predicted walleye pollock early juvenile non-zero CPUE to be higher at stations that are exposed or semi-protected from wave exposure than at protected locations (Fig. 9).

The median Spearman's ρ of the final delta-Gamma GAM of walleye pollock early juveniles of PWS equaled 0.73 (CI: 0.67-0.81) and was found to be significantly different from zero. Therefore, the final delta-Gamma GAM of walleye pollock early juveniles of PWS passed the validation test. The Gamma GAM predicted that the non-zero density of walleye pollock early juveniles is highest in the northern part of PWS and moderately high in the southernmost part of PWS (Fig. A6). The delta-Gamma GAM, which results from the product of predictions from the binomial GAM by the predictions from the Gamma GAM, predicted that (1) the density hotspots of walleye pollock early juveniles are located in the northern and southernmost parts of PWS; and (2) the density of walleye pollock early juveniles is lowest south of Tatitlek (Fig. 8b).

4. Discussion

In the present study, we demonstrated the utility of compiling large fish survey and habitat databases for nearshore ecosystems by using this information in a practical approach that employs species distribution models (SDMs) to generate very fine-scale nearshore EFH information. Specifically, we designed a GAM approach that used the NFA and *ShoreZone* databases to produce very fine-scale maps of probability of encounter (EFH level 1 information) and density (EFH level 2 information) for nearshore areas of Alaska. We applied our GAM approach to Pacific cod early juveniles of the NSEA area and walleye pollock early juveniles of PWS, and our final products were maps describing the probability of encounter and density of early juvenile fishes at ~10 m coastline segments. In the following, we first compare our GAM approach to previous SDM studies that partially modeled fish habitat in some Alaska nearshore areas, and show how our GAM approach is better suited for the management of natural resources in nearshore ecosystems. Then, we analyze GAM predictions for Pacific cod early juveniles of the NSEA area and walleye pollock early juveniles of PWS. Next, we discuss the use of our GAM approach and nearshore maps beyond simply to inform EFH for the species that inhabit nearshore habitats and their prey, including assisting ecosystem-based fisheries management (EFBM) efforts and addressing some fundamental ecological questions. Finally, we recommend further research to improve methods for modeling spatial distribution and density along coastlines within Alaska and worldwide.

4.1. Modeling and mapping nearshore fish habitat

While modeling and mapping of EFH employing SDMs has been conducted already for Alaska marine regions (Echave et al., 2012; and those described by Laman et al., 2018, including Rooney et al., 2018), only a few recent studies (Miller et al., 2016 for the Yukon River Estuary in the Bering Sea; Rooney et al., 2018 and Pirtle et al., 2019 for the GOA) have partially modeled habitat for demersal fishes/fish life stages in the nearshore areas. Rooney et al. (2018) and Pirtle et al. (2019) used MaxEnt to predict patterns of relative probability of encounter of the demersal juveniles and early juveniles, respectively, of several economically important species of the GOA across 100 m × 100 m raster grids. Both studies relied on a blending of data collected in both nearshore and offshore areas by monitoring programs that used beach seines and bottom trawls of various mesh sizes to target demersal fishes. MaxEnt is a popular SDM approach because it can be employed in cases where encounter and non-encounter data are not available from all surveys or sampling designs within the extent of the study area when response data are already limited (Elith et al., 2006; Merow et al., 2013). However, MaxEnt models can result in biased estimates of population density because they rely solely on encounter-only data which inherently result in the generation of maps that confound population density and sampling intensity (Fithian et al., 2015; Winship et al., 2020). Moreover, Rooney et al. (2018) and Pirtle et al. (2019) aimed at mapping relative fish probabilities of encounter over the entire GOA fishery management area, consistent with the spatial extent of SDM EFH maps and, therefore, the two studies did not aim at delivering comprehensive, very fine-scale information about nearshore fish habitats. Our GAM approach provides such comprehensive, very fine-scale information, particularly for the nearshore areas of the GOA that were not covered by the surveys and spatial scale of the covariates considered in Rooney et al. (2018) and Pirtle et al. (2019) such as the "Southeast Northern Inside" (SENI) area in the case of Pacific cod early juveniles of the NSEA area (Fig. 7).

In this study, we had access to a larger amount of nearshore survey data via the latest version of the NFA data, and we were able to predict probabilities of encounter and densities for around 930,000 ~10 m coastal segments for the NSEA area and 574,000 ~10 m coastal segments for PWS. Such very fine-scale information is critically needed to evaluate the potential impacts of non-fishing anthropogenic activities that take place nearshore or in upland terrestrial locations (e.g., mining, timber harvest, and municipal pollutant discharges) and that may adversely impact nearshore fish habitats (Limpinsel et al., 2017). Fisheries scientists and resource managers can also utilize the information provided by our GAM approach to evaluate the potential impacts of stressors or management actions at coarser spatial scales by summing across the set of coastline segments that are impacted, potentially weighted by their relative exposure (Shelton et al., 2017).

The very fine-scale information provided by our GAM approach will allow for more accurate nearshore EFH designations for future EFH reviews, and has also the potential to demonstrate ontogenetic habitat shifts and linkages where present between nearshore and offshore fish habitats (Sigler et al., 2017), which is also meaningful to fisheries stock assessment and management. To include nearshore habitat information (e.g., EFH Level 2 habitat-related density) in EFH designations, nearshore EFH maps can be developed using our GAM approach at fine spatial scales (e.g., 10s of m) and paired with EFH maps developed at courser spatial scales (100s of m or several kms) for the extent of the fishery management areas (Laman et al., 2018; Pirtle et al., 2019). In this effort, it would be advantageous to produce rasters of predictor variables (e.g., bathymetry, bottom temperature, and substrate) covering nearshore areas (e.g., from the high tide line to 20 m depth) in all Alaska regions so that informative predictor variables included in the management area SDMs can be included in nearshore SDMs where appropriate. By these approaches, SDM output maps can be merged as multi-resolution EFH map products for future EFH reviews that capture both nearshore and offshore habitat processes affecting fish distribution and density at meaningful and appropriate spatial scales.

4.2. Applications to Pacific cod early juveniles of the NSEA area and walleye pollock early juveniles of PWS

The present study, as most SDM studies, used delta models combining the predictions of a binomial model and a positive model, as fish survey datasets (and ecological datasets in general) usually include many zeros (Barry and Welsh, 2002; Martin et al., 2005). As previous studies that relied on delta models (e.g., Vaz et al., 2006; Grüss et al., 2014; Weijerman et al., 2019), we found that an habitat variable having a significant effect on fish probability of encounter does not necessarily have a significant effect on non-zero density, and vice versa. For instance, the eelgrass factor was found to have a significant effect on the probability of encounter of both study life stages but not on their non-zero density, while wave exposure was found to have a significant effect on their non-density but not on their probability of encounter. The predictions from the delta GAM for Pacific cod early juveniles usually reflected the predictions from the Gamma GAM for the life stage, and suggested that the density of Pacific cod early juveniles is high in all of the western part of the NSEA area, particularly around Port Alexander. On the other hand, the predictions from the delta GAM for walleye pollock early juveniles reflected the predictions from both the binomial and Gamma GAMs for the life stage, and indicated that the density hotspots of walleye pollock early juveniles are located in the northern and southernmost parts of PWS.

The percentage of encounters of both Pacific cod early juveniles of the NSEA area and walleye pollock early juveniles of PWS was predicted to be higher where eelgrass beds are present than where eelgrass beds are absent. This was to be expected because, in Alaska nearshore ecosystems, gadoid early juveniles use eelgrass beds as refuge from predation (Blackburn and Jackson, 1982; Laur and Haldorson, 1996; Dean et al., 2000; Murphy et al., 2000; Johnson et al., 2003b; Laurel et al., 2007). We also found that the percentage of encounters of both life stages was higher where eelgrass beds are patchy than where eelgrass beds are continuous. Concerning walleye pollock early juveniles, this result concurs with Johnson et al. (2003b), who reported that walleye pollock early juveniles in southeastern Alaska were most often caught in areas with spatially discrete eelgrass patches. For Pacific cod early juveniles, this result can be analyzed in light of the findings of Laurel et al. (2007)

and Gorman et al. (2009). Laurel et al. (2007) found that the frequency of use of eelgrass beds by Pacific cod early juveniles was significantly correlated to the presence of predators. This finding from Laurel et al. (2007) somewhat concurs with the findings of experiments conducted in Gorman et al. (2009) with Atlantic cod (*Gadus morhua*) early juveniles of Newfoundland, Canada, in which larger eelgrass areas offered substantial refuge from predation despite the preference of larger eelgrass beds by predators; therefore, predation risk for cod early juveniles may be lower in isolated eelgrass patches of intermediate size than in networks of smaller eelgrass patches (Gorman et al., 2009).

higher percentage of encounters of Pacific cod early juveniles in patchy eelgrass found in the present study. However, further exploration of habitat-specific catchability for beach seines or other sampling gears will require assembling a data set of paired (calibration) sampling, and we recommend this as a topic for future research.

We also found that rockweed had a significant effect on the non-zero density of Pacific cod early juveniles of the NSEA area. However, the Gamma GAM predicted that the non-zero CPUE of Pacific cod early juveniles was lower where rockweed beds are present than where rockweed beds are absent. This result was not expected, as several Alaska studies have mentioned that macroalgae, including rockweed, provide some refuge from predation to Pacific cod early juveniles (Johnson et al., 2003b; Laurel et al., 2007; Pirtle et al., 2019). Nonetheless, another study in Alaska found that macroalgae had virtually no effect on the CPUE of Pacific cod early juveniles (Abookire et al., 2007). We posit that Pacific cod early juveniles may prefer eelgrass and subtidal kelps over rockweed to hide from predators, at least in the NSEA area, but this idea remains to be investigated in future studies (see Subsection 4.3).

The Gamma GAMs also predicted that the non-zero density of both Pacific cod early juveniles of the NSEA area and walleye pollock early juveniles of PWS was significantly higher at locations that are exposed or semi-protected from wave exposure than at protected locations. Concerning walleye pollock early juveniles, this result was expected as previous studies found that walleye pollock early juveniles generally occur deeper than the early juvenile stages of other fish species, often in habitats that are exposed to waves such as the perimeters of rock reefs, channels within the bays, or the edges of gullies (Blackburn and Jackson, 1982; Hinckley et al., 1991; Laurel et al., 2007; Wilson et al., 2011). Concerning Pacific cod early juveniles, no study has examined the effects of wave exposure on Pacific cod early juveniles. However, Pirtle et al. (2019)'s MaxEnt model for Pacific cod early juveniles included the effects of aspect northness, which gives an indication of exposure to oceanic currents in the north-south direction, and aspect northness was found to be minimally descriptive. We posit that the significant effect of wave exposure on the non-zero density of both Pacific cod early juveniles can be explained in relation to eelgrass spatial patterns in the NSEA area. Specifically, the higher non-zero CPUEs of Pacific cod early juveniles at the exposed and protected locations may be due to the fact that these locations are usually associated with patchy or continuous eelgrass beds (Figs. 2a-b); and Pacific cod early juvenile CPUE was found to be high at the sampling stations where eelgrass is present (Johnson et al., 2012).

4.3. Employing our GAM approach and nearshore maps beyond simply to assist EFH

Nearshore maps of probability of encounter and density can also be useful beyond EFH designation for the species that use nearshore habitats. For example, juvenile stages of fish stocks exclusively or preferentially inhabit nearshore habitats (Thayer et al., 1978; Beck et al., 2003). In cases where juvenile density-dependence regulates population dynamics (Iles and Beverton, 1998), a change in the spatial extent of nearshore habitat (e.g., a reduction due to land development) can substantially affect population productivity. This has then led to interest in informing population-density dependence using information about the spatial extent of nearshore habitats (Roth et al., 2008). Similarly, environmental processes that affect nearshore habitats will affect cohort strength for Alaska fish populations such as the Pacific cod population of the GOA. In the GOA, the Pacific marine heatwave likely eliminated several juvenile cohorts simultaneously from 2016 to 2018, synchronous with starvation of offshore adults, and this led to a population collapse and federal emergency-declaration for the GOA in 2019 (Zador and Yasumiishi, 2018). In this case, GAMs or other SDMs for nearshore habitat could be used to inform adaptive sampling strategies to measure real-time impacts on nearshore juveniles for offshore fisheries during anomalous environmental conditions. Likewise, SDMs estimating the relative productivity and contribution of nearshore nursery habitats to the offshore life stages targeted by the fisheries could benefit fishery management strategies for Pacific cod and species with similar life histories.

Nearshore maps of probability of encounter and density can also support EBFM efforts. One major EBFM issue in Alaska is the access of fish, seabird and marine mammal predator populations to forage fishes, which make up a large portion of their prey (Springer and Speckman, 1997; Mundy and Hollowed, 2005). Nearshore maps of probability of encounter and density can provide a basis for marine protected area (MPA) planning scenarios aiming to protect the forage fish resources used by large marine predators (Pikitch et al., 2014; Fifield et al., 2017; Grüss et al., 2019a). It would be particularly interesting to produce hypothetical MPA scenarios for the Alaska populations of Pacific sand lance, which makes up a large fraction of the diet of 45 fish species, 40 bird species and 12 marine mammal species (Field, 1988; Willson et al., 1999), especially for the Aleutian Islands where Pacific sand lance was found to be extremely abundant (Johnson et al., 2012). We also recommend exploring hypothetical MPA scenarios to protect some of the forage fish resources of The Brothers Islands area in southeastern Alaska, as both forage fishes and Steller sea lion are very abundant in The Brothers Islands area (Thedinga et al., 2006; Johnson et al., 2012).

Besides providing information to habitat and natural resource damage assessments and resource management, our GAM approach will allow some fundamental ecological questions to be addressed. In particular, the present study highlights the need to better understand if early juvenile fishes that use structural habitat as refuge from predators have a higher probability of encounter or higher density in patchy or continuous eelgrass, kelp or macroalgal beds (Johnson et al., 2003b; Laurel et al., 2007; Pirtle et al., 2019). To allow for these investigations, we recommend that future studies develop GAMs for the early juvenile stages of multiple species that associate with structural habitat, for several nearshore areas of Alaska. These GAMs would retain the eelgrass, kelp and macroalgal factors even if they were found to be non-significant, and the relative importance of eelgrass, kelps and macroalgae in explaining spatial patterns of probability of encounter and density would then be evaluated using, for example, the relative importance method of Grüss et al. (2016, 2019a). Moreover, contingency tables (similar to Tables 2-3) and CPUE boxplots (similar to Figs. 6 and 9) would help better understand if and why the early juvenile fishes of different species tend to prefer patchy over continuous structural habitat to hide from predators (Johnson et al., 2003b; Gorman et al., 2009).

4.4. Avenues for future nearshore habitat modeling efforts

The SDM approach that we developed in this study is a simple GAM approach that can be employed and adapted by fisheries scientists and resource managers to develop new EFH information and maps for species life stages in the nearshore areas, including the prey of EFH species. Yet, we recommend further research to improve methods for modeling spatial distribution and density along coastlines within Alaska and worldwide. Fish densities are typically governed by a combination of bottom-up and top-down effects, some of which cannot be measured directly (Elith and Leathwick, 2009; Brodie et al., 2020). Unmeasured (latent) processes will then typically result in spatial patterns in model residuals, with resulting loss of predictive accuracy and overly permissive tests for significance of included variables (Thorson et al., 2015). The GAMs presented in this study include a tensor product smooth between eastings and northings that accounts for unmeasured (latent) processes at a broad spatial scale (Swartzman et al., 1992; Denis et al., 2002; Politou et al., 2008). We note that, even if the GAMs fitted in the present study included a tensor product smooth between eastings and northings, empirical variograms revealed that the residuals from the fitted GAMs still exhibited some spatial autocorrelation (results not shown). Thus, we encourage further research on SDMs involving nearshore habitat regarding techniques to model correlations along one-dimensional habitats at a finer scale than allowed by the tensor product smooth between eastings and northings, whether using GAMs including cyclic splines (Benjamins et al., 2017), estimating spatial correlations within coastal networks assuming an Ornstein-Uhlenbeck process (Hocking et al., 2018), or employing other techniques that allow residual patterns to be predicted from coastline distances (e.g., O'Donnell et al., 2014). We also recommend further research regarding joint SDMs for nearshore fish habitats; joint models have shown promise when inferring habitat for poorly sampled species within a community based on their estimated similarity to other well-sampled species (Thorson and Barnett, 2017).

In the present study, we fitted delta-Gamma GAMs that combined the predictions of a binomial GAM and a Gamma GAM, where the Gamma GAM relied on CPUE data expressed in number of fish per m sampled, and we predicted fish densities expressed in number of fish per m of coastline. Alternatively, we could have fitted delta-Poisson GAMs, which would have combined the predictions of a binomial GAM and a (quasi-)Poisson GAM, where the (quasi-)Poisson GAM would have relied on count data (number of fish caught) and would have included sampling effort (the distance sampled, in m) as an offset, and we would have then predicted fish abundance (Grüss et al., 2014, 2016). However, working with delta-Poisson GAMs to model nearshore fish habitat would have been challenging, because, in the great majority of cases, the ~10 m coastline segments for which we need predictions are smaller than the distances covered by sampling events. In other words, working with delta-Poisson GAMs to model nearshore fish habitat would have resulted in a "change in support" issue. Therefore, we recommend future research to develop a "change in support" procedure allowing for the generation of fish abundance estimates for very small coastline segments with delta-Poisson GAMs. Moreover, we acknowledge that nearshore survey samples very often integrate across a distance than the ~10 m coastline segments for which we made predictions. Similar issues arise in offshore SDMs, where bottom trawl tows typically follow track-lines that extend over several kilometers in length but often treated as arising from predicted density (and associated habitat characteristics) at a single location, often the midpoint (Shelton et al., 2014; Cosandey-Godin et al., 2015; Rooper et al., 2016). Therefore, we also recommend further research adapting change-in-support methods to account for heterogeneity in the distance sampled in both nearshore and offshore sampling gears.

4.5. Concluding remarks

We demonstrated the utility of large survey and habitat databases for nearshore ecosystems, by developing SDMs that deliver fine-scale information about nearshore fish habitats in Alaska which are meaningful to habitat and natural resource conservation and management. . The NFA and *ShoreZone* databases employed in the present study are invaluable resources, and we recommend their further augmentation and use for modeling and mapping nearshore fish habitats and ecological research in general, as well as some improvements in the NFA database (Appendix A7). The *Exxon Valdez* oil spill of 1989 in Alaska (Peterson et al., 2003) and the *Deepwater Horizon* oil spill of 2010 in the U.S. Gulf of Mexico (Mendelssohn et al., 2012) have demonstrated the vulnerability of coastal habitats and living resources to disturbances, as well as the importance of large databases, tools such as SDMs, and extensive knowledge for being prepared to respond to human and natural catastrophes. Therefore, we hope that the developments and efforts for Alaska reported in this study will encourage similar development and efforts in other marine regions globally, including regions of the U.S. where large survey or habitat databases have already been produced (e.g., the U.S. Gulf of Mexico; Appendix A7) or not (e.g., the U.S. southeastern region).

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version of the manuscript.

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Figures

Fig. 1. Study areas. (a) Map of Alaska. Important regions and locations are labeled and include: the Arctic region, the Eastern Bering Sea, the Aleutian Islands, and the Gulf of Alaska, as well as: 1) Juneau, 2) Yakutat Bay, 3) the Copper River area, 4) Cook Inlet, 5) Bristol Bay, and 6) the Yukon River Estuary. The red rectangle delineates the northern southeastern Alaska (NSEA) area, while the blue rectangle delineates Prince William Sound. (b) Map of the NSEA area showing the predictive coastline that was produced for this area in the present study (highlighted in red). Important locations are labeled and include the SENI (Southeast Northern Inside) area, the SENO (Southeast Northern Outside) area, and The Brothers Islands (TBI). (c) Map of Prince William Sound showing the predictive coastline that was produced for this area in the present study (highlighted in blue).

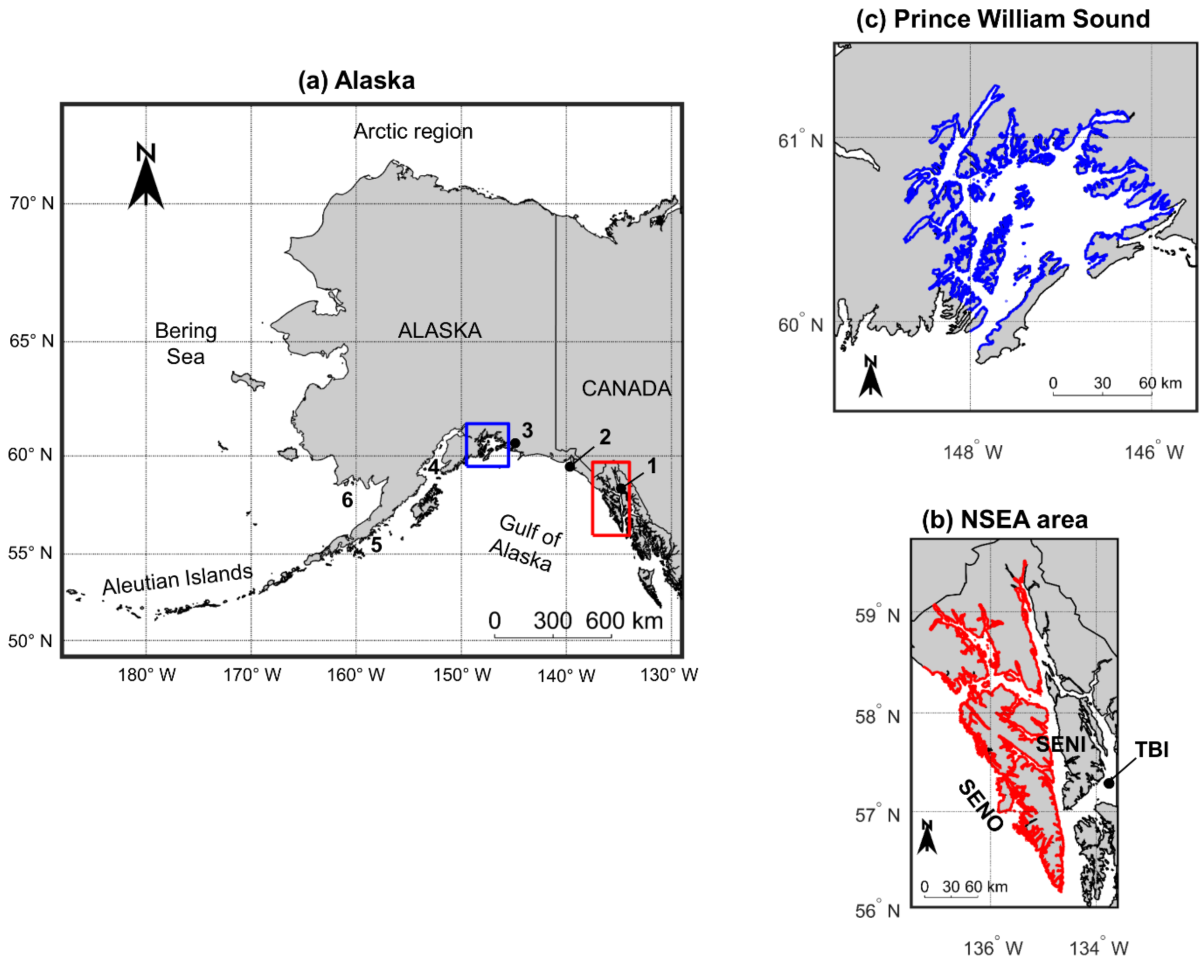


Fig. 2. Examples of the information provided in the *ShoreZone* database. (a, c) Physical wave exposure and (b, d) eelgrass (*Zostera marina*) in (a, b) the northern southeastern Alaska (NSEA) area and (c, d) Prince William Sound. Note that, in the case of physical wave exposure, "exposed" encompasses the "semi-exposed" and "exposed" categories for (a, c), and "protected" encompasses "semi-protected" and "protected" categories for (c).

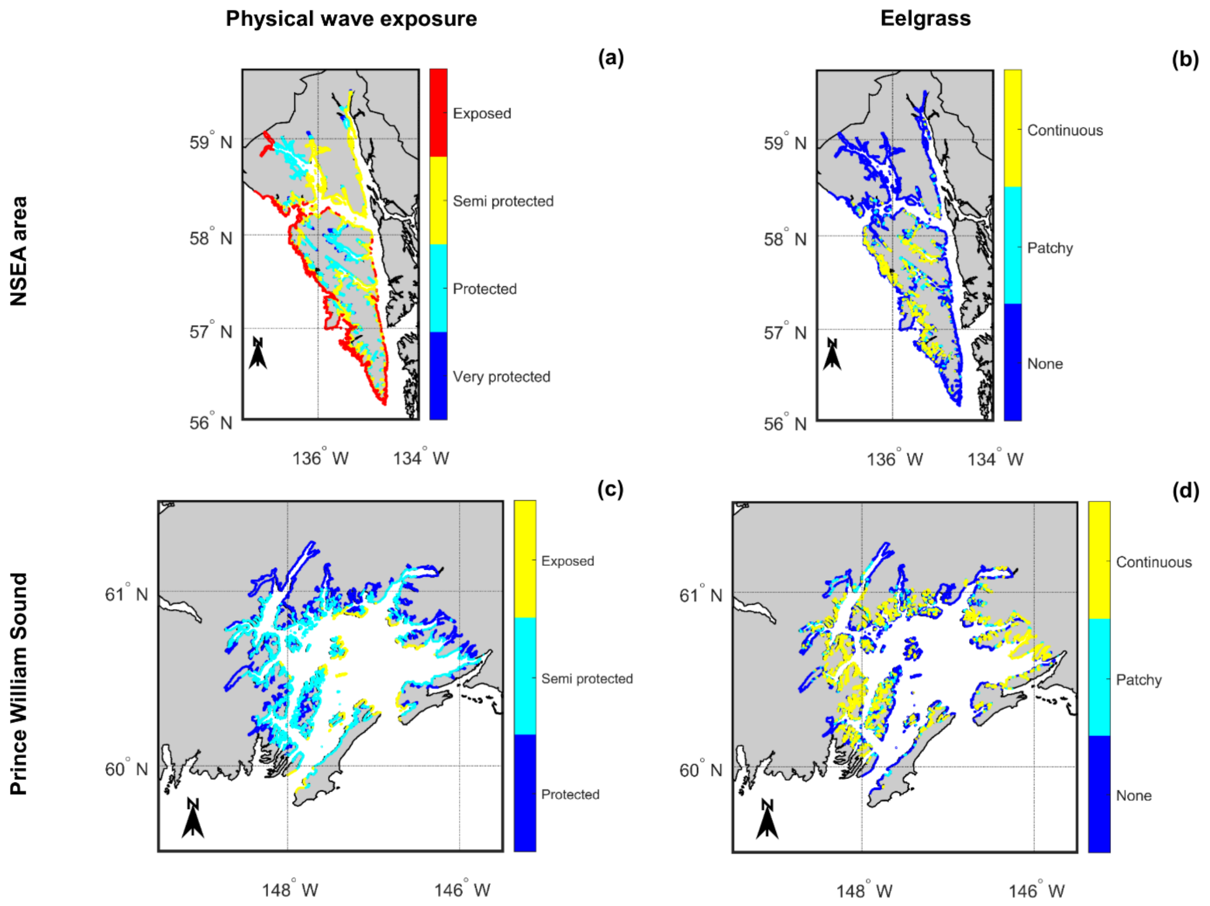


Fig. 3. Beach seine stations of the northern southeastern Alaska area where Pacific cod (*Gadus macrocephalus*) early juveniles were encountered in at least one year of the period 1998-2013 (red dots) or not encountered at all over the period 1998-2013 (white dots).

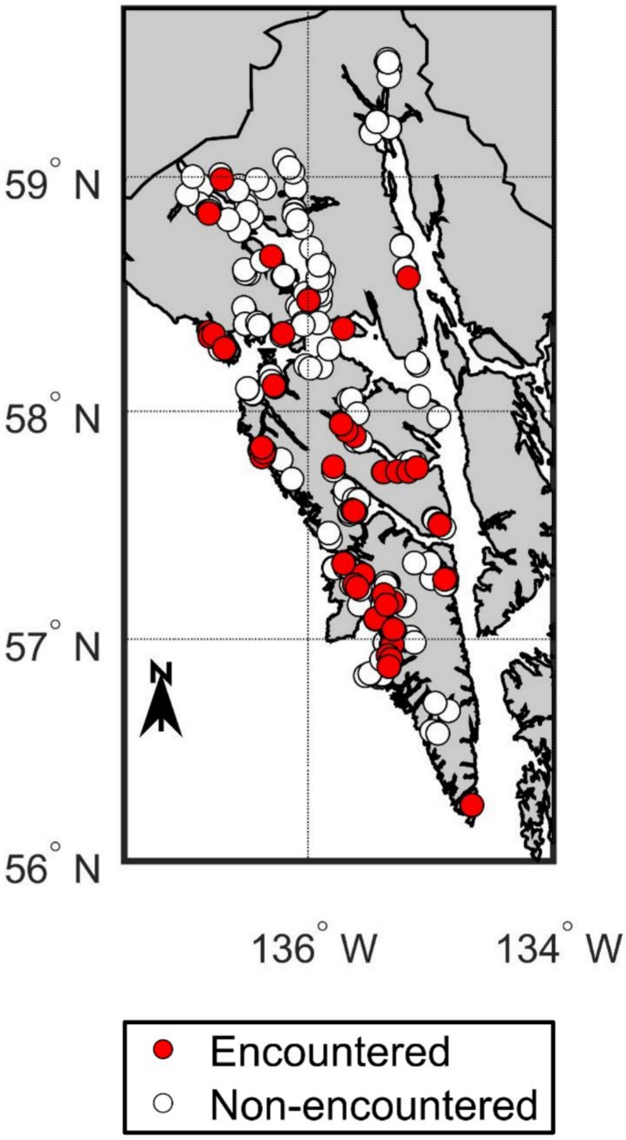


Fig. 4. Beach seine and trawl stations of Prince William Sound where walleye pollock (*Gadus chalcogrammus*) early juveniles were encountered in at least one year of the period 1999-2015 (colored dots) or not encountered at all over the period 1999-2015 (white dots).

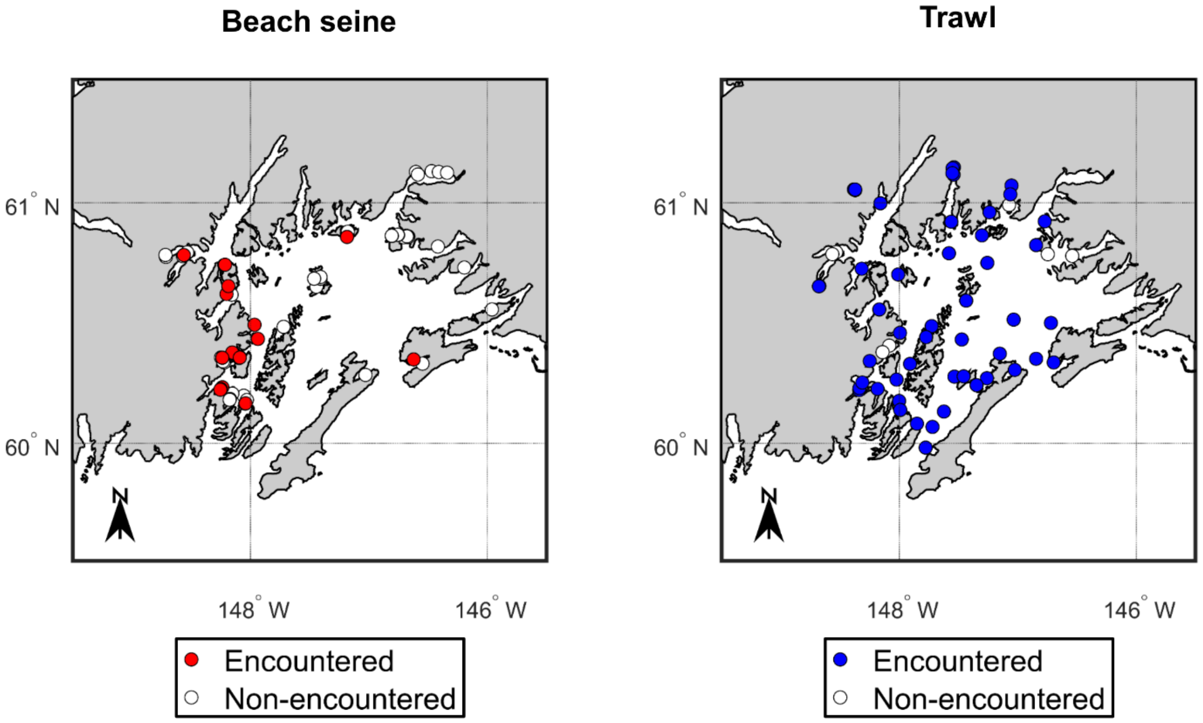


Fig. 5. Spatial patterns of (a) probability of encounter and (b) log(density) (in number.m^{-1}) of Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area predicted by the generalized additive models (GAMs) developed for the life stage in this study. GB = Glacier Bay National Park and Preserve; CI = Chichagof Island; BI = Baranof Island; PA = Port Alexander area.

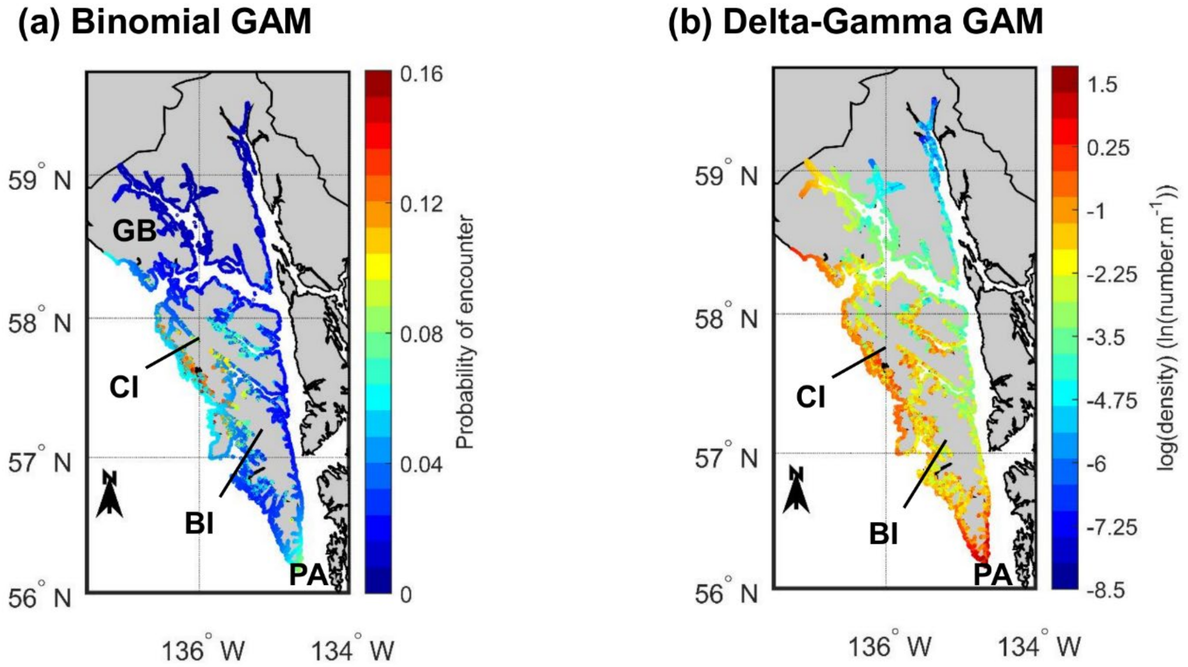


Fig. 6. Distribution of the non-zero catch-per-unit-effort (CPUE) of Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area (in number.m^{-1}) for (a) each physical wave exposure factor level (E = exposed, P = protected, SP = semi-protected, VP = very protected) and (b) each rockweed (*Fucus distichus*) factor level (C = continuous, N = none, P = patchy) predicted by the Gamma generalized additive model fitted for the life stage.

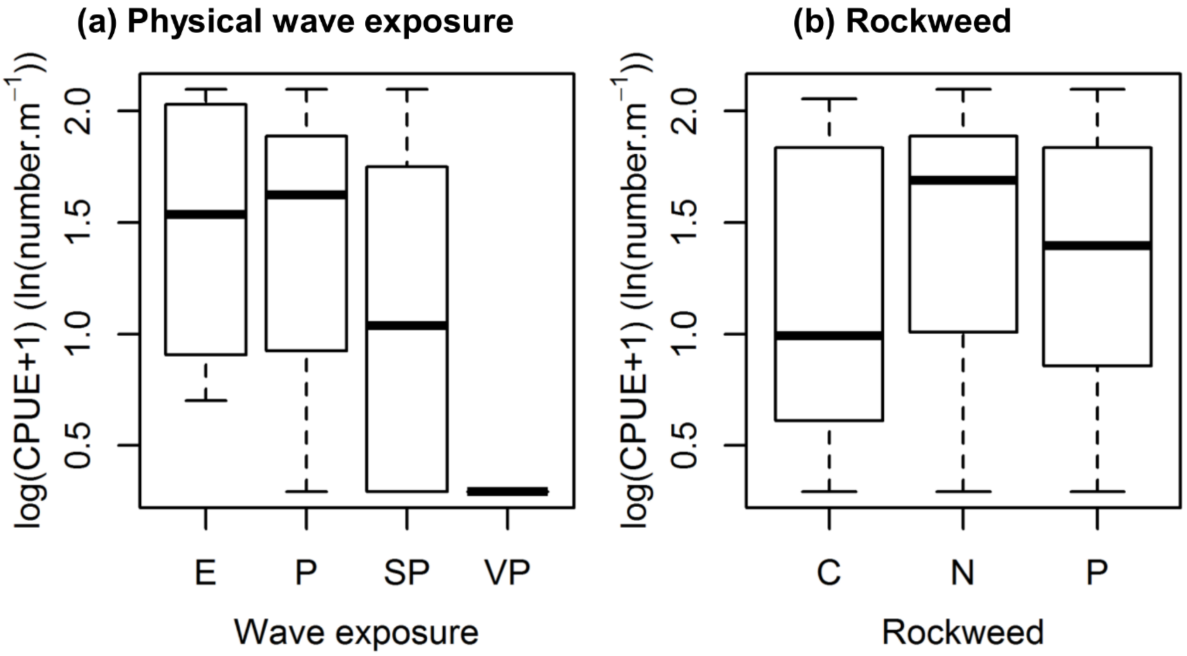


Fig. 7. Spatial patterns of log(density) (in number.m^{-1}) of Pacific cod (*Gadus macrocephalus*) early juveniles in some locales of the northern southeastern Alaska area, predicted by the delta-Gamma generalized additive model developed for the life stage in this study.

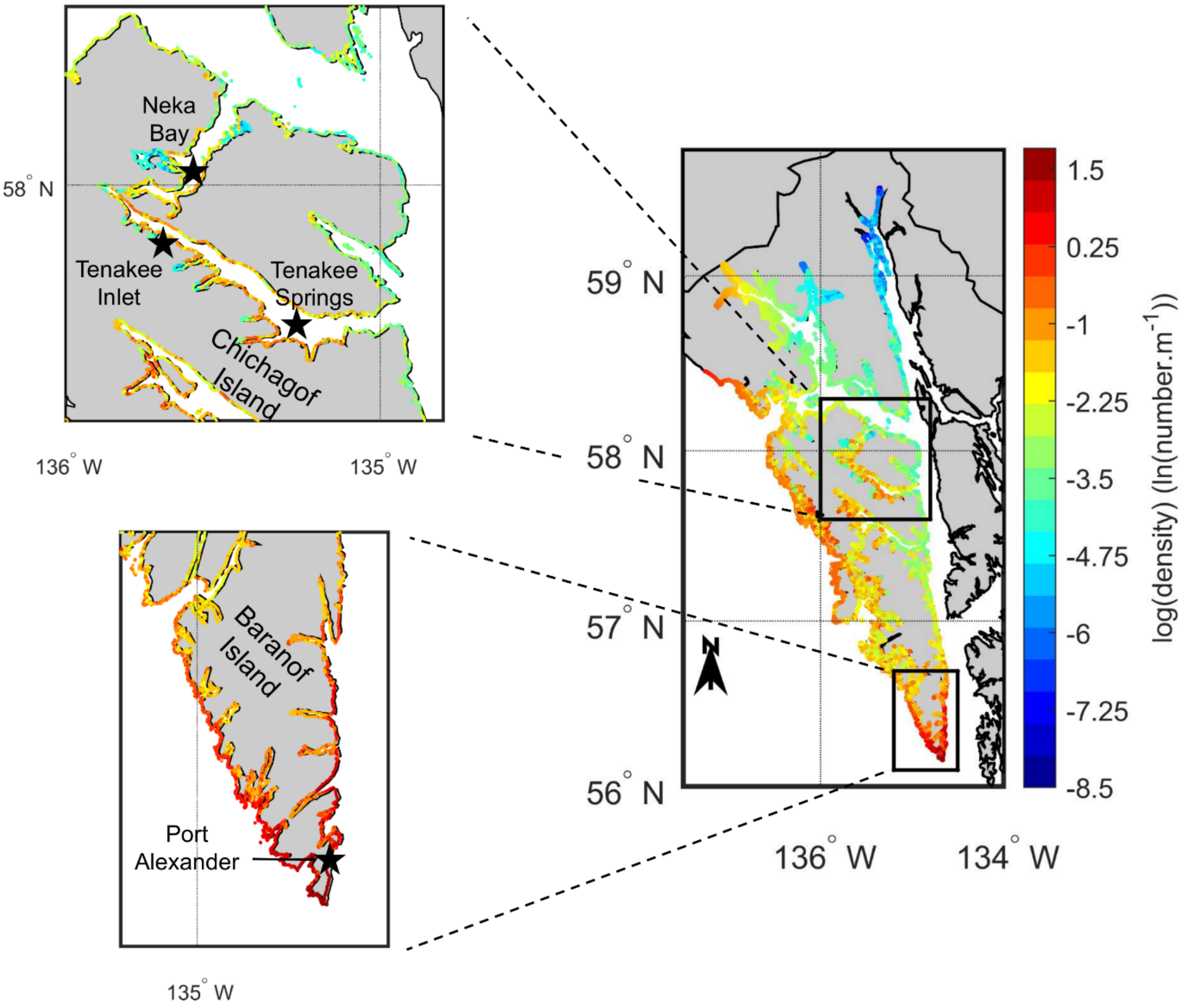


Fig. 8. Spatial patterns of (a) probability of encounter and (b) log(density) (in number.m^{-1}) of walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound predicted by the generalized additive models (GAMs) developed for the life stage in this study.

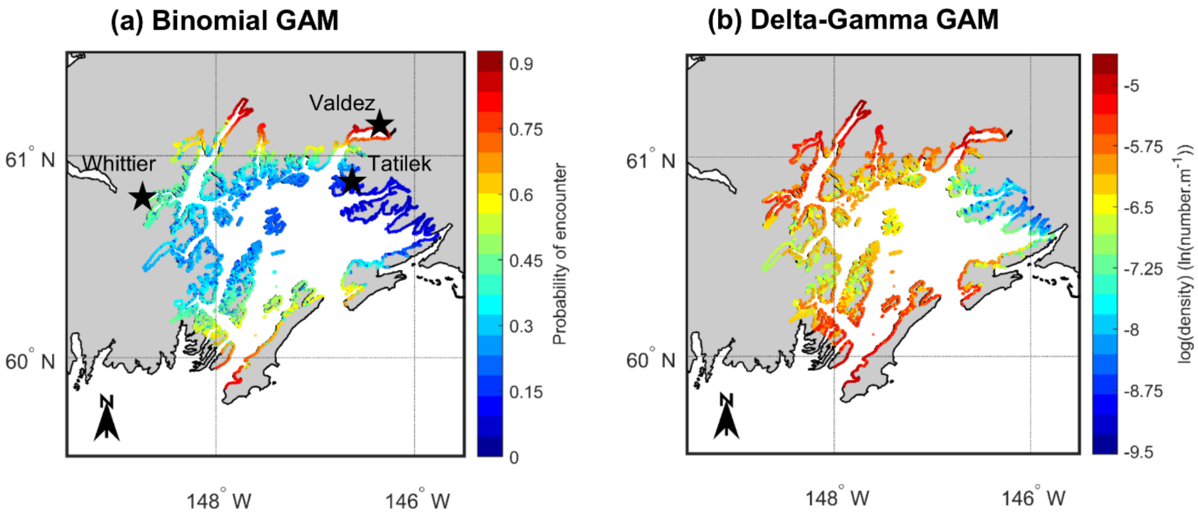
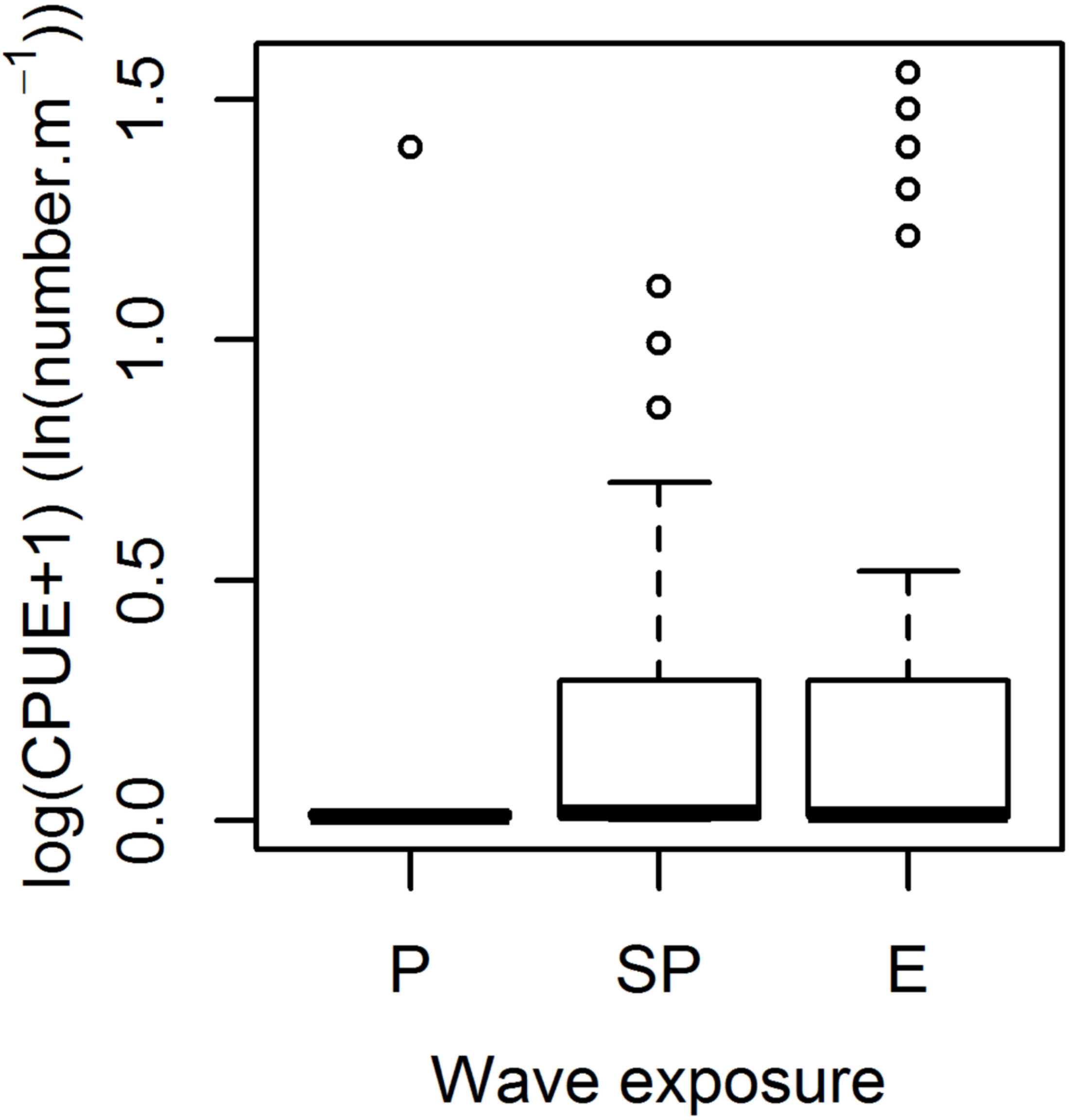


Fig. 9. Distribution of the non-zero catch-per-unit-effort (CPUE) of walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound (in number.m^{-1}) for each physical wave exposure factor level (P = protected; SP = semi-protected; E = exposed).



Tables

Table 1. ShoreZone factors included in the full generalized additive models (GAMs) of Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area and walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound, and references supporting these modeling choices.

Life stage	***ShoreZone* factors included in the full GAMs developed for the life stage**
Pacific cod early juveniles	Coastal type[a, b], physical wave exposure[c], eelgrass[b, c, d, e, f], rockweed[b, g], soft brown kelps[b, c, d, e, g]
Walleye pollock early juveniles	Coastal type[a, b, g, h], physical wave exposure[c, i, j], eelgrass[c, d, g, k, l], rockweed[c], soft brown kelps[b, c, d, e, f, g]

[a] Abookire et al. (2001), [b] Abookire et al. (2007), [c] Pirtle et al. (2019), [d] Laurel et al. (2007), [e] Laurel et al. (2009), [f] Gorman et al. (2009), [g] Johnson et al. (2012), [h] Blackburn and Jackson (1982), [i] Jones et al. (2015), [j] Simpson et al. (2017), [k] Murphy et al. (2000), [l] Johnson et al. (2003a)

Table 2. Contingency table of the binomial distribution's eelgrass (*Zostera marina*) factor level for Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area, as well as the percentage of encounters of where Pacific cod early juveniles for survey stations in each eelgrass factor level.

Eelgrass factor level	**Non-encountered**	**Encountered**	**% encounters for the survey stations in this eelgrass factor level**
None	231	26	10.1
Patchy	30	11	26.8
Continuous	78	21	21.2

Table 3. Contingency table of the binomial distribution's eelgrass (*Zostera marina*) factor level for walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound, as well as the percentage of encounters of where walleye pollock early juveniles for survey stations in each eelgrass factor level.

Eelgrass factor level	**Non-encountered**	**Encountered**	**% encounters for the survey stations in this eelgrass factor level**
None	43	17	28.3
Patchy	23	48	67.6
Continuous	20	6	23.1

Appendix A. Supplementary data

Appendix A1. Details of the Nearshore Fish Atlas (NFA).

The NFA is a centralized, relational database of nearshore fish surveys curated by National Marine Fisheries Service (NMFS)'s Auke Bay Laboratories (ABL) in Juneau, Alaska (NMFS, 2020). The NFA database was developed in 2003 to consolidate the ABL's southeastern Alaska beach seine data going back to 1998 when NOAA's essential fish habitat (EFH) funds first became available. Beach seine surveys were conducted in vegetated (i.e., eelgrass and kelp) and unvegetated (i.e., bedrock and sand) habitats within 20 m of shore and less than 5 m deep. By the end of 2004, 538 beach seine hauls had been made with a standard net by one sampling team, with thousands of fish captured, identified to species, counted, measured, and released (Johnson et al., 2005). This effort resulted in an unprecedented amount of information on the distribution, abundance, frequency of occurrence, habitat use, and length frequency distributions of nearshore fishes in Alaska. In 2006, following recognition of the collective value of these standardized data to resource managers, an online NFA application was launched. By the end of 2011, more than 1,000 beach seine hauls had been made in the shallow, nearshore waters of southeastern Alaska, the Aleutian Islands, Prince William Sound (PWS), Cook Inlet, Bristol Bay and the Arctic region, and posted to the online application (Thedinga et al., 2008; Johnson et al., 2012). Currently, the NFA web site contains 19 years of fish catch data from more than 1,300 beach seine hauls, making it the largest online repository of Alaska nearshore fish data.

Although the NFA started as and is best known as a beach seine database, catch data from other gear types have been archived in the offline version for years. Hook-and-line jigging took place concurrently with beach seining in 2001 through 2003 to better assess Steller sea lion (*Eumetopias jubatus*) prey availability in the nearshore waters of southeastern Alaska (Thedinga et al., 2006). A small bottom trawl was added in 2007 to the nearshore fish survey protocol in the Arctic (Johnson et al., 2010). The concurrent use of beach seine and bottom trawl in the Arctic expanded sampling coverage to a depth of 15 m and a distance up to 2.5 km from shore, thereby generating a more comprehensive understanding of nearshore fish assemblages in the region (Thedinga et al., 2013). Since late 2019, the offline NFA database has included catch data from a diverse array of beach seines, bottom and midwater trawls, purse seines, gillnets, jigs, fyke nets, and minnow traps (Table A1.1 and Fig. A1.1).

The 2019 expansion of gear types resulted from an effort to identify and acquire disparate sources of contemporary, Alaska nearshore fish catch data for inclusion in the NFA for the primary purpose of modeling and mapping EFH. To that end, a wealth of nearshore catch data from more than 20 projects were generously shared by more than 13 scientists from the Alaska Fisheries Science Center (AFSC), U.S. Geological Survey, U.S. Army Corps of Engineers, University of Alaska Fairbanks College of Fisheries and Ocean Sciences, Wildlife Conservation Society, and Kachemak Bay National Estuarine Research Reserve. All of these data are now in the offline NFA database, and the majority of the data are expected to be publicly accessible on an updated NFA web site by the end of 2021.

In October 2019, the NFA included fish catch data from a total of 1,848 unique stations sampled between 1995 and 2018 by surveys that used beach seine, trawl, purse seine, gillnet, jig, fyke net or minnow trap (Table A1.1). The great majority of these stations (1,220) were sampled by beach seine. The remainder included 304 trawl stations, 199 purse seine stations, and 251 stations sampled with either gillnet, jig, fyke net, or minnow traps. Some of the stations sampled by beach seine, trawl and gillnet surveys were visited several times over the period 1995-2018 (Table A1.1), resulting in an overall total of 5,643 stations-years. Habitat and environmental condition data (e.g., temperature, salinity, and tidal stage) are recorded in the NFA for many of the sampling events.

In October 2019, the NFA had 109,078 data entries, the great majority of which were within the Gulf of Alaska (85,827). There are 11,372 data entries for the Bering Sea, 7,829 data entries for the Arctic region, and 4,050 data entries for the Aleutian Islands. Fish captures are identified to species or genus levels in the NFA, and the length of most of the fish has been recorded to the nearest millimeter. Most data in the NFA were collected during daylight hours and primarily during the summer season. Of the 196 fish species included in the NFA, 45 are either target or potential target (e.g., Arctic cod *Boreogadus saida*) species in either a groundfish or salmon fishery management plan (FMP) in Alaska, where these species must receive EFH designations. In addition, another 25 species from 7 families (Ammodytidae, Bathylagidae, Mytophidae, Osmeridae, Pholidae, Stichaeidae, and Trichodontidae) are included in the ecosystem component or as forage fish in one or more FMP in Alaska.

Survey data for the northern southeastern Alaska (NSEA) area

In the NSEA area, data were collected at a total of 365 unique sampling stations between 1998 and 2013 by surveys that used beach seine, purse seine, trawl or jig (Fig. A1.2a and Table A1.2). The majority of these unique stations (225) were sampled by beach seine. Another 85 stations were sampled by purse seine, 28 by trawl, and 27 by jig. Some of the stations sampled by beach seine and jig were visited several times over the period 1998-2013 (Table A1.2), resulting in an overall total of 391 stations-years in the NSEA area. Species encountered at the largest number of NSEA area stations over the period 1998-2013 (i.e., at the largest number of stations-years) included crescent gunnel (*Pholis laeta*), pink salmon ( ), silverspotted sculpin ( ), Pacific sand lance (*Ammodytes personatus*), and Pacific herring (*Clupea pallasii*) (Table A1.3). Pacific cod (*Gadus macrocephalus*) was encountered at a total of 99 station-year combinations in the NSEA area over the period 1998-2013 (Table A1.3).

Survey data for Prince William Sound (PWS)

In PWS, data were collected at a total of 177 unique sampling stations between 1999 and 2015 by surveys that employed beach seine, trawl, jig, purse seine, or gillnet (Fig. A1.2b and Table A1.4). Some of the stations sampled by beach seine were visited several times over the period 1999-2015 (Table A1.4), resulting in an overall total of 201 stations-years in PWS. The majority of the stations were sampled by beach seine (99 stations) or trawl (59). Another 37 stations were sampled by jig, 5 by purse seine, and 1 by gillnet (Table A1.4). Species encountered at the largest number of stations over the period 1999-2015 included Pacific herring (encountered at 90 of the 177 sampled stations), walleye pollock (*Gadus chalcogrammus*; encountered at 88 stations), saffron cod (; encountered at 82 stations), and crescent gunnel (encountered at 73 stations) (Table A1.5).

References of Appendix A1

Johnson, S.W., Neff, A.D., Thedinga, J.F., 2005. An atlas on the distribution and habitat of common fishes in shallow nearshore waters of southeastern Alaska. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-157 (89 P).

Johnson, S.W., Neff, A.D., Thedinga, J.F., Lindeberg, M.R., Maselko, J.M., 2012. Atlas of nearshore fishes of Alaska: A synthesis of marine surveys from 1998 to 2011. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-AFSC-239 (261 P).

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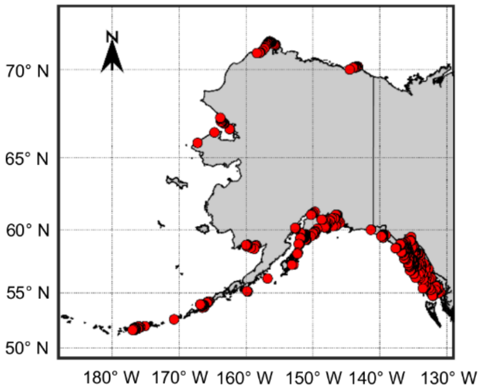
Thedinga, J.F., Johnson, S.W., Neff, A.D., Hoffman, C.A., Maselko, J.M., 2013. Nearshore fish assemblages of the northeastern Chukchi Sea, Alaska. Arctic 257–268.

Thedinga, J.F., Johnson, S.W., Neff, A.D., Lindeberg, M.R., 2008. Fish assemblages in shallow, nearshore habitats of the Bering Sea. Transactions of the American Fisheries Society 137, 1157–1164.

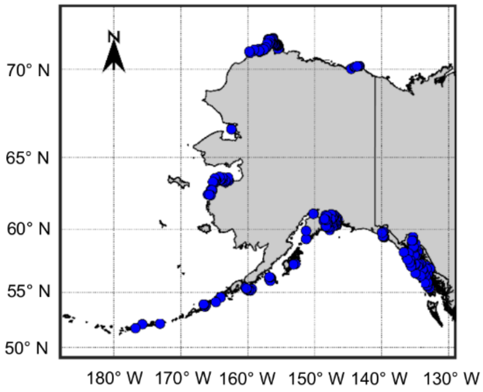
Figures of Appendix A1

Fig. A1.1. Stations sampled in Alaska waters by (a) beach seine (red dots), (b) trawl (blue dots), (c) purse seine (green dots), (d) gillnet (yellow dots), (e) jig (cyan dots), (f) fyke net (brown dots) and (g) minnow trap (magenta dots).

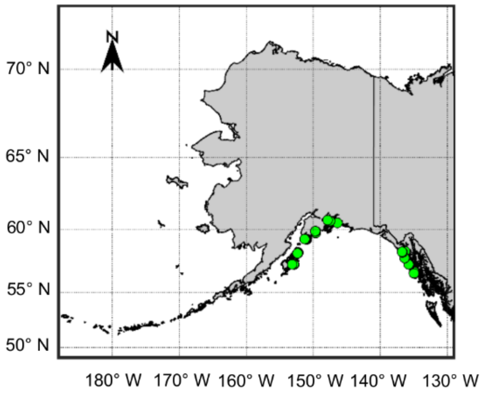
(a) Beach seine



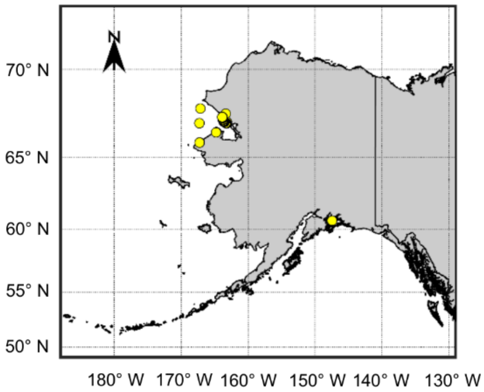
(b) Trawl



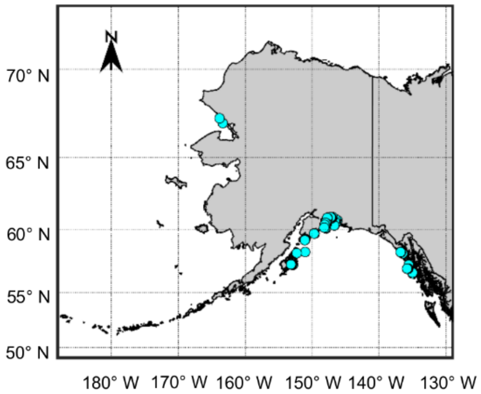
(c) Purse seine



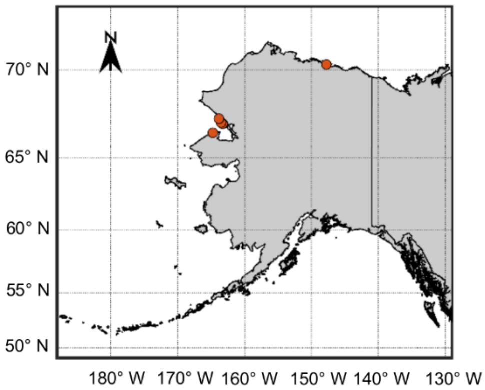
(d) Gillnet



(e) Jig



(f) Fyke net



(g) Minnow trap

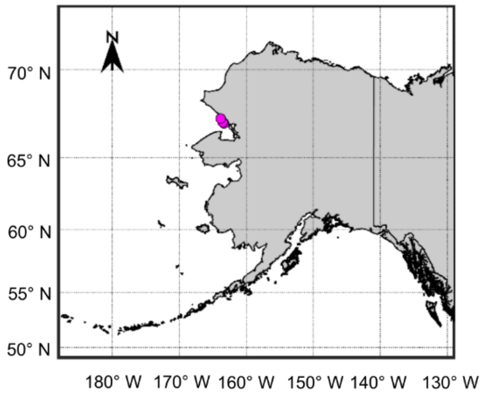
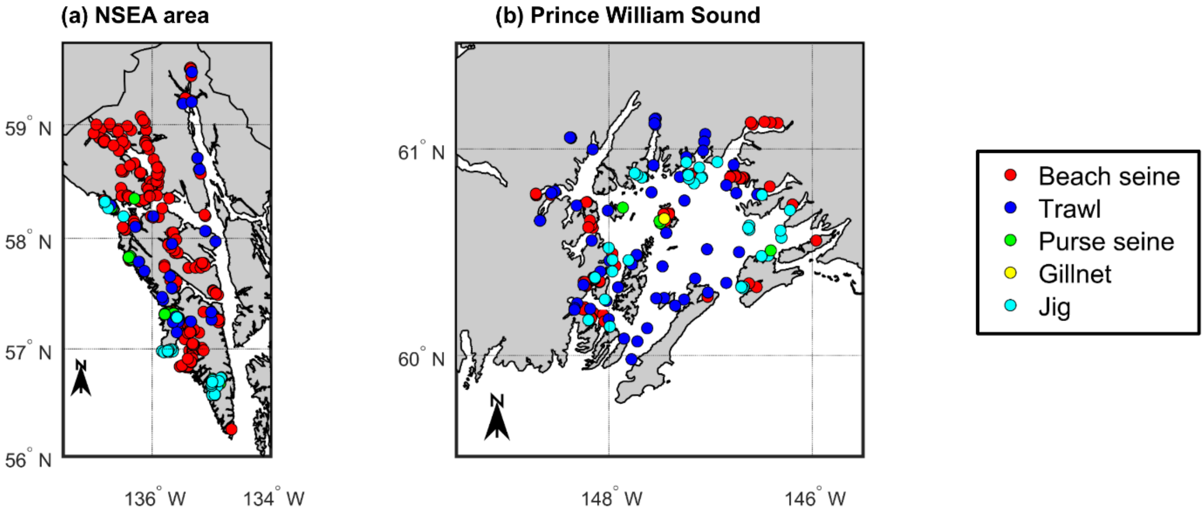


Fig. A1.2. Stations sampled in (a) the northern southeastern Alaska (NSEA) area and (b) Prince William Sound by beach seine (red dots), trawl (blue dots), purse seine (green dots), gillnet (yellow dots), and jig (cyan dots).



Tables of Appendix A1

Table A1.1. Number of unique stations and total number of stations-years sampled over the period 1995-2018 in Alaska.

Gear	Number of unique stations sampled	Total number of stations-years sampled
Beach seine	1220	1590
Trawl	304	367
Purse seine	199	199
Gillnet	140	147
Jig	88	88
Fyke net	13	13
Minnow trap	10	10

Table A1.2. Number of unique stations and total number of stations-years sampled over the period 1998-2013 in the northern southeastern Alaska area.

Gear	Number of unique stations sampled	Total number of stations-years sampled
Beach seine	225	251
Purse seine	85	85
Trawl	28	28
Jig	27	27

Table A1.3. Number of stations-years sampled over the period 1998-2013 where different species were encountered in the northern southeastern Alaska area. Only species encountered in at least 80 stations-years are considered here. BSAI = Bering Sea and Aleutian Islands; EFH = essential fish habitat; FMP = fishery management plan; GOA = Gulf of Alaska.

Species	**Considered in an FMP?**	**Number of sampled stations-years where the species was encountered**
Crescent gunnel (*Pholis laeta*)	Yes (forage fish in the ecosystem component of the GOA and BSAI Groundfish FMPs)	251
Pink salmon (*Oncorhynchus gorbuscha*)	Yes (targeted species in the Salmon FMP, receive EFH designations)	161
Silverspotted sculpin (*Blepsias cirrhosus*)	Yes (ecosystem component of the GOA and BSAI Groundfish FMPs)	134
Pacific sand lance (*Ammodytes personatus*)	Yes (forage fish in the ecosystem component of the GOA and BSAI Groundfish FMP)	126
Pacific herring (*Clupea pallasii*)	Yes (prohibited species in the ecosystem component of the GOA and BSAI Groundfish FMPs)	126
Pacific staghorn sculpin (*Leptocottus armatus*)	Yes (ecosystem component of the GOA and BSAI Groundfish FMPs)	121
Chum salmon (*Oncorhynchus keta*)	Yes (targeted species in the Salmon FMP, receive EFH designations)	117
Bay pipefish (*Syngnathus leptorhynchus*)	No	114
Great sculpin (*Myoxocephalus polyacanthocephalus*)	Yes (ecosystem component of the GOA and BSAI Groundfish FMPs)	106
Shiner perch (*Cymatogaster aggregata*)	No	104
Tubesnout (*Aulorhynchus flavidus*)	No	99
Pacific cod (*Gadus macrocephalus*)	Yes (targeted species in the GOA and BSAI Groundfish FMPs, receive EFH designations)	99
Kelp greenling (*Hexagrammos decagrammus*)	Yes (forage fish in the ecosystem component of the GOA and BSAI Groundfish FMPs)	98

Table A1.4. Number of unique stations and total number of stations-years sampled over the period 1999-2015 in Prince William Sound.

Gear	Number of unique stations sampled	Total number of stations-years sampled
Beach seine	75	99
Trawl	59	59
Jig	37	37
Purse seine	5	5
Gillnet	1	1

Table A1.5. Number of stations-years sampled over the period 1999-2015 where different species were encountered in Prince William Sound. Only species encountered in at least 50 stations-years are considered here. BSAI = Bering Sea and Aleutian Islands; EFH = essential fish habitat; FMP = fishery management plan; GOA = Gulf of Alaska.

Species	**Considered in an FMP?**	**Number of sampled stations-years where the species was encountered**
Pacific herring (*Clupea pallasii*)	Yes (prohibited species in the ecosystem component of the GOA and BSAI Groundfish FMPs)	90
Walleye pollock (*Gadus chalcogrammus)*	Yes (targeted species in the GOA and BSAI Groundfish FMPs, receive EFH designations)	88
Saffron cod (*Eleginus gracilis*)	Yes (Arctic FMP, receive EFH designations)	82
Crescent gunnel (*Pholis laeta*)	Yes (forage fish species in the ecosystem component of the GOA and BSAI Groundfish FMPs)	73

Appendix A2. Details of the *ShoreZone* habitat database.

ShoreZone is a coastal habitat classification and mapping system, which inventories the physical attributes (such as morphology, substrate and wave energy) and biological attributes (such as eelgrass and kelp bed characteristics) of the shoreline for most of the west and Arctic coasts of North America (Cook et al., 2017). The conceptual framework of *ShoreZone* was created in 1979 to allow for habitat classification and mapping of the Victoria area in British Columbia (Cook et al., 2017). Standardized protocols for imaging surveys and coastal habitat classification were established shortly thereafter (Owens 1980) and have been frequently updated. Cook et al. (2017) describes the latest version of these protocols. *ShoreZone* data for the nearshore areas of Alaska can be accessed via a user-friendly online query system (NMFS, 2020).

To populate *ShoreZone*, imaging surveys that typically employ helicopters are conducted to acquire oblique images and videos of the shoreline during the lowest tides of the year (Cook et al., 2017). *ShoreZone* uses the high-resolution aerial imagery to partition the coastline into relatively homogeneous linear segments called “units” and describes the physical and biological attributes of the supratidal, intertidal, and subtidal zones of these units (Cook et al., 2017). This physical and biological information stored in *ShoreZone* has many potential usages, including emergency and risk management, habitat and species modeling, marine spatial planning, public outreach and education, and detection of coastal changes such as coastline erosion (Harney, 2007; Cook et al., 2017).

The *ShoreZone* physical attributes that we considered to model nearshore fish habitats in Alaska included coastal class, physical wave exposure, Irribaren category (which defines wave morphology as spilling, plunging, collapsing or surging), aspect (shore normal compass direction that the *ShoreZone* unit faces), intertidal zone slope, and intertidal slope categories (Table A2.1). The coastal class factor has 39 potential levels, which allows one to distinguish between different intertidal coastal morphologies (wave-structured, riparian, anthropogenic, channel, glacial, lagoon, and periglacial); and, with respect to wave-structured *ShoreZone* units, between different shore types based on substrate, sediment, intertidal zone width, and intertidal zone slope (Cook et al., 2017). We derived a "coastal type" factor specific to each case study from the coastal class factor to model nearshore fish habitats in Alaska (Table A2.1 and Appendices A3 and A4).

The *ShoreZone* biological attributes that we considered to model nearshore fish habitats in Alaska included 19 "biobands" (e.g., eelgrass, rockweed (*Fucus distichus*), and soft brown kelps (*Saccharina latissima*, *Cystoseira* sp., *Sargassum muticum*)), as well as biological wave exposure and habitat class (Table A2.1). A bioband is an assemblage of coastal biota that is encountered on specific substrates and at characteristic across-shore elevations and wave energies (Cook et al., 2017). Each of the 19 biobands we considered for modeling nearshore fish habitats had three potential levels: continuous, patchy, and absent (none). Biological wave exposure is a factor derived from several *ShoreZone* biobands, which is very similar to the "physical wave exposure" factor. Finally, habitat class is a composite attribute that combines both physical and biological characteristics observed for a particular *ShoreZone* unit: coastal class, substrate mobility (determined in great part from several biobands), coastal type, and biological wave exposure (Table A2.1).

References of Appendix A2

Cook, S., Daley, S., Morrow, K., Ward, S., 2017. ShoreZone Coastal Imaging and Habitat Mapping Protocol. Report prepared by Coastal and Ocean Resources, Victoria, BC, Canada.

Harney, J.N., 2007. Modeling habitat capability for the non-native European green crab (*Carcinus maenas*) using the ShoreZone mapping system in Southeast Alaska, British Columbia, and Washington state. Report prepared for NOAA National Marine Fisheries Service by Coastal and Ocean Resources Inc, Victoria, BC, Canada (75 P).

National Marine Fisheries Service (NMFS), 2020b. Alaska ShoreZone coastal mapping and imagery. http://alaskafisheries.noaa.gov/shorezone/ (accessed 1 Feburary 2020).

Tables of Appendix A2

Table A2.1. Information provided in the *ShoreZone* database that was used for nearshore habitat modeling.

Factor/variable name	**Factor levels**	**Comments**
Coastal class	0 to 38	Alternatively, one can distinguish between 7 intertidal coastal morphologies rather than 38: wave-structured (0-30), riparian (31, 39), anthropogenic (32-33), channel (34), glacial (35), lagoon (36), and periglacial (37-38); see the "coastal type" factor
Coastal type	Variable	We derived this factor from the "coastal class" factor. The number and definition of coastal type levels depends on the case study under consideration (see Appendices A1 and A2)
Physical wave exposure	Very protected, protected, semi-protected, semi-exposed, exposed, very exposed	The "physical wave exposure" factor is derived from fetch measurements
Aspect	N, NE, E, SE, S, SW, W, NW	-
Intertidal zone slope	-	The slope of the intertidal zone is calculated from tidal height and intertidal zone width. The estimated slope can be converted into a slope category with levels: flat (0-1°), low incline (2-4°), moderate incline (5-10°), high incline (11-20°), steep (21-45°) and very steep (≥46°); see the "intertidal slope category"
Intertidal slope category	Flat, low incline, moderate incline, high incline, steep, very steep	This factor is derived from "intertidal zone slope" estimates; see above
Iribarren category	Spilling, plunging, collapsing, surging	The Iribarren category categorizes wave morphology. This factor is defined from the "physical wave exposure" factor and "intertidal slope" category. Therefore, either the Iribarren category or (the physical wave exposure and the intertidal slope category) should be included in a species distribution model, but not both
Eelgrass (*Zostera marina*)	Continuous, patchy, none	-
Dune grass (*Leymus mollis*)	Continuous, patchy, none	-
Sedges (*Carex lyngbyei*)	Continuous, patchy, none	-
Salt marsh	Continuous, patchy, none	The salt marsh bioband includes the following species: *Puccinellia* spp., *Plantago maritima*, *Glaux maritime*, and *Deschampsia* spp.
Dune grass, sedges and salt marsh	Continuous, patchy, none	-
Rockweed (*Fucus distichus*)	Continuous, patchy, none	-
Blue mussels (*Mytilus trossulus*)	Continuous, patchy, none	-
Green algae	Continuous, patchy, none	The green algae bioband includes the following species: *Ulva* sp., *Monostroma* sp., *Cladophora* sp., and *Acrosiphonia* sp.

1370 **Table A2.1.** Continued.

Factor/variable name	Factor levels	Comments
Red algae	Continuous, patchy, none	The red algae bioband includes the following species: *Corallina* sp., *Lithothamnion* sp., *Odonthalia* sp., *Neorhodomela* sp., *Palmaria* sp., *Neoptilota* sp., *Mazzaella* sp., *Porphyra pseudolanceolata*, *Porphyra hiberna*, and *Gracilaria* spp.
Alaria (*Alaria marginata*)	Continuous, patchy, none	-
Soft brown kelps	Continuous, patchy, none	The soft brown kelps bioband includes the following species: *Saccharina latissima*, *Cystoseira* sp., and *Sargassum muticum*
Dark brown kelps	Continuous, patchy, none	The dark brown kelps bioband includes the following species: *Laminaria setchelli*, *Lessoniopsis littoralis*, *Laminaria longipes*, and *Laminaria yeozensis*
Surfgrass (*Phyllospadix* sp.)	Continuous, patchy, none	
Canopy kelps	Continuous, patchy, none	A combination of the *ShoreZone* biobands bull kelp (*Nereocystis luetkeana*), dragon kelp (*Eularia fistulosa*) and giant kelp (*Macrocystis pyrifera*)
Tundra	Continuous, patchy, none	The tundra bioband includes the following species: *Salix* spp., *Vaccinium* spp., and *Dupontia fisheri*
European beach grass (*Ammophila* spp.)	Continuous, patchy, none	-
Mud flat shrimps	Continuous, patchy, none	The mud flat shrimps bioband includes the following species: *Neotrypaea californiensis*, and *Upogebia puggetensis*
Oyster (*Crassostrea gigas*)	Continuous, patchy, none	-
Shrub meadow	Continuous, patchy, none	The shrub meadow bioband includes the following species: *Deschampsia caespitosa*, and *Picea sitchensis*
Biological wave exposure		This factor is derived from several *ShoreZone* biobands. It is very similar to the "physical wave exposure" factor
Habitat class		This factor combines both physical and biological characteristics observed for a particular *ShoreZone* unit: coastal class, substrate mobility (determined in great part from several biobands), coastal type and biological wave exposure. Thus, the habitat class factor is a composite attribute that should be included in a species distribution model only if the attributes used to derive the habitat class factor are not included in the species distribution model as well

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Appendix A3. Additional details of nearshore habitat modeling efforts for Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area.

We applied our nearshore habitat modeling approach to Pacific cod early juveniles (≤15 cm TL) of the northern southeastern Alaska (NSEA) area. For this application, we relied on survey data collected over the period 1998-2013. Although trawl and purse seine surveys collected a few Pacific cods in the NSEA area, we employed only beach seine survey data for this application. Pacific cods (all life stages combined, measured and unmeasured) were encountered at 65 of the 397 stations-years sampled by beach seine surveys over the period 1998-2013; Pacific cod early juveniles were encountered at 58 of these stations-years, Pacific cod late juveniles (15-42 cm TL) were encountered at 2 of these stations-years, and Pacific cod adults (>42 cm TL) were encountered at none of these stations-years (Table A3.1 and Fig. A3.1). Pacific cod early juveniles were encountered by beach seine surveys in the NSEA area in all years of the period 1998-2013, except 2002 and 2011 (Table A3.2). The year 1998 was the most frequent year level from the encounter/non-encounter dataset, and the year 2006 was the most frequent year level from the non-zero catch-per-unit-effort (CPUE) dataset.

Sampling effort for this application was the distance sampled by the beach seine (in m). NRC (1989) reported three ways to estimate the area sampled by beach seine surveys (in m^2): (1) multiplying net width by the distance sampled; (2) calculating the area of a circle whose circumference is the net width; and (3) multiplying net width by the average width of a tidal slough. For the NSEA area, we do not know the distance sampled by beach seines, although we know net width. Therefore, using (1) and (2), we estimated the distance sampled by beach seines for the present application.

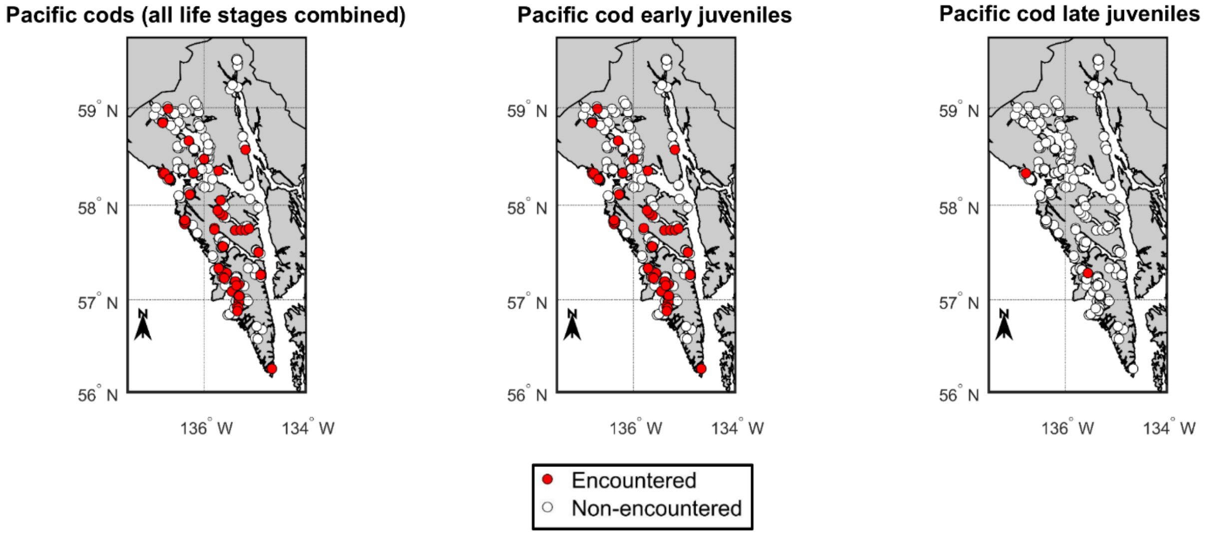
The literature suggested including the following fixed effect habitat factors in the initial (full) generalized additive models (GAMs) of Pacific cod early juveniles of the NSEA area: coastal type, physical wave exposure, eelgrass (*Zostera marina*), rockweed (*Fucus* *distichus*), and soft brown kelps (*Saccharina latissima*, *Cystoseira* sp. and *Sargassum muticum*). Because the amount of survey data available for Pacific cod early juveniles of the NSEA area was limited, we needed to redefine the levels of two of the fixed effect habitat factors to be able to fit the GAMs: coastal type, and physical wave exposure (Table A3.3 and Fig. A3.2).

References of Appendix A3

NRC, 1989. Outer Continental Shelf Environmental Assessment Program: Final Reports of Principal Investigators. Volume 63. National Oceanic and Atmospheric Administration, National Ocean Service, Anchorage, AK.

Figures of Appendix A3

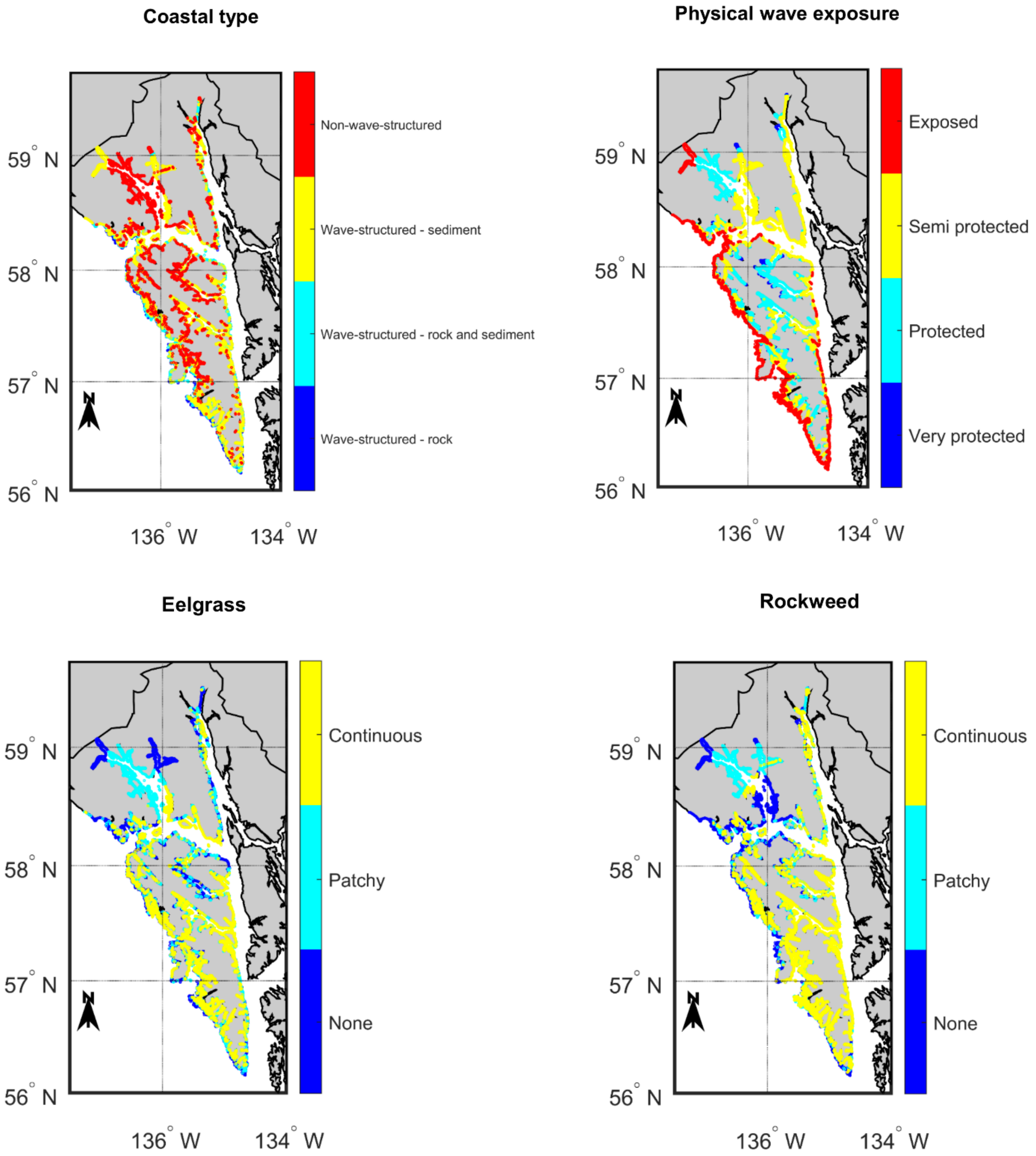
Fig. A3.1. Beach seine stations of the northern southeastern Alaska area where Pacific cods (*Gadus macrocephalus*; all life stages combined, measured and unmeasured), Pacific cod early juveniles (≤15 cm TL) and Pacific cod late juveniles (15-42 cm TL) were encountered in at least one year of the period 1998-2013 or not encountered at all over the period 1998-2013.

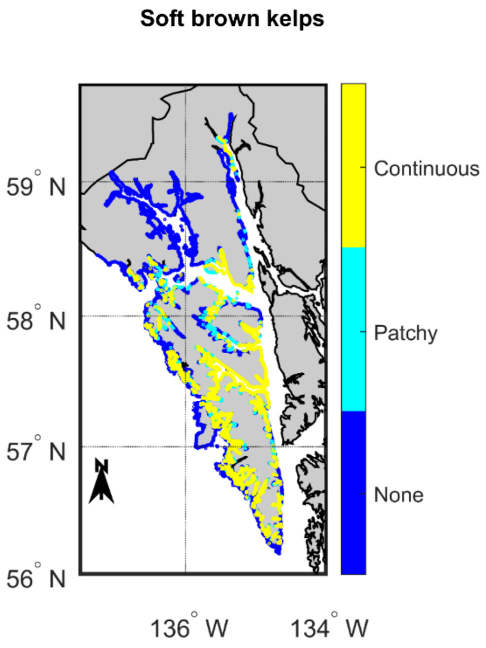

Pacific cods (all life stages combined)

Pacific cod early juveniles

Pacific cod late juveniles

Fig. A3.2. Information provided by the *ShoreZone* database that was used for Pacific cod (*Gadus macrocephalus*) early juveniles (≤15 cm TL) of the northern southeastern Alaska area. See also Table A3.3.





Soft brown kelps

Tables of Appendix A3

Table A3.1. Number of stations-years sampled using beach seine over the period 1998-2013 where Pacific cods (*Gadus macrocephalus*; all life stages combined, measured and unmeasured), Pacific cod early juveniles (≤15 cm TL), Pacific cod late juveniles (15-42 cm TL) and Pacific cod adults (>42 cm TL) were encountered in the northern southeastern Alaska area.

Number of stations-years sampled where Pacific cods (all life stages combined, measured and unmeasured) were encountered	65
Number of stations-years sampled where Pacific cod early juveniles were encountered	58
Number of stations-years sampled where Pacific cod late juveniles were encountered	2
Number of stations-years sampled where Pacific cod adults were encountered	0

Table A3.2. Number of beach seine stations of the northern southeastern Alaska area where Pacific cods (*Gadus macrocephalus*; all life stages combined, measured and unmeasured), Pacific cod early juveniles (≤15 cm TL) and Pacific cod late juveniles (15-42 cm TL) were encountered in each sampling year.

Sampling year	**Number of beach seine stations where Pacific cods (all life stages combined, unmeasured and measured) were encountered**	**Number of beach seine stations where Pacific cod early juveniles were encountered**	**Number of beach seine stations where Pacific cod late juveniles were encountered**
1998	4	4	0
1999	9	6	0
2000	9	9	0
2001	2	0	0
2002	8	6	0
2003	2	2	0
2006	15	15	0
2009	1	1	0
2010	12	12	0
2011	0	0	0
2013	3	3	2

Table A3.3. Changes made to the information provided by the *ShoreZone* database for the application to Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area.

Factor	**Changes made**
Coastal type	Coastal type factor levels were defined from the "coastal class" factor as follows: "wave-structured – rock" (coastal classes 1-5), "wave-structured – rock and sediment" (coastal classes 6-20), "wave-structured – sediment" (coastal classes 21-30), and "non-wave-structured" (coastal classes 31-35)
Physical wave exposure	The "semi-exposed" and "exposed" factor levels were merged into one unique "exposed" level

Appendix A4. Additional details of nearshore habitat modeling efforts for walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound.

We applied our nearshore habitat modeling approach to walleye pollock early juveniles (≤14 cm TL) of Prince William Sound (PWS). For this application, we relied on survey data collected over the period 1999-2015. Although purse seine and jig surveys collected a few walleye pollocks in PWS, we employed only beach seine and trawl survey data for this application. Walleye pollocks (all life stages combined, measured and unmeasured) were encountered at 21 of the 99 stations-years sampled by beach seine surveys over the period 1999-2015; walleye pollock early juveniles were also encountered at 21 of these stations-years, walleye pollock late juveniles (14-37 cm TL) were encountered at one of these stations-years, and walleye pollock adults (>37 cm TL) were encountered at none of these stations-years (Table A4.1 and Fig. A4.1). Moreover, walleye pollocks (all life stages combined, measured and unmeasured) were encountered at 54 of the 58 stations-years sampled by trawl surveys over the period 1999-2015; walleye pollock early juveniles were encountered at 50 of these stations-years, walleye pollock late juveniles were encountered at 16 of these stations-years, and walleye pollock adults were encountered at 7 of these stations-years (Table A4.1 and Fig. A4.1). Walleye pollock early juveniles were not encountered by beach seine or trawl surveys in PWS in many years of the period 1999-2015, particularly prior to 2006 (Table A4.2). Beach seine was the most frequent gear level from the encounter/non-encounter dataset, and trawl was the most frequent gear level from the non-zero catch-per-unit-effort (CPUE) dataset. The year 2012 was the most frequent year level from both the encounter/non-encounter and non-zero CPUE datasets.

Sampling effort for beach seine surveys was the distance sampled by the beach seine (in m). NRC (1989) reported three ways to estimate the area sampled by beach seine surveys (in m^2): (1) multiplying net width by the distance sampled; (2) calculating the area of a circle whose circumference is the net width; and (3) multiplying net width by the average width of a tidal slough. For PWS, we do not know the distance sampled by beach seines, although we know net width. Therefore, using (1) and (2), we estimated the distance sampled by beach seine surveys in PWS.

Sampling effort for trawl surveys was the distance sampled by the trawl (in m). We determined the distance sampled by each trawl tow by calculating the Euclidian distance between the start and end points of the trawl tow (Grüss and Thorson, 2019).

The literature suggested including the following fixed effect habitat factors in the initial (full) generalized additive models (GAMs) of walleye pollock early juveniles of PWS: coastal type, physical wave exposure, eelgrass (*Zostera marina*), rockweed (*Fucus distichus*), and soft brown kelps (*Saccharina latissima*, *Cystoseira* sp. and *Sargassum muticum*). Because the amount of survey data available for walleye pollock early juveniles of PWS was limited, we needed to redefine the levels of two of the fixed effect habitat factors to be able to fit the GAMs: coastal type, and physical wave exposure (Table A4.3 and Fig. A4.2).

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Figures of Appendix A4

Fig. A4.1. Beach seine and trawl stations of Prince William Sound where walleye pollocks (*Gadus chalcogrammus*; all life stages combined, measured and unmeasured), walleye pollock early juveniles (≤14 cm TL), walleye pollock late juveniles (14-37 cm TL) and walleye pollock adults (>37 cm TL) were encountered in at least one year of the period 1999-2015 or not encountered at all over the period 1999-2015.

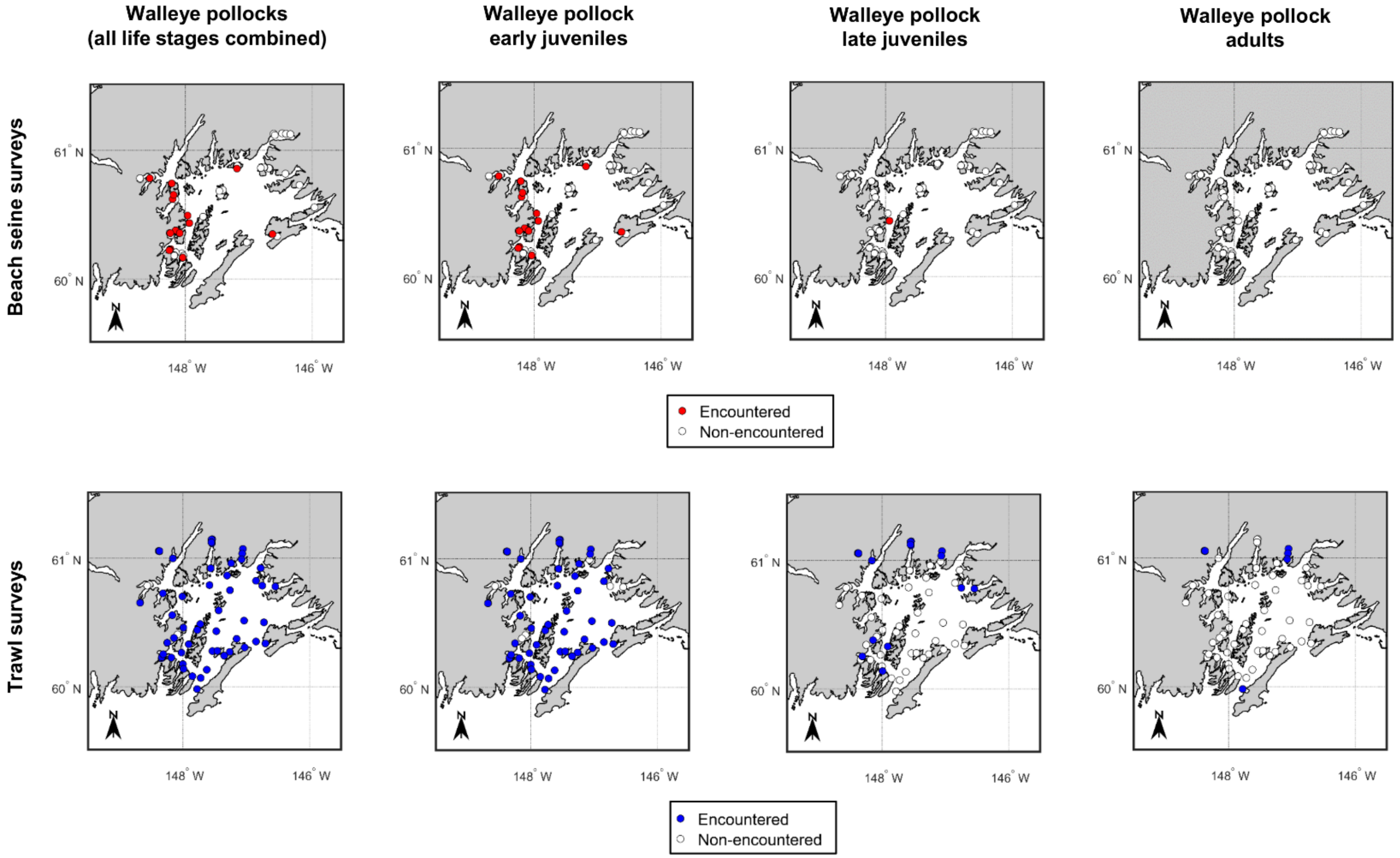
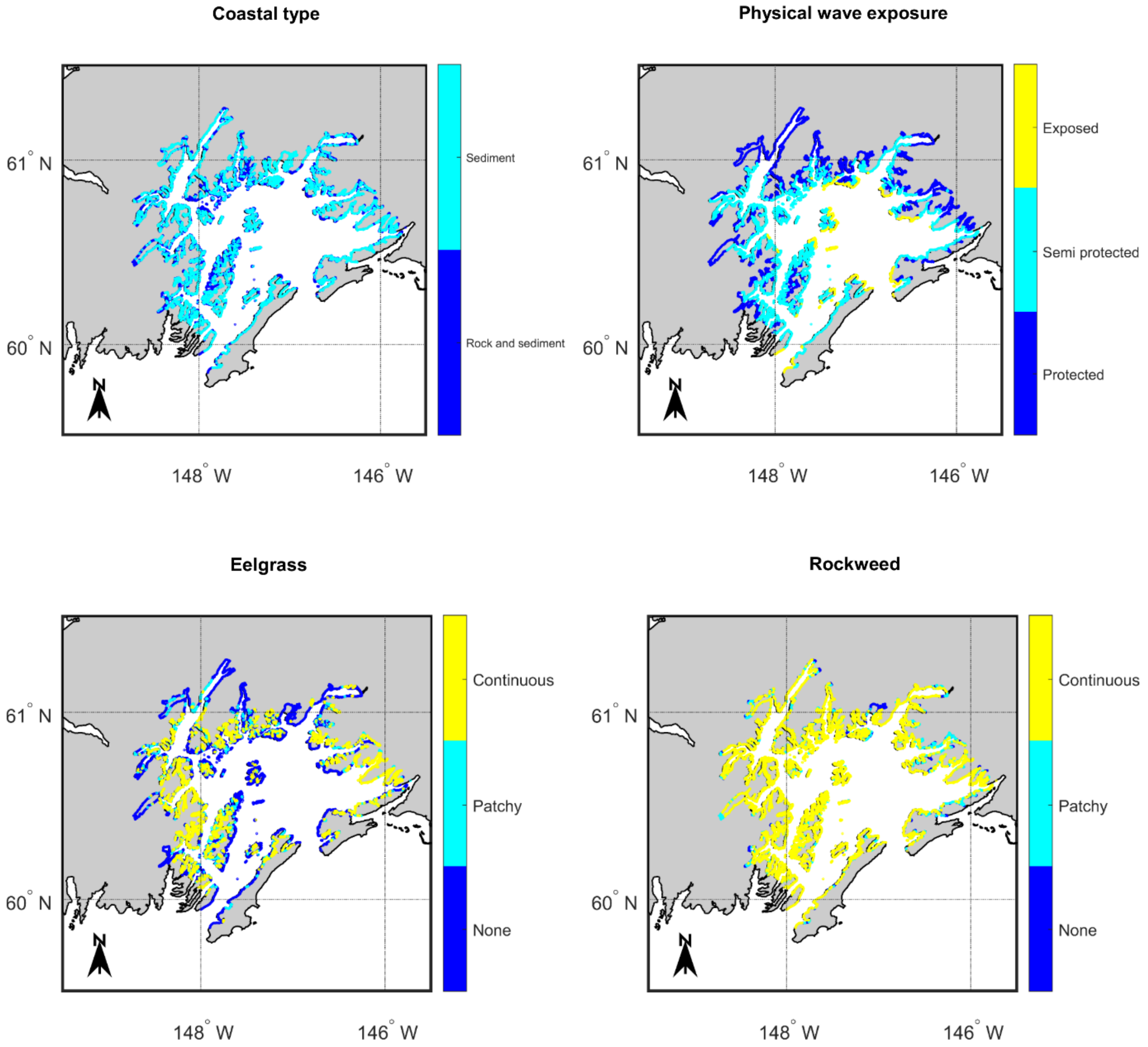
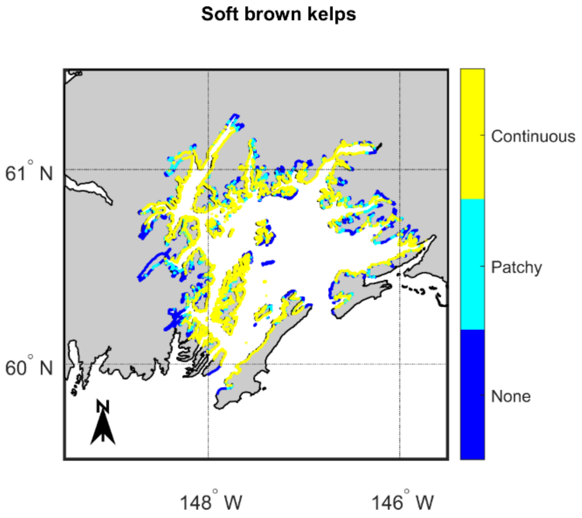


Fig. A4.2. Information provided by the *ShoreZone* database that was used for walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound. See also Table A4.3.





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Tables of Appendix A4

Table A4.1. Number of stations-years sampled using beach seine and trawl over the period 1999-2015 where walleye pollocks (*Gadus chalcogrammus*; all life stages combined, measured and unmeasured), walleye pollock early juveniles (≤14 cm TL), walleye pollock late juveniles (14-37 cm TL) and walleye pollock adults (>37 cm TL) were encountered in Prince William Sound.

Number of stations-years sampled using beach seine where walleye pollocks (all life stages combined, measured and unmeasured) were encountered	21
Number of stations-years sampled using trawl where walleye pollocks (all life stages combined, measured and unmeasured) were encountered	54
Number of stations-years sampled using beach seine where walleye pollock early juveniles were encountered	21
Number of stations-years sampled using trawl where walleye pollock early juveniles were encountered	50
Number of stations-years sampled using beach seine where walleye pollock late juveniles were encountered	1
Number of stations-years sampled using trawl where walleye pollock late juveniles were encountered	16
Number of stations-years sampled using beach seine where walleye pollock adults were encountered	0
Number of stations-years sampled using trawl where walleye pollock adults were encountered	7

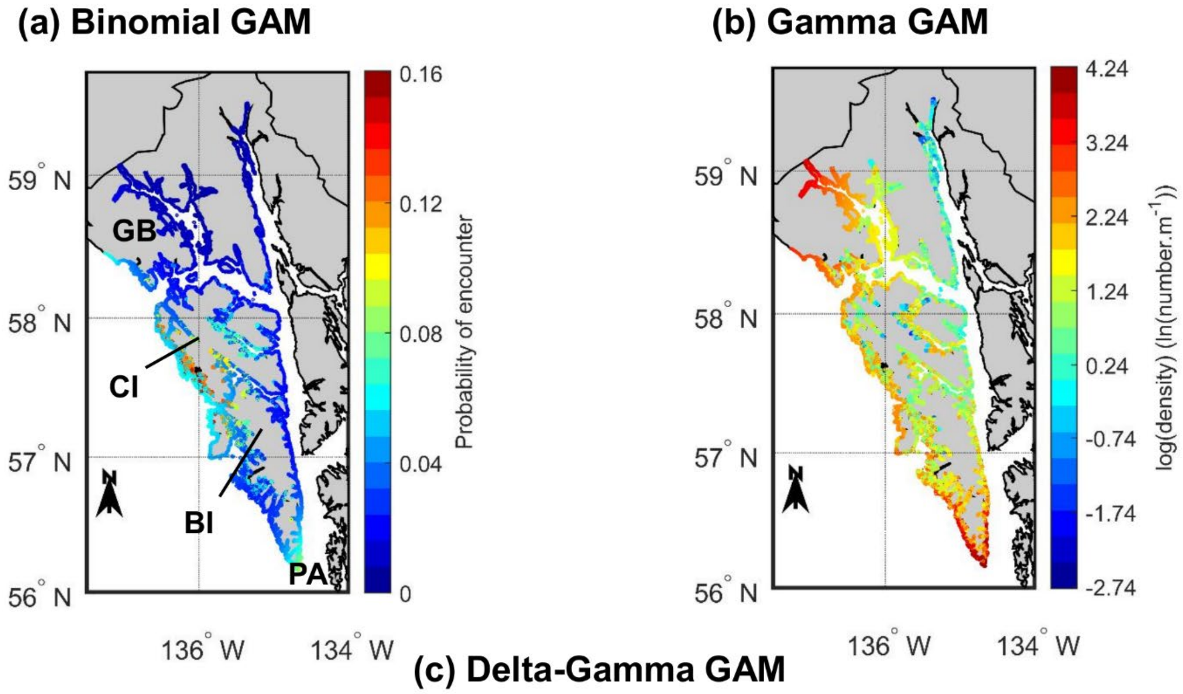
Table A4.2. Number of beach seine and trawl stations of Prince William Sound where walleye pollocks (*Gadus chalcogrammus*; all life stages combined, measured and unmeasured), walleye pollock early juveniles (≤14 cm TL), walleye pollock late juveniles (14-37 cm TL) and walleye pollock adults (>37 cm TL) were encountered in each sampling year

Sampling year	**Number of beach seine stations where walleye pollocks (all life stages combined, unmeasured and measured) were encountered**	**Number of trawl stations where walleye pollocks (all life stages combined, unmeasured and measured) were encountered**	**Number of beach seine stations where walleye pollock early juveniles were encountered**	**Number of trawl stations where walleye pollock early juveniles were encountered**	**Number of beach seine stations where walleye pollock late juveniles were encountered**	**Number of trawl stations where walleye pollock late juveniles were encountered**	**Number of trawl stations where walleye pollock adults were encountered**
1999	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0
2006	11	0	11	0	0	0	0
2007	6	0	6	0	0	0	0
2009	0	0	0	0	0	0	0
2010	0	0	0	0	0	0	0
2012	3	30	3	30	1	7	4
2013	1	8	1	7	0	3	1
2014	0	5	0	4	0	1	0
2015	0	11	0	9	0	5	2

Table A4.3. Changes made to the information provided by the *ShoreZone* database for the application to walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound.

Factor	**Changes made**
Coastal type	Coastal type factor levels were defined from the “coastal class” factor as follows: “rock and sediment” (coastal classes 1-20 and 31-35), and “sediment” (coastal classes 21-30)
Physical wave exposure	The “semi-exposed” and “exposed” factor levels were merged into one unique “exposed” level; and the “semi-protected” and “protected” factor levels were merged into one unique “protected” level

Fig. A5. Spatial patterns of (a) probability of encounter predicted by the binomial generalized additive model (GAM), (b) log(density) (in number.m^{-1}) predicted by the Gamma GAM, and (c) log(density) (in number.m^{-1}) predicted by delta-Gamma GAM for Pacific cod (*Gadus macrocephalus*) early juveniles of the northern southeastern Alaska area. GB = Glacier Bay National Park and Preserve; CI = Chichagof Island; BI = Baranof Island; PA = Port Alexander area.


(a) Binomial GAM
(b) Gamma GAM

(c) Delta-Gamma GAM

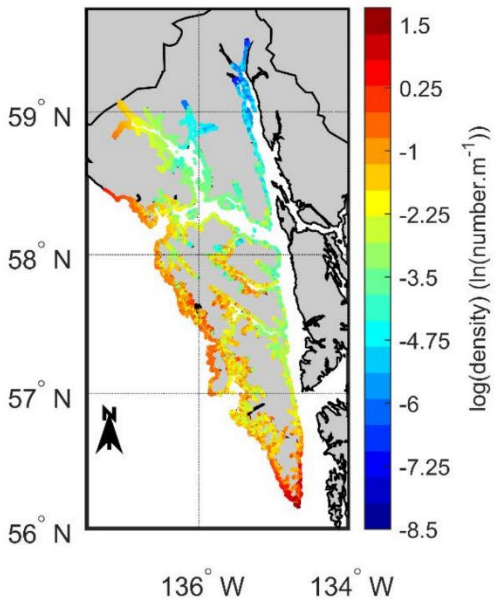
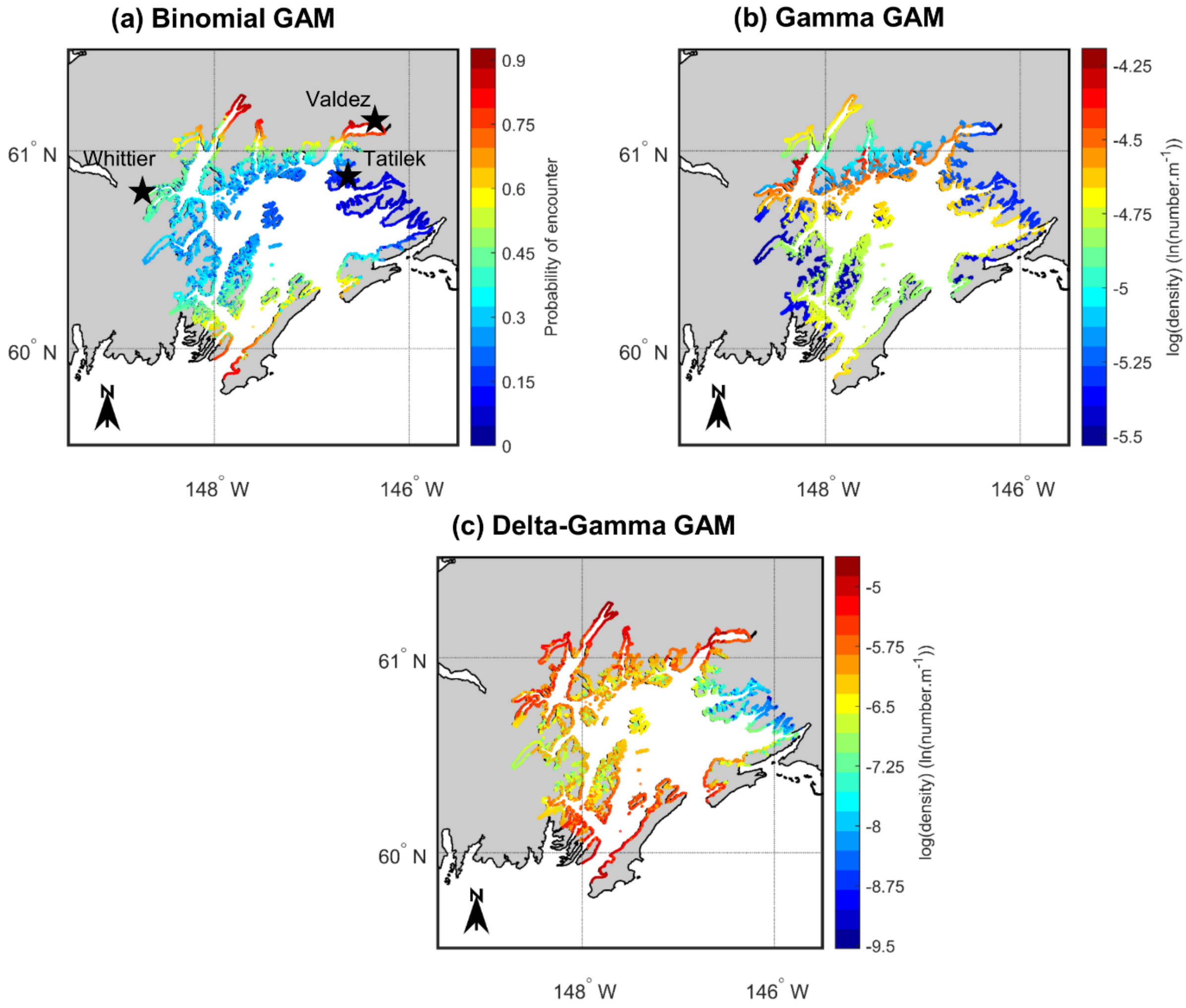


Fig. A6. Spatial patterns of (a) probability of encounter predicted by the binomial generalized additive model (GAM), (b) log(density) (in number.m^{-1}) predicted by the Gamma GAM, and (c) log(density) (in number.m^{-1}) predicted by delta-Gamma GAM for walleye pollock (*Gadus chalcogrammus*) early juveniles of Prince William Sound.



Appendix A7. Further using and improving fish survey and habitat databases in Alaska and the U.S. Gulf of Mexico (U.S. GOM).

Alaska and the U.S. GOM are two geographically distinct areas that are managed by National Marine Fisheries Service (NMFS) and regional fishery management councils by authority of the Magnuson-Stevens Fishery Conservation and Management Act (MSA) with respect to fisheries and essential fish habitat (EFH). We here discuss how fish survey and habitat databases in Alaska and the U.S. GOM can be further used and improved with respect with meeting fisheries management and conservation needs for nearshore coastal areas.

The Nearshore Fish Atlas (NFA) database and the habitat database *ShoreZone* employed in the present study are invaluable resources for modeling and mapping nearshore fish habitats. The large amount of survey data available for numerous Alaska nearshore areas via the NFA also allows for extensive ecological investigations. These extensive ecological investigations include, *inter alia*, understanding spatial variations in species distribution patterns, species assemblages and species richness (Johnson et al., 2012), and identifying indicator species to track the changes in fish assemblages that may result from climate change (Johnson and Thedinga, 2005). The large amount of fine-scale habitat information available for almost all the Alaska coastline via *ShoreZone* also allows, among other things, for analyses to assist emergency and risk management in nearshore areas, inform marine spatial planning, and detect coastal changes over time such as coastline erosion (Cook et al., 2017). Many issues could not be tackled without combining the information provided by the NFA and *ShoreZone* databases. For example, without combining the information provided by these two resources, it would not be possible to describe the spatial patterns of probability of encounter and density of forage fish species in The Brothers Islands area in relation to habitat characteristics, and then determine the degree of overlap between forage fish hotspots and Steller sea lion haulouts (Thedinga et al., 2006; Johnson et al., 2012).

The NFA and *ShoreZone* databases, as well as the nearshore habitat modeling and mapping efforts reported in this study, are relatively unique and will establish a strong reference for similar developments and efforts in other marine regions. Somewhat similar developments and efforts were made in the U.S. GOM. In the early 2010s, all the survey data collected in U.S. GOM estuaries using 4.9-m and 6.1-m trawls were gathered in a large database called CAGES (Comparative Assessment of Gulf Estuarine Systems; Brown et al., 2013). More recently, Grüss et al. (2018) compiled a larger database gathering all the fisheries-independent and fisheries-dependent data collected in the U.S. GOM using random sampling schemes. This larger database includes some of the data stored in CAGES, as well as other survey data collected in nearshore ecosystems of the U.S. GOM using random sampling schemes (Grüss et al., 2018). However, the large monitoring database for the U.S. GOM does not include the large amount of survey data collected at fixed sampling stations in nearshore areas of the U.S. GOM, particularly in Louisiana nearshore areas. Moreover, nearshore habitat information for the U.S. GOM is not available via a centralized database like *ShoreZone*, but rather via individual resources for the entire U.S. GOM (e.g., oyster beds; Anson et al., 2011; mangroves; Osland et al., 2013) or individual resources for the individual U.S. GOM states (e.g., seagrass; see Love et al. (2015) for a review). Therefore, we encourage future studies to (1) expand the large monitoring database for the U.S. GOM, so that it also includes the survey data collected at fixed sampling stations in nearshore areas of the U.S. GOM; (2) create an equivalent of *ShoreZone* for the entire U.S. GOM; and (3) leverage the expanded large monitoring database and the equivalent of *ShoreZone* for the U.S. GOM to address the pressing ecological and management issues that pertain to nearshore ecosystems of the U.S. GOM. Similar recommendations apply to other regions of the U.S. and globally to integrate existing, disparate habitat datasets in a centralized database and to map coastal nearshore locations, using a continuous and standardized mapping protocol such as *ShoreZone*.

Although the NFA currently provides a large amount of survey data, some data gaps need to be filled. Importantly, as of October 2019, around 79% of the data entries of the NFA were for the Gulf of Alaska (GOA). Therefore, there is a clear need to obtain more data entries for the other Alaska regions, namely the Aleutian Islands, the Bering Sea, and the Arctic region. Moreover, even if the amount of survey data available for the GOA region via the NFA is substantial, some locales of the GOA are currently data-poor. For example, no nearshore survey data exists for the Copper River area south to Yakutat Bay (Appendix A1), where these large river systems support forage fishes such as eulachon (*Thaleichthys pacificus*), Pacific sand lance (*Ammodytes personatus*) and Pacific herring (*Clupea pallasii*), as well as abundant outmigrations of Pacific salmon species transitioning as juveniles to marine waters (Moffitt et al., 2002; Dozier et al., 2005; Powers et al., 2007; Savereide, 2015). Another example is the northern southeastern Alaska area, where fewer survey data are currently available for the Southeast Northern Inside (SENI) area compared to the Southeast Northern Outside (SENO) area (Appendix A1). Moreover, sufficiently large time series are needed to allow for spatio-temporal analyses with the NFA. In particular, there are concerns about the potential impacts of climate change in the nearshore areas of Alaska regions, including the consequences of resulting beach erosion and the appearance and/or disappearance of species (Johnson et al., 2012; Gibbs and Richmond, 2015), and these concerns can be addressed only if sufficiently large time series of survey data are available for the fish species and life stages of interest.

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