

2 Climate and Ocean Conditions

Lisa G. Crozier and Nathan J. Mantua

2.1 Climate Effects

Projected Impacts of Future Climate Change on West Coast Salmon

Climatic conditions affect salmonid abundance, productivity, spatial structure, and diversity through direct and indirect impacts at all life stages (e.g., ISAB 2007; Lindley et al. 2007; Crozier et al. 2008; Moyle et al. 2013; Wainwright and Weitkamp 2013). Salmon have adapted to a wide variety of climatic conditions in the past, and thus inherently could likely survive substantial climate change at the species level in the absence of other anthropogenic stressors.

Currently, the adaptive ability of these threatened and endangered species is depressed due to reductions in population size, habitat quantity and diversity, and loss of behavioral and genetic variation. Without these natural sources of resilience, systematic changes in local and regional climatic conditions due to anthropogenic global climate change will likely reduce long-term viability and sustainability of populations in many of these ESUs and DPSs. Adapting to climate change may eventually involve changes in multiple life-history traits and/or local distribution, and some populations or life-history variants might not survive. Importantly, the character and magnitude of these effects will vary within and among ESUs/DPSs.

The Intergovernmental Panel on Climate Change (IPCC) and U.S. Global Change Research Program recently published updated assessments of anthropogenic influence on climate, as well as projections of climate change over the next century (IPCC 2013; Melillo et al. 2014). Reports from both groups document ever-increasing evidence that recent warming bears the signature of rising concentrations of greenhouse gas emissions.

The U.S. Global Change Research Program report contains regional-focus chapters for the northwest (Snover et al. 2013; Mote et al. 2014) and southwest U.S. (Garfin et al. 2014). These regional reports synthesize information from an extensive literature review, including a broad array of analyses of regional observations and climate change projections. These synthesis reports were the primary source for this West Coast summary. References to the primary literature can be found in those reports. Updates to this summary can be found in annual literature reviews conducted by National Marine Fisheries Service (available at http://www.nwfsc.noaa.gov/trt/lcm/freshwater_habitat.cfm).

Historical Climate Trends

Observed historical trends in climate reflect the early influence of greenhouse gas emissions, and often indicate the general direction of future climate change. These observations also reflect natural variability in climate at multiple time scales. Natural

variability alternately intensifies and relaxes (or partially reverses) the long-term trends. Attribution of historical trends to anthropogenic factors is most certain at the global scale over time scales of centuries to millennia because at these scales we can better account for natural variability.

Historical records show pronounced warming in both sea-surface and land-based air temperatures. There is moderate certainty that the 30-year average temperature in the Northern Hemisphere is now higher than it has been over the past 1,400 years. In addition, there is high certainty that ocean acidity has increased with a drop in pH of 0.1. Furthermore, glaciers and sea-ice have receded, while sea level has risen (global mean rose 0.19 m over the last century). In recent decades, the frequency of extreme high temperature or heavy precipitation events has increased in many regions. An anthropogenic influence on this shift in frequency is “very likely” (IPCC 2014).

Regional and local trends include the following observations:

- In both the Northwest and Southwest:
 - air temperatures have increased since the late 1800s
 - springtime snow-water equivalent has decreased (since 1950)
 - snowmelt occurs earlier in the year
- In the Southwest, drought over the past four years is unprecedented in the historical record and may be the worst in over 1,000 years. This drought has been attributed to a combination of anthropogenic influence on temperature and natural variability in precipitation (Williams et al. 2015). Trends in precipitation vary spatially up or down, with no statistically significant trends in precipitation averages or extremes in the Northwest.
- In both the Northwest and Southwest, widespread tree mortality has been observed, wildfires have increased in both frequency and area burned, and insect outbreaks have increased (Garfin et al. 2014; Mote et al. 2014).
- Historical trends in the California Current are heavily influenced by patterns in wind-driven ocean circulation, which correlates with large-scale climate drivers such as the North Pacific Gyre Oscillation (Peterson et al. 2013) and Pacific Decadal Oscillation (Jacox et al. 2014). Spatially variable trends in upwelling intensity (Jacox et al. 2014) and hypoxia (Peterson et al. 2013), and longer trends in atmospheric forcing and sea surface temperature (Johnstone and Mantua 2014) probably reflect natural climate variability to a much greater extent than anthropogenic forcing.
- The pH of the California Current has decreased by about 0.1 and by 0.5 in aragonite saturation state since pre-industrial times (Hauri et al. 2009). Furthermore, infrastructure in coastal areas is increasingly damaged by erosion and flooding (Garfin et al. 2014; Mote et al. 2014; Sweet et al. 2014).

Projected Climate Changes

Trends in warming and ocean acidification are highly likely to continue during the next century (IPCC 2103). Scenarios considered in the IPCC fifth assessment report range

from the severely curtailed greenhouse gas emissions of representative concentration pathway (RCP) 2.6 to business as usual in RCP 8.5.

Based on means across global climate models spanning the full breadth of these emissions scenarios, IPCC projected the following ranges across the Northern Hemisphere by 2081-2100:

- Spring snow cover declines of 7-25%
- Glacier recessions of 15-85%
- Sea surface temperature increases of 1.1-3.6°C
- Global sea level increases of 11-38 inches
- Global ocean pH decreases of 38 to 109%, which correspond to a drop in pH of 0.14-0.32.

Regional projections add spatial variability and specificity to these themes. In winter across the west, the highest elevations (e.g., in the Rocky Mountains) will shift from consistent longer (>5 months) snow-dominated winters to a shorter period (3-4 months) of reliable snowfall (Klos et al. 2014); lower, more coastal or more southerly watersheds will shift from consistent snowfall over winter to alternating periods of snow and rain (“transitional”); lower elevations or warmer watersheds will lose snowfall completely, and rain-dominated watersheds will experience more intense precipitation events and possible shifts in the timing of the most intense rainfall (e.g., Salathé et al. 2014).

By the 2080s, Tohver et al. (2014) anticipate a complete loss of snow-dominated basins in the Cascades and U.S. portion of the Rockies, with only a few “mixed” basins of rain- and snow-fed runoff remaining at the highest elevations. Flooding is projected to increase in basins that experience a mix of snow and rain in winter (Mote et al. 2014; Salathé et al. 2014; Tohver et al. 2014). Erosion and flooding in coastal areas are projected to increase with rising sea levels (Garfin et al. 2014; Mote et al. 2014; Sweet et al. 2014).

Among seasons, the greatest temperature shifts are expected in summer. Warmer summer air temperatures will increase both evaporation and direct radiative heating. When combined with reduced winter water storage, warmer summer air temperatures will lead to lower minimum flows in many watersheds. Higher summer air temperatures will depress minimum flows and raise maximum stream temperatures even if annual precipitation levels do not change (e.g., Sawaske and Freyberg 2014). Summer precipitation also influences summer flows, but projections for precipitation are less certain than for temperature. Coastal weather can differ from region-wide projections due to changes in fog, on-shore winds, or precipitation (Johnstone and Dawson 2010; Potter 2014).

Widespread ecosystem shifts are very likely, and may be abrupt due to disturbances from increasing wildfires, insect outbreaks, droughts, and tree diseases (Garfin et al. 2014; Mote et al. 2014). Climate projections often favor invasive fish species over native species, with declines exacerbated by the greater vulnerability of native species to existing anthropogenic stressors (Lawrence et al. 2012; Lawrence et al. 2014; Quiñones and Moyle 2014).

In response to projected changes in both climate and land use practices, estuary dynamics are expected to change as well, with depth and salinity altered by changing sea level, upwelling regimes, and freshwater input (Yang et al. 2015). Intense upwelling events can move hypoxic and acidic water into estuaries, especially when freshwater input is reduced (e.g., Columbia River estuary, Roegner et al. 2011). Sea level projections differ at local versus global scales due to local wind and temperature trends and land movement. Specifically, the National Research Council (2012) predicted a lower rise in sea level off the coasts of Washington and Oregon (62 cm) than off the coast of California (92 cm) by 2100.

Higher sea surface temperatures and increased ocean acidity are predicted for marine environments in general (IPCC 2013). However, regional marine impacts will vary, especially in relation to productivity. The California Current is strongly influenced by seasonal upwelling of cool, deep, water that is high in nutrients and low in dissolved oxygen and pH. Ecological effects of climate change in the California Current are very sensitive to impacts on upwelling intensity, timing, and duration. Projections of how climate change will affect upwelling are highly variable across models, with predicted trends ranging from negative to positive (Bakun 1990; Mote and Mantua 2002; Snyder et al. 2003; Diffenbaugh et al. 2008; Bakun et al. 2010). An analysis of 21 global climate models found that most predicted a slight decrease in upwelling in the California Current, although there is a latitudinal cline in the strength of this effect, with less impact toward the north (Rykaczewski et al. 2015).

Much of the near-shore California Current is expected to be corrosive (undersaturated in aragonite) in the top 60 m during all summer months within the next 30 years, and year-round within 60 years (Gruber et al. 2012). Thermal stratification and hypoxia are expected to increase (Doney et al. 2014).

Impacts on Salmon

Studies examining the effects of long-term climate change to salmon populations have identified a number of common mechanisms by which climate variation is likely to influence salmon sustainability. These include direct effects of temperature such as mortality from heat stress, changes in growth and development rates, and disease resistance. Changes in the flow regime (especially flooding and low flow events) also affect survival and behavior. Expected behavioral responses include shifts in seasonal timing of important life-history events, such as the adult migration, spawn timing, fry emergence timing, and juvenile migration.

Indirect effects on salmon mortality, growth rates and movement behavior are also expected to follow from changes in the freshwater habitat structure and the invertebrate and vertebrate community, which governs food supply and predation risk (Petersen and Kitchell 2001; ISAB 2007; Crozier et al. 2008). Both direct and indirect effects of climate change will vary among Pacific salmon ESUs and among populations in the same ESU. Adaptive change in any salmonid population will depend on the local consequences of climate change as well as ESU-specific characteristics and existing local habitat characteristics.

Because climate has such profound effects on survival and fecundity, salmon physiology and behavior are exquisitely adapted to local environmental conditions. These adaptations vary systematically among populations and are exhibited in traits such as age and timing of juvenile and adult migrations, with potential differences in physiology and migration routes (Quinn 2005). These traits often have a significant plastic (non-genetic) component, which allows them to respond quickly to environmental change. Yet these traits also differ genetically among populations (Carlson and Seamons 2008).

Directional climate change could therefore drive many salmonid populations into a maladaptive state. Such an outcome would likely cause reductions in abundance, productivity, population spatial structure, and population diversity. In some cases, this can lead to extirpation if a population cannot adapt quickly enough. In other cases an adaptive solution may not exist because of conflicting pressures within or between life stages.

Climate impacts in one life stage generally affect body size or timing in the next life stage. For this reason, the cumulative life-cycle effects of climate change must be considered to fully appreciate the scope of risk to a given population. Even without interactions among life stages, the sum of impacts in many stages will have cumulative effects on population dynamics.

Climate effects tend to be negative across multiple life stages (Healey 2011; Wade et al. 2013; Wainwright and Weitkamp 2013). However, there may be mitigating responses in some ESUs or life stages. Individualistic impacts within and among ESUs will depend on factors such as existing physical and biological heterogeneity, proximity to the limits of physiological tolerance under present climate conditions, and the extent of localized climate change.

In many cases, directional climate change exacerbates existing anthropogenic threats. Examples include streams or rivers where stream temperatures are already elevated due to land-use modifications (Battin et al. 2007) or where flow is reduced due to water diversions (Walters et al. 2013). In the Columbia River, dams have altered the hydrological regime by causing an earlier and smaller freshet, which is the same type of effect expected from climate change (Naik and Jay 2011a; Naik and Jay 2011b). Any of these stressors in combination with one another or with climate impacts will present pressures of much greater concern than they would individually, but they also offer potential solutions (McClure et al. 2013).

Changes in winter precipitation will likely affect incubation and/or rearing stages of most populations. Changes in the intensity of cool-season precipitation could influence migration cues for fall and spring adult migrants, such as coho salmon and steelhead. Egg survival rates may suffer from more intense flooding that scours or buries redds.

Changes in hydrological regime, such as a shift from mostly snow to more rain, could drive changes in life history, potentially threatening diversity within an ESU. It is possible that even characteristic life-history traits used to help define the ESU will be threatened. For example, the juvenile freshwater rearing period is very sensitive to temperature, with the yearling life-history strategy used only by populations in cooler watersheds (Beechie et al. 2006). Frequency of the yearling life-history type will likely decline as movement downstream into estuaries or near-shore habitat is initiated at

younger ages. Implications of this behavioral shift for juvenile survival, ocean migration behavior, and age at maturity are uncertain.

Changes in summer temperature and flow will affect both juvenile and adult stages in some populations, especially those with yearling life histories and summer migration patterns. Juvenile rearing and migration survival is often correlated with these factors (Quinn 2005; Crozier and Zabel 2006; Crozier et al. 2010).

Adults that migrate or hold during peak summer temperatures can experience very high mortality in unusually warm years. For example, in 2015 only 4% of adult Redfish Lake sockeye salmon survived the migration from Bonneville Dam to Lower Granite Dam after confronting temperatures over 22°C in the lower Columbia River. After prolonged exposure to temperatures over 20°C, salmon are especially likely to succumb to diseases that they might otherwise have survived (Materna 2001; Miller et al. 2014). They are also more vulnerable to any sort of stress, such as catch-and-release fisheries (Boyd et al. 2010).

Changing hydrology and temperature will also affect the timing of smolt migrations and spawning (Crozier and Hutchings 2014; Hayes et al. 2014; Otero et al. 2014). If smolts migrate at a smaller size because they leave freshwater habitat earlier, they might have lower survival due to size-selective predation (Thompson and Beauchamp 2014). Marine arrival timing is extremely important for smolt-to-adult survival (Scheuerell et al. 2009), and has been historically synchronized with the timing and predictability of favorable ocean conditions (Spence and Hall 2010). Given the uncertain effects of climate change on upwelling timing and intensity, impacts on juvenile survival from shifts in migration timing are also difficult to predict.

In some populations, behavior during the early ocean stage is consistent among years, suggesting a genetic rather than a plastic response to environmental conditions (Burke et al. 2014; Hassrick et al. 2016). These populations might change their behavior over time if the fitness landscape changes, but responses will likely be relatively slow and could be dominated by decadal ocean dynamics or productivity outside the California Current (e.g., the Gulf of Alaska for northern migrants).

Other populations show more variable behavior after ocean entry (Weitkamp 2010; Fisher et al. 2014), and some show heightened sensitivity to interannual climate variation, such as the El Niño Southern Oscillation (L. Weitkamp, NMFS NWFSC, personal communication). Such variability might increase ESU-level resilience to climate change, assuming some habitats remain highly productive.

Marine migration patterns could also be affected by climate-induced contraction of thermally suitable habitat. Abdul-Aziz et al. (2011) modeled changes in summer thermal ranges in the open ocean for Pacific salmon under multiple IPCC warming scenarios. For chum salmon, pink salmon, coho salmon, sockeye salmon, and steelhead, they predicted contractions in suitable marine habitat of 30-50% by the 2080s, with an even larger contraction (86-88%) for Chinook salmon under the medium and high emissions scenarios (A1B and A2).

Northward range shifts are a climate response expected in many marine species, including salmon (Cheung et al. 2015). However, salmon populations are strongly

differentiated in the northward extent of their ocean migration, and hence will likely respond individualistically to widespread changes in sea surface temperature.

In most Pacific salmon species, size at maturation has declined over the past several decades. This trend has been attributed in part to rising sea surface temperatures (Bigler et al. 1996; Pyper and Peterman 1999; Morita et al. 2005). Mechanisms involved in such responses are likely complex, but appear to reflect a combination of density-dependent processes, including increased competition due to higher salmon abundance in recent years and temperature (Pyper and Peterman 1999). Temperature-related size effects could involve increased metabolic costs at higher temperatures, and/or shifts in spatial distribution in response to ocean conditions. Younger spawners affect population growth rates by exhibiting lower fecundity and reducing the population stability that stems from having multiple age classes reproduce.

Numerous researchers have reported that salmon marine survival is highly variable over time and often correlated with large-scale climate indices (Mueter et al. 2002; Mueter et al. 2005; Petrosky and Schaller 2010; Litzow et al. 2014; Stachura et al. 2014; Sydeman et al. 2014). For example, Pacific salmon from Washington and Oregon exhibited extremely low marine survival and dramatic population declines during a “warm phase” of the Pacific Decadal Oscillation in the 1980s and 1990s (Levin 2003; Zabel et al. 2006). These declines were attributed to low ocean productivity in the warm ocean of that period.

Many fish communities, including key salmon prey and predators, experience changes in abundance and distribution during warm ocean periods (Pearcy 2002; Wing 2006; Cheung et al. 2009). However, food chain dynamics in the open ocean are flexible and difficult to predict into the future.

The full implications of ocean acidification on salmon are not known at this time. Olfaction and predator-avoidance behavior are negatively affected in some fish species, including pink salmon (Leduc et al. 2013; Ou et al. 2015). Pink salmon also showed reductions in growth and metabolic capacity under elevated CO₂ conditions (Ou et al. 2015). Some high-quality salmon prey (e.g., krill) might be negatively affected by ocean acidification, but there are several possible pathways by which higher trophic levels might compensate for changes at a lower trophic level. From their analysis of multi-trophic responses to ocean acidification, Busch et al. (2013) concluded that impacts to salmon could conceivably be positive. However, they emphasized that a better understanding of both direct and indirect feedback loops is necessary before drawing definitive conclusions.

To what extent a future warmer ocean will mimic historical conditions of warm-ocean, low-survival periods is not known. Current indications are that a warmer Pacific Ocean is generally less productive at mid latitudes, and hence likely to be less favorable for salmon.

Analysis of ESU-specific vulnerabilities to climate change by life stage will be available in the near future, upon completion of the *West Coast Salmon Climate Vulnerability Assessment* being conducted by the National Marine Fisheries Service. Climate effects on one Pacific salmon ESU, the Oregon coastal coho salmon ESU, were recently assessed

by Wainwright and Weitkamp (2013); many of the effects they reported for this ESU are likely shared by other ESUs (Table 2.1).

In summary, both freshwater and marine productivity tend to be lower in warmer years for most populations considered in this assessment. These trends suggest that many populations might decline as mean temperature rises. However, the once historically high abundance of many California populations of Pacific salmonids is reason for optimism and warrants considerable effort to restore the natural climate resilience of these species.

2.2 2012-2015 Drought Impacts on West Coast Salmon and Salmon Habitat

California has experienced well below average precipitation in each of the past four water years (2012, 2013, 2014, and 2015), record high surface air temperatures the past two water years (2014 and 2015), and record low snowpack in 2015. Some paleoclimate reconstructions suggest that the current four-year drought is the most extreme in the past 500 or perhaps more than 1000 years. Anomalously high surface temperatures have made this a “hot drought”, in which high surface temperatures substantially amplified annual water deficits during the period of below average precipitation.

The combination of four consecutive years of drought and record-high air temperatures in 2014 and 2015 favored elevated stream temperatures, and these were documented to have severe impacts in some watersheds. The lack of cold water behind Shasta Dam on the upper Sacramento River, in combination with water release decisions, led to unfavorably high stream temperatures below Shasta Dam 2014 (SRTTG 2014) and 2015. Brood years 2014 and 2015 experienced the lowest egg-to-fry survival rates on record (5.6% and 4.5%, respectively) (Poytress 2016, PFMC 2016). Concerns over a high potential for fish kills in the Klamath River basin were also high in the summers of 2014 and 2015 because of warm stream temperatures and elevated presence of pests and pathogens detected in salmon. These concerns prompted emergency reservoir releases aimed at lowering downstream temperatures to alleviate those risks.

Exceptionally Warm Ocean Conditions in the NE Pacific

Much of the northeast Pacific Ocean, including parts typically used by California salmon and steelhead, experienced exceptionally high temperatures of the upper 100 m of the ocean beginning early in 2014 and areas of extremely high ocean temperatures continued to cover most of the northeast Pacific Ocean through all of 2015 (NMFS 2015). A “warm blob” formed offshore of the Pacific Northwest (PNW) region in fall 2013 (Bond et al. 2015). Off the coast of southern and Baja California, upper ocean temperatures became anomalously warm in spring 2014, and this warming spread to the central California coast in July 2014. In fall 2014, a shift in wind and ocean current patterns caused the entire northeast Pacific Ocean domain to experience unusually warm upper ocean temperatures from the West Coast offshore for several hundred kilometers. In spring 2015 nearshore waters from Vancouver Island south to San Francisco mostly experienced

Table 2.1. Projected climate changes affecting Oregon coho salmon (*O. kisutch*), as reported by Wainwright and Weitkamp (2013). Abbreviations: LWD (large woody debris) -- strongly negative, - negative, o neutral, + positive, ++ strongly positive.

Physical/chemical pattern	Certainty of change	Process affecting Oregon coast coho salmon	Range of effects					Certainty of effect
			--	-	o	+	++	
Terrestrial habitat								
Warmer, drier summers	Moderate	Increased fires, increased tree stress and disease affect LWD, sediment supplies, riparian zone structure	X	X	X			Low
Reduced snow pack, warmer winters	High	Increased growth of higher elevation forests affect LWD, sediment, riparian zone structure				X	X	Low
Freshwater habitat								
Reduced summer flow	High	Less accessible summer rearing habitat		X				Moderate
Earlier peak flow	High	Potential migration timing mismatch	X	X	X			Moderate
Increased floods	Moderate	Redd disruption, juvenile displacement, sediment dynamics	X	X	X	X		Moderate
Higher summer stream temperature	Moderate	Thermal stress, restricted habitat availability, increased susceptibility to disease, parasites, and predators	X	X				Moderate
Higher winter stream temperatures	Low	Increased fry growth, shorter incubation				X	X	Low
Estuarine habitat								
High sea level	High	Reduced availability of wetland habitats	X	X				Moderate
Higher water temperature	Moderate	Thermal stress, increased susceptibility to disease, parasites, and predators	X	X				Moderate
Combined effects		Changing ecosystem composition and structure	X	X	X	X	X	Low
Marine habitat								
Higher ocean temperature	High	Thermal stress, shifts in migration, range shifts, susceptibility to disease, parasites, and predators	X	X				Moderate
Intensified upwelling	Moderate	Increased nutrients (food supply), coastal cooling, ecosystem shifts; increased offshore transport			X	X	X	Low
Delayed spring transition	Low	Food timing mismatch with juvenile migrants, ecosystems shifts		X	X			Low
Intensified stratification	Moderate	Reduced food supply, change in habitat structure	X	X				Low
Increased acidity	High	Disruption of food supply, ecosystem shifts	X	X				Moderate
Combined effects		Changing ecosystem composition and structure; food supply and predation		X	X	X	X	Low

strong and at times above average coastal upwelling that created a relatively narrow band (~50 to 100 km wide) of near normal upper ocean temperatures, while the exceptionally high temperature waters remained offshore and in coastal regions to the south and north.

Expectations for Future Climate Risks and Likely Impacts on West Coast Salmon

Adult coho salmon returns from the fall/winter of 2015–2016 and in the fall/winter of 2016–2017 have likely been negatively impacted by poor stream and ocean conditions. Adult Chinook salmon (and steelhead) returns for the fall/winter 2015–2016 and for the next two to three years (depending on ocean residence times, maturing in 2016, 2017, and 2018) have likely been negatively impacted by poor stream or ocean conditions.

Typical of El Niño winters, there was a more coastally oriented warming of the northeast Pacific in winter 2016 that persisted into early spring 2016. Spring 2016 ocean migrants will likely encounter an ocean strongly influenced by (if not dominated by) a subtropical food-web that favors poor early marine survival for both coho salmon and Chinook salmon.

Summary

Four consecutive years of drought (2012–2015) and the past two years (2014–2015) of exceptionally high air, stream, and upper ocean temperatures have together likely had negative impacts on the freshwater, estuary, and marine phases for many populations of Chinook salmon, coho salmon, and steelhead.



NOAA Technical Memorandum NMFS

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JULY 2016

**VIABILITY ASSESSMENT FOR PACIFIC SALMON
AND STEELHEAD LISTED UNDER THE
ENDANGERED SPECIES ACT: SOUTHWEST**

Thomas H. Williams, Brian C. Spence, David A. Boughton, Rachel C. Johnson,
Lisa G. Crozier*, Nathan J. Mantua, Michael R. O'Farrell, and Steven T. Lindley

NOAA National Marine Fisheries Service
SWFSC Fisheries Ecology Division
110 Shaffer Road
Santa Cruz, CA 95060

* NOAA National Marine Fisheries Service
Northwest Fisheries Science Center
2725 Montlake Boulevard E
Seattle, WA 98112

NOAA-TM-NMFS-SWFSC-564

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NOAA Technical Memorandum NMFS

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This document should be cited as follows:

Williams, T.H., B.C. Spence, D.A. Boughton, R.C. Johnson, L.G. Crozier, N.J. Mantua, M.R. O'Farrell, and S.T. Lindley. 2016. Viability assessment for Pacific salmon and steelhead listed under the Endangered Species Act: Southwest. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-564.

Individual sections (Recovery Domains) should be cited as follows:

Spence, B.C. 2016. North-Central California Coast Recovery Domain. Pages 32–82 *in* T.H. Williams, B.C. Spence, D.A. Boughton, R.C. Johnson, L.G. Crozier, N.J. Mantua, M.R. O'Farrell, and S.T. Lindley. Viability assessment for Pacific salmon and steelhead listed under the Endangered Species Act: Southwest. U.S. Department of Commerce, NOAA Technical Memorandum NMFS-SWFSC-564.