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Distribution of juvenile Pacific herring relative to environmental and geospatial factors in Prince William Sound, Alaska

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ABSTRACT

Documenting distribution patterns of juvenile Pacific herring (*Clupea pallasii*) can clarify habitat preferences and provide insight into ecological factors influencing early life survival. However, few analyses relating juvenile Pacific herring density to habitat characteristics have been conducted. We sampled age-0 Pacific herring in nine bays and fjords distributed throughout Alaska's Prince William Sound during November over a 3-year period (2013–2015) and investigated associations between catch rate and habitat covariates using generalized linear mixed models. Our results indicated that the night-time distribution of age-0 Pacific herring in the pelagic environment was influenced by proximity to eelgrass (*Zostera marina*) beds, salinity, and water depth. Age-0 Pacific herring catch rate was negatively associated with tow depth, with herring favoring shallower water across the range of depths sampled (7.2–35.4 m). In addition, Pacific herring distribution was positively associated with fresher water within the sampled salinity gradient (24.1–32.3 psu) and proximity to eelgrass beds. Seasonal changes in juvenile Pacific herring distribution were investigated by sampling one bay over a seven month period (October-April). Age-0 Pacific herring tended to remain in the inner bay region throughout the seven months, while age-1 Pacific herring had shifted from the inner to the outer bay by spring (March-April). Additionally, catch rate of age-0 Pacific herring in areas where ice breakup had just occurred was higher than in open water, suggesting that age-0 herring preferentially select ice-covered habitats when available. Based on our results we recommend that habitat preferences of age-0 Pacific herring should be considered in the development of Pacific herring year-class strength indices from catch data.

1. Introduction

Pacific herring *(Clupea pallasii)* is a widely distributed pelagic forage fish with life-history adaptations that allow the species to thrive in many regional ecosystems throughout the North Pacific Ocean. They are aggregate spawners that converge on spawning grounds with remarkable synchrony (Hay, 1985). Dispersal is an important ecological process for Pacific herring larvae because spawning grounds often do not overlap spatially with nursery habitat (Norcross et al., 2001). From an evolutionary perspective, this spatial mismatch between spawning and nursery habitat indicates that habitat favorable to Pacific herring juvenile survival are not necessarily favorable to the fertilization and survival of eggs (Ciannelli et al., 2015). Larvae are transported from spawning grounds to nursery areas by oceanic currents (Norcross et al., 2001). As larval herring develop and grow in size, locomotion becomes an increasingly important dispersal mechanism because the metabolic cost of movement declines (Maes et al., 2005). Under this dispersal model, larval herring are transported by ocean currents and subsequently actively congregate in areas with favorable environmental conditions for early life survival (Hourston, 1959). However, the biological and physical characteristics of habitats that are associated with juvenile herring congregations are not well understood and further investigation is warranted (Stokesbury et al., 2000). Mechanistic distribution models relating juvenile Pacific herring density to environmental and geospatial factors (spatial data relating habitat features to local geography) can provide insight into habitat types that provide quality nursery habitat (Elith and Leathwick, 2009).

Hypotheses relating to early life survival can be investigated through examination of distribution patterns. By combining distribution data with current modeling, Ciannelli et al. (2007) examined spatiotemporal trends in survival of age-0 Atlantic cod (*Gadus morhua*). Survival was negatively associated with older conspecifics and age-0 abundance, suggesting that predation and competition were important mechanisms influencing survival (Ciannelli et al., 2007). Bottom-up control on juvenile capelin *(Mallosus villosus)* and age-0 walleye pollock (*Gadus chalcogrammus)* was examined using trawl catch data (Logerwell

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et al., 2010). Distribution of capelin and walleye pollock was influenced by densities of preferred zooplankton prey and both species exhibited pelagic habitat selection (Logerwell et al., 2010). Finally, changes in juvenile red snapper (*Lutjanus campechanus*) distribution among years with varying hypoxia severity revealed that age-0 juveniles were driven into deeper, cooler habitat during years with high hypoxia severity (Switzer et al., 2015). Based on this observed habitat shift and an association between hypoxia severity and adult recruitment, Switzer et al. (2015) hypothesized that hypoxic conditions reduced the extent of high quality nursery habitat. These examples illustrate that when relevant covariates are measured, empirical distribution data can be used to clarify ecological mechanisms influencing distribution and survival of juvenile fishes.

In southcentral Alaska, the Prince William Sound (PWS) Pacific herring population historically supported regionally important commercial fisheries. These fisheries were closed in 1989 due to contamination concerns from the 1989 *Exxon Valdez* oil spill, intermittently reopened, and closed again in 1999 due to precipitous biomass declines (Botz et al., 2013). While the cause and timing of the biomass decline are debated (Carls et al., 2002; Pearson et al., 2012; Thomas and Thorne, 2003; Thorne and Thomas, 2015, 2008), reduced biomass levels have persisted (Botz et al., 2013).

Early life survival and disease-induced mortality are hypothesized drivers of PWS Pacific herring population dynamics. The disease hypothesis was supported by modeling efforts: stock-assessment models for PWS Pacific herring were improved by including time-varying natural mortality rates associated with indices of disease prevalence (Marty et al., 2003). Additionally, several hypotheses regarding ecological controls on early life survival have been proposed: predation by marine birds and fishes (Bishop et al., 2015; Bishop and Powers, 2013), variable zooplankton transport from the Gulf of Alaska into PWS (Kline, 1999), competition and predation from hatchery-reared juvenile pink salmon (*Oncorhynchus gorbuscha*; Pearson et al., 2012), poor nutrition associated with oceanic factors (Pearson et al., 2012), and overwinter survival of age-0 herring (Norcross et al., 2001). These mechanisms are related; reduced zooplankton availability can lead to lowered body condition which, in turn, increases susceptibility to disease. Lowered body condition, poor nutrition, reduced overwinter survival, and high predation rates are all associated with reduced early life survival.

Juvenile Pacific herring distribution and habitat preferences provide insight into early life survival strategies. Thus, management and conservation of Pacific herring in PWS could be advanced by increased understanding of juvenile distribution patterns. Previous research indicates that juvenile Pacific herring tend to aggregate in sheltered pelagic areas near the heads of bays (Abookire et al., 2000; Hourston, 1959; Stokesbury et al., 2000). Additionally, seasonal distribution patterns have been documented (Stokesbury et al., 2000). However, the factors influencing juvenile herring distribution are unclear because few analyses relating juvenile Pacific herring density to specific habitat characteristics have been conducted.

We developed predictive models of juvenile herring distribution by investigating associations between juvenile herring catch rates and environmental and geospatial factors. Catch data from night-time midwater trawl tows conducted during November in PWS bays and fjords thought to contain relatively high densities of juvenile Pacific herring were used to accomplish this objective. Bottom depth and distance to shore, geospatial factors negatively associated with inner-bay habitat, were considered potential predictors of juvenile Pacific herring distribution. Juvenile Pacific herring density was hypothesized to be negatively associated with bottom depth and distance from shore based on previous documentation of aggregations near bay heads in PWS (Stokesbury et al., 2000). However, the predictive capacity of distance from shore may depend upon shoreline habitat. Age-0 herring catch rates were higher in habitats containing eelgrass (*Zostera marina*) compared to kelp (Laminariales) or rock in PWS nearshore habitats during the summer (Johnson et al., 2010). As such, we hypothesized that proximity to shoreline containing eelgrass habitat may be a better predictor of juvenile herring distribution than proximity to shoreline.

Thermohaline conditions were also considered potential predictive factors. Salinity was hypothesized to be positively associated with juvenile Pacific herring distribution because PWS has a considerable salinity gradient due to large freshwater inputs (Niebauer et al., 1994) and salinity is positively associated with the distribution of other estuarine fishes (Boehlert and Mundy, 1988). We hypothesized that juvenile herring would tend to congregate in higher temperature areas because temperatures within PWS bays and fjords were highest near bay heads during October (Gay and Vaughan, 2001), suggesting that temperature could be an important aspect of inner-bay habitat driving distribution of juvenile Pacific herring. Finally, clupeids tend to congregate higher in the water column at night (Cardinale et al., 2003; Huse and Korneliussen, 2000; Thorne and Thomas, 1990). Based on this behavior, we predicted that tow depth would be negatively associated with juvenile Pacific herring catch rates.

We also investigated temporal dynamics of distribution patterns in one location (Simpson Bay) to determine if seasonal changes depended upon age class. We hypothesized that both age-0 and age-1 herring would tend to occupy inner-bay habitat during winter and move into outer-bay habitat during spring. Age-0 and age-1 PWS Pacific herring have previously been documented in mixed schools within inner-bay regions during October and farther offshore by March (Stokesbury et al., 2000). Differences in seasonal distribution may be due to forage availability. During October zooplankton densities are higher and can support energetic requirements of higher densities of juvenile herring, whereas during March zooplankton densities are lower and finding adequate forage may require dispersal throughout a larger area (Norcross et al., 2001).

Finally, ice cover may be a characteristic of inner-bay habitat important to juvenile herring. Within PWS, sea surface temperatures in the fjords can be as low as 1 °C in late winter and some inner bays and fjords become choked with ice (Gay and Vaughan, 2001). We qualitatively assessed the effects of ice cover on juvenile herring distribution patterns by sampling areas near the head of Simpson Bay within 24 h of ice breakup. This comparison allowed us to investigate the influence of ice cover on juvenile herring distribution patterns.

2. Materials and methods

2.1. Study area

Prince William Sound is a large embayment along the coast of south-central Alaska, primarily between 60° and 61° N, and is separated from the adjacent Gulf of Alaska by large, mountainous islands. A number of marine passageways provide access to the sound, including Hinchinbrook Entrance and Montague Strait (Fig. 1). The PWS coastline is rugged and irregular with numerous islands, fjords, and bays. Bays and fjords are diverse, with average depths ranging from < 50 m (typically referred to as bays) to > 400 m (typically fjords). Outside the bays and fjords are basins and passages of varying depths down to 700 m. There are several large icefields and more than 20 tidewater glaciers (Molnia, 2001). The northern half of PWS is strongly influenced by glacial runoff in the fjords and tends to be colder and fresher relative to the ACC-influenced waters that are warmer and more saline (Wang et al., 2001). Abundant rain, snow, and glacial melt result in a strong cyclonic circulation that generally travels east to west (Niebauer et al., 1994). Finally, during summer the waters of PWS are highly stratified, but during winter months they are more mixed (Niebauer et al., 1994).

2.2. Field methods

Nine locations distributed throughout PWS were sampled for juvenile herring during November 2013, 2014, and 2015: Windy Bay, Simpson Bay, Port Gravina, Port Fidalgo, Eaglek Bay, Lower Herring