Pacific herring − *Clupea pallasii*

Overall Vulnerability Rank = Low

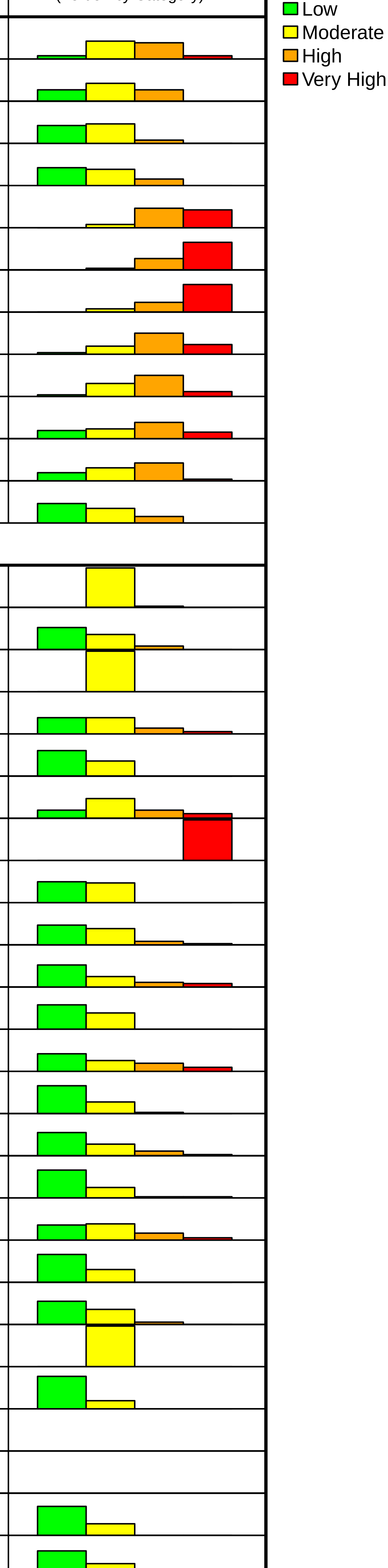
Biological Sensitivity = High

Climate Exposure = Low

Sensitivity Data Quality = 92% of scores ≥ 2

Exposure Data Quality = 64% of scores ≥ 2

	Clupea pallasii	Expert Scores	Data Quality	Expert Scores Plots (Portion by Category)
Sensitivity attributes	Habitat Specificity	2.5	2.2	
	Prey Specificity	2.0	2.2	
	Adult Mobility	1.6	2.4	
	Dispersal of Early Life Stages	1.7	2.4	
	Early Life History Survival and Settlement Requirements	3.4	2.2	
	Complexity in Reproductive Strategy	3.6	2.6	
	Spawning Cycle	3.6	3.0	
	Sensitivity to Temperature	3.0	2.4	
	Sensitivity to Ocean Acidification	2.7	2.0	
	Population Growth Rate	2.5	2.2	
	Stock Size/Status	2.3	2.4	
	Other Stressors	1.7	1.8	
	Sensitivity Score	High		
Exposure factors	Sea Surface Temperature	2.0	2.5	
	Sea Surface Temperature (variance)	1.5	2.5	
	Bottom Temperature	2.0	3.0	
	Bottom Temperature (variance)	1.9	3.0	
	Salinity	1.4	2.0	
	Salinity (variance)	2.2	2.0	
	Ocean Acidification	4.0	3.0	
	Ocean Acidification (variance)	1.5	3.0	
	Phytoplankton Biomass	1.7	1.2	
	Phytoplankton Biomass (variance)	1.7	1.2	
	Plankton Bloom Timing	1.4	1.0	
	Plankton Bloom Timing (variance)	2.0	1.0	
	Large Zooplankton Biomass	1.3	1.0	
	Large Zooplanton Biomass (variance)	1.6	1.0	
	Mixed Layer Depth	1.4	1.0	
	Mixed Layer Depth (variance)	1.9	1.0	
	Currents	1.3	2.0	
	Currents (variance)	1.5	2.0	
	Air Temperature	2.0	2.5	
	Air Temperature (variance)	1.2	2.5	
	Precipitation	NA	NA	
	Precipitation (variance)	NA	NA	
	Sea Surface Height	1.3	2.5	
	Sea Surface Height (variance)	1.3	2.5	
	Exposure Score	Low		
Overall Vulnerability Rank		Low		



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Eastern Bering Sea herring (*Clupea pallasii*)

Overall Climate Vulnerability Rank: **Low**. (88% certainty from bootstrap analysis).

Climate Exposure: **Low**. With the exception of ocean acidification (4.0), all exposure factors had scores less than 2.5.

Biological Sensitivity: **High**. Spawning cycle (3.6) and complexity in reproductive strategy (3.6) were ranked as "very high", and early life history survival (3.4) was ranked as "high" sensitivity.

Potential for distribution change: **High** (98% certainty from bootstrap analysis). Adult mobility and dispersal of early life stages indicated high potential for distribution change.

Directional Effect in the Eastern Bering Sea: Projected climate change in the eastern Bering Sea is expected to have a negative effect on eastern Bering Sea herring, with 97% certainty in expert scores.

Data Quality: 92% of the sensitivity attributes, and 64% of the exposure factors, had average data quality scores of 2 or greater (indicating at least "moderate" data quality).

Climate Effects on Abundance and Distribution:

Environmental conditions greatly impact the abundance, distribution (all life stages), and productivity (the change in population size due to growth, recruitment and mortality) of eastern Bering Sea (EBS) Pacific herring (*Clupea pallasii*). Pacific herring in the eastern Bering Sea (EBS) have highly variable recruitment, with few above average year classes and many weak ones (Wespestad and Gunderson 1991). While there is not agreement in the literature regarding the specific early life history stage at which herring (Pacific herring, *Clupea pallasii*, or Atlantic herring, *Clupea harengus*) year-class size is determined, authors appear to agree that year-class size is determined before or during the juvenile stage and that the environment plays a large role in the process (e.g. Corten 1986, Cushing 1990, Groger et al. 2010, Iles and Sinclair 1982, Laevastu and Favorite 1980). Specific causes of mortality differ between early life history stages, but climate plays an important role for each stage. As the level of recruitment (year-class size) contributes to overall population abundance and population productivity, environmental conditions therefore affect abundance and productivity. As a result, environmental factors affecting egg, larval, juvenile, and mature herring are all integral for understanding the effects of the environment on the abundance, distribution and productivity of EBS herring.

Pacific herring are known to experience extremely high levels of mortality at the egg stage (Rooper et al. 1999, Wespestad and Gunderson 1991). Pacific herring eggs are deposited demersally in the intertidal and subtidal zones (Blaxter 1985, Hay 1985, Rooper et al. 1999). Eggs are subjected to high mortality due to desiccation in the intertidal zone, wave action (washing eggs from the shore), and predation (Haegele and Schweigert 1985, Rooper et al. 1999, Wespestad and Fried 1983, Wespestad and Gunderson 1991), as well suffocation due to high egg densities and silting (Haegele and Schweigert 1985). Depth of spawn and cumulative time of air exposure have been identified as an important variables determining egg loss (Rooper et al. 1999), egg loss by wave action (Haegele and Schweigert 1985), and predation (Rooper et al. 1999). Air temperature, winds, and the locations at which eggs are deposited by spawning adults are likely important for survival at the egg stage, since they influence egg desiccation, wave action and silting.

The survival of larval herring likely depends upon multiple factors, such as predation, food supply, and retention in nearshore waters where feeding and temperatures are optimal for growth. Survival of Atlantic herring larvae has been proposed to be primarily influenced by environmental factors linked to climate (Groger et al. 2010). Herring larvae are particularly susceptible to physical oceanographic process due to their small size and limited mobility (Sinclair and Iles 1988). Larval development is inversely related to temperature, such that the duration of the larval stage is extended in cooler temperatures (Cushing 1990). The timing of the spring bloom (which depends on physical oceanographic conditions and determines the availability and quality of prey) relative to the first feeding of larvae, has been proposed as critical for survival at the larval stage (Cushing 1990). Retention of larvae to suitable waters favorable for growth has also been proposed as a critical factor for larval survival (Iles and Sinclair 1982; Wespestad and Gunderson 1991). In fact, the size of the retention areas has been proposed to largely determine year-class size and, as a result, total stock size (Iles and Sinclair 1982). Although herring spawning grounds in the Eastern Bering Sea appear to be oriented to allow wind driven retention of larvae (Wespestad 1991), larvae are susceptible to being washed offshore and out of nursery grounds by wind-driven transport (Alderdice and Hourston 1985, Hay 1985, Wespestad and Gunderson 1991). Strong year classes of EBS herring generally have been found to result in years when sea surface temperatures are warm, the direction of transport is north to northeast (onshore), and transport velocity is low (Wespestad and Gunderson 1991), while weak year classes generally occur in years when sea surface temperatures are cold, wind transport is west to northwest (offshore), and transport velocity is high (Wespestad and Gunderson 1991). Finally, predicted increases in ocean acidification may negatively affect larval herring. Laboratory research on larval Atlantic herring has shown that exposure to elevated CO2 levels has resulted in stunted growth and development, decreased condition, and severe tissue damage in many organs (Frommel et al. 2014).

Juvenile herring, defined here as herring that have completed metamorphosis from the larval stage and are not yet mature, are also impacted by climate. Herring in the EBS spend their first two to three years in coastal waters and the inner shelf regime, where they are more susceptible to the environment through air-sea interactions (Schumacher and Reed 1983, as cited in Wespestad and Gunderson 1991). The inner domain on the EBS shelf is an important nursery area for age-0 to age-1 herring, particularly in the northern EBS (Andrews et al. 2015). The distribution of herring in summer months ranges across the EBS shelf, with the size of herring increasing towards the outer shelf (Andrews et al. 2015). For age-0 juvenile herring, increased water temperatures in the summer appear to enhance feeding rates and promote growth, while warm winter temperatures appear to be associated with reduced average size and survival (Norcross et al. 2001). Modeling has suggested that overwinter energetics of age-0 herring are driven less by temperature than by stored energy, which is the determining factor of winter survival of age-0 herring (Foy and Paul 1999). Variability in survival may be linked to interannual variations in local climate and oceanographic conditions such as watershed hydrology, water temperatures, and haline stratification, since these factors potentially affect production of phytoplankton, zooplankton, and growth and survival of age-0 herring (Gay and Vaughan 2001, Norcross et al. 2001).

Climatic conditions impact the distribution of mature herring. Once herring reach sexual maturity, they join the adult population and undergo repeated seasonal migrations between feeding and spawning areas (Tojo et al. 2007). The distribution of overwintering adult herring is directly related to water dynamics in the Bering Sea (Kachina 1978 and Naumenko 1979, as cited in Barton and Wespestad 1980). Specifically, herring usually keep within vast anticyclonic eddies where relatively stable conditions of warmer and salty water occur, as apparently form in various years northwest of the Pribilof Islands and near Cape Navarin. However, in years when no eddies are formed or where they occupy vast areas in the Bering Sea, the result is a wide and relatively uniform distribution of wintering herring along the continental shelf from 58 N to 62 N latitude (Kachina 1978 and Naumenko 1979 as cited in Barton and Wespestad 1980). Andrews et al. (2015) found that the distribution and relative abundance of herring in summer months remained stable between cold and warm climate states among years 2003-2011. Tojo et al. (2007) found a possible northward shift of the northern overwintering concentration based on 1977-2003 herring data, relative to studies based on fishery data collected before 1976. The northward shift possibly occurred in response to regional warming since 1989, and a shift in the Arctic Oscillation (Overland et al. 2004, Tojo et al. 2007).

Climate has been found to affect the condition and survival of herring. Natural mortality of mature herring, which directly affects population productivity and abundance, has been correlated with sea surface temperature (Hulson et al. 2018). Lower sea surface temperatures, as measured through the Pacific Decadal Oscillation, have been correlated with lower natural mortality and higher sea surface temperatures with higher natural mortality (Hulson et al. 2018). Differences in dietary compositions between warm and cold climate periods (most notably a lack of large, lipid-rich crustacean prey in stomachs during warm periods and a switch from large crustaceans to age-0 walleye pollock) have been detected for EBS herring (Andrews et al. 2015). The dependence of herring on copepods may be substantial and the lack of copepods in their diet may be critical for good condition and survival of herring, as it has been suggested that Atlantic herring in the eastern North Sea altered their feeding season to match that of a copepod species (Corten 2000).

Climate effects on EBS herring maturity, spawning migrations, and spawn timing may also impact herring production, and thereby also herring abundance. Precise timing of female and male maturation and spawn timing, as well as the location of eggs spawned is necessary for successful egg survival (Hay 1985). Mature Pacific herring herring, undergo annual spawning migrations (Hay 1985, Tojo et al. 2007, Wespestad 1991) and exhibit fidelity to spawning grounds (Hourston 1982). Research suggests the timing and migration route of EBS herring is related to timing of sea ice retreat and associated temperature changes (Tojo et al. 2007), as the herring follow specific isotherms along the ice edge (Tojo et al. 2007). The timing of spawning is also related to climatological conditions, specifically the timing of ice breakup, commencing in late April to late May in Bristol Bay and progressively later to the north (Barton 1978 as cited in Barton and Wespestad 1980). EBS herring spawning occurs at temperatures of 5-12 degrees Celsius and the time of spawning is related to winter water temperatures with early spawning in warm years and delayed spawning in cold years (Barton and Wespestad 1980). The majority of spawning in the EBS occurs in Bristol Bay (Barton and Steinhoff 1980, Barton and Wespestad 1980), an area that under prevailing winds generally produces onshore retention of water and larvae (Wespestad and Gunderson 1991). It has been suggested that less available suitable spawning habitat in areas north of the Yukon River may be a major factor limiting the biomass of herring that spawn in the northern EBS (Barton 1978 as cited in Barton and Wespestad 1980). If the location of overwintering herring shifts north with climate warming and the location of quality spawning sites remain in Bristol Bay, there may be increased energetic costs required for the spawning migration since the adults may need to swim larger distances between overwinter feeding areas and spring spawning areas. If so, climate warming may decrease survival, stock productivity, and abundance due to changes in distribution and length of the spawning migration.

Life history traits such as fecundity, age at maturation, and annual timing of maturity can influence productivity and abundance and are likely affected by climate. As fecundity, age at maturation, and annual timing of maturation vary spatially, they may be driven by climatic conditions. For instance, size-specific fecundity of Pacific herring varies by latitude, with California herring producing more eggs per female of a given length than Alaska herring (Hay 1985). Similarly, Pacific herring age at maturation varies by latitude, with later maturation occurring in cooler, northern latitudes (Hay 1985), and earlier maturation occurring in warmer, southern latitudes. Finally, the annual timing of maturation and spawning also varies by latitude, occurring earlier in southern latitudes and later in northern latitudes. If these latitudinal patterns are linked to climate conditions such as temperature, the age at maturation, annual timing of maturation, and fecundity may shift as climate changes and temperatures rise (age at maturation and annual timing of maturation would get earlier and fecundity would increase), resulting in productivity and abundance changes of EBS herring.

Life History Synopsis:

Pacific herring are a clupeiod species that occur in the North Pacific and Arctic Oceans, from southern California, Japan and Korea in the south, to the Beaufort Sea in the Canadian Arctic, and the White Sea in the Russian Arctic (Haegele and Schweigert 1985, Hay 1985, Mecklenburg et al. 2002). Along the Alaska shore of the Bering Sea, herring spawn from Atka Island in the Aleutian Islands to Kotzebue Sound, with the greatest concentration of spawn in the Togiak District of Bristol Bay (Barton and Steinhoff 1980, Barton and Wespestad 1980). In Alaska, eastern Bering Sea herring are genetically distinct from Northern Gulf of Alaska herring (Grant and Utter 1984). Within the eastern Bering Sea, herring north of Norton Sound are genetically distinct from herring south of Norton Sound (Grant and Utter 1984). Herring in the eastern Bering Sea can also be separated into two (Fried and Wespestad 1985) or three (Rowell et al. 1991, Wespestad and Barton 1979) groupings based on differences in growth rates, with herring in the northeastern Bering Sea exhibiting slower growth than those in the southeastern Bering Sea.

Pacific herring have a complex reproductive strategy. Pacific herring spawn in the winter to spring, although there are some isolated instances of unusually early and late spawning populations (Haegele and Schweigert 1985). Mature herring undergo annual spawning migrations (Hay 1985, Tojo et al 2007) and exhibit fidelity to spawning grounds (Hourston 1982). In the eastern Bering

Sea, in particular, adult herring undergo long spawning migrations from overwintering grounds (concentrated over the outer continental shelf from Unimak Pass to the Pribilof Islands and west of St. Matthew Island) eastward across the middle shelf to coastal spawning sites (Tojo et al. 2007, Wespestad 1991). EBS herring appear to follow optimum isotherms as they migrate to spawning grounds (Tojo et al. 2007). Herring migrate from offshore waters (near the shelf break) to nearshore waters in March and April, and spawning occurs between late April and July with timing linearly related to sea surface temperature (Wespestad 1991). Herring in the southeastern Bering Sea spawn earlier than those in the northeastern Bering Sea, and spawning continues for days to weeks depending on location (Tojo et al. 2007, Wespestad 1991) and year. Pacific herring spawn their eggs in the intertidal and subtidal zones (Blaxter 1985, Hay 1985, Tojo et al. 2007) on a wide range of substrate including aquatic vegetation, bare rock, cobbles, and gravel (Wespestad and Fried 1983). The adhesive, demersal eggs hatch to become larvae after several weeks (Hay 1985, Wespestad 1991). Depending on temperature, herring larvae survive approximately 6-9 days after yolk sack absorption without food (McGurk 1984). After several months, larvae metamorphose and the pelagic larval stage lasts several more months (Hay 1985). Survival of larval herring depends upon their retention in nearshore waters, as larval herring can be carried unknown distances by currents (Iles and Sinclair 1982, Wespestad 1991), and on timing of the larval stage in relation to predation and food availability (Alderdice and Hourston 1985, Hay 1985). Larval wind-driven transport north or northeast (onshore) and at low velocities has been correlated with higher EBS herring recruitment, while transport of larvae west or northwest (offshore) and at high velocities has been correlated with poorer recruitment (Wespestad 1991).

Juvenile herring in the EBS spend their first two to three years in coastal waters and the inner shelf regime (Schumacher and Reed 1983 as cited in Wespestad and Gunderson 1991). The inner domain on the EBS shelf is an important nursery area for age-0 to age-1 herring, particularly in the northern EBS (Andrews et al. 2015). The distribution of herring in summer months ranges across the EBS shelf, with the size of herring increasing towards the outer shelf (Andrews et al. 2015).

Adult herring spend a majority of the year on offshore feeding grounds and overwintering grounds (Hay 1985), however some adults remain in nearshore waters after spawning to feed before beginning the return migration (Tojo et al. 2007). A majority of herring spawners, mainly from Bristol Bay, migrate southward along the Alaska Peninsula after spawning and accumulate near Unimak Pass to feed in summer and fall (Tojo et al. 2007). Other herring spawners from the northern EBS migrate back across the shelf directly rather than migrating southward along the Alaska Peninsula (Tojo et al. 2007). A majority of overwintering EBS adult herring are distributed northwest of the Pribilof Islands and north of Unimak Pass, extending to the northwest in the direction of the Pribilof Islands (Tojo et al. 2007). Although there is a clear northward movement of herring in the fall, some herring remain in the southern habitat around the southeastern EBS shelf area in the winter (Tojo et al. 2007). Norton Sound herring may overwinter near the Pribilof Islands with herring from spawning areas south of Norton Sound or may remain in the vicinity of Norton Sound all year (Barton and Wespestad 1980). Based upon differences in behavior, growth rates and maturity, herring that spawn north of Norton Sound are believed to remain in the immediate area year round and winter in ice-covered coastal lagoons and brackish bays (Barton 1978 as cited in Barton and Wespestad 1980, Barton and Steinhoff 1980).

Herring are schooling fish that are both particulate and filter feeders (Blaxter 1985, Gibson and Ezzi 1992). They undergo diel vertical migration cycles for feeding (Blaxter 1985). Studies from Prince William Sound show that juvenile herring diet varies by location and season (Foy and Norcross 1999). The same studies found that high lipid copepod taxa are likely important given the high energy density identified during diet analyses (Foy and Norcross 1999). EBS herring diets also vary by location comprise a wide range of prey including large and small copepods, euphausiids, fish (particularly age-0 walleye pollock), and the hyperiid amphipod *Themisto libellula* (Andrews et al. 2015).

While Pacific herring off California have a relatively short lifespan, Pacific herring in the eastern Bering Sea commonly reach age 10 and have been observed to reach a maximum age of 17 (Williams and Quinn 1997). Natural mortality rates of Pacific herring in the Eastern Bering Sea likely range from intermediate to relatively high (instantaneous rates of 0.16-0.44 yr^{-1}) (Wespestad 1982, Williams and Quinn 1997), consistent with an observed maximum age in the region of 17 years (Williams and Quinn 1997). Pacific herring approach their asymptotic size at a relatively rapid rate, with the von Bertalanffy K parameter estimated between 0.14 and 0.35, increasing to the north (Shaboneev 1965 as cited in Wespestad 1982, Wespestad 1991, Williams and Quinn 1997). The age at 50% maturity has been estimated to be between 3 and 5 years (Naumenko 1979 as cited in Wespestad 1991), but is currently estimated at approximately age-6 in the Alaska Department of Fish and Game statistical catch at age model.

The State of Alaska recognizes ten spawning stocks for management purposes in the Eastern Bering Sea (Port Moller/Port Heiden, Togiak, Security Cove, Goodnews Bay, Cape Avinof, Nelson Island, Nunivak Island, Cape Romanzof, Norton Sound, and Port Clarence). Although fishing and historical survey efforts occurred in all of these locations, current surveys are currently limited to Togiak and Port Moller/Port Heiden due to low market demand and State of Alaska budget cuts. Recent directed fisheries for EBS herring have occurred in Togiak, Port Moller/Port Heiden, and Dutch Harbor (mixed stock bait fishery). The Togiak stock, which has been estimated to comprise at least 70% of the eastern Bering Sea mature biomass (Barton and Steinhoff 1980, Barton and Wespestad 1980, Buck and Dressel 2018), increased substantially in response to strong year classes following the 1977 regime shift, declined through the mid-1990’s as those year classes passed through the population and has remained stable that time (Buck and Dressel 2018).

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