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# Climate change vulnerability assessment for Pacific Lamprey in rivers of the Western United States

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#### ABSTRACT

Pacific Lamprey (Entosphenus tridentatus) are a native anadromous species that, like salmon, historically returned to spawn in large numbers in watersheds along the west coast of the United States (U.S.). Lamprey play a vital role in river ecosystems and are one of the oldest vertebrates that have persisted over time likely influencing the evolution of many aquatic species. Pacific Lamprey have declined in abundance and are restricted in distribution throughout Washington, Oregon, Idaho and California. A key uncertainty influencing Pacific Lamprey status is the impact of climate change. We modified the NatureServe Climate Change Vulnerability Index (CCVI) to accommodate climate predictions from the International Panel on Climate Change. Using downscaled information, we characterized changes in 15 rivers occupied by Pacific Lamprey in the western U.S. We evaluated this risk under Representative Concentration Pathways (RCP) 4.5 and 8.5 for two time periods (mid-century 2040-2069 and end-century 2070–2099). The CCVI scores generally increased when going from RCP 4.5 to RCP 8.5 in three Global Climate Models for both mid-century and end-century, which our analyses forecasts degraded stream temperature and hydrologic conditions under increasing greenhouse gas emissions. The geographically assessed results suggest that climate change impacts to Pacific Lamprey vulnerability are magnified in highly altered rivers. If we continue to observe greenhouse gas emission levels associated with the RCP 8.5, Pacific Lamprey will be at greater risk to climate change impacts. In order to mitigate the risk from climate change toward the end of the century, additional actions will need to be prioritized to rapidly reduce the impact of these threats such as increasing flow, creating backwater habitat, restoring riparian vegetation and reducing stream disturbances. The findings revealed the patterns of vulnerability for Pacific Lamprey across their U.S. range are informative for prioritizing river restoration actions when paired with regional implementation plans.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/tjfe. ¶Retired.

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# Introduction

Pacific Lamprey (*Entosphenus tridentatus*) are a native anadromous species that, like salmon, historically returned to spawn in large numbers in watersheds along the west coast of the United States. Lamprey are one of the oldest living groups of vertebrates from the Agnatha assemblage that dates back to about 500 million years ago (Wang and Schaller 2015). Lamprey have persisted through four major extinction events and, as a living fossil, provide valuable information about the evolution of vertebrates (Docker et al. 2015).

Pacific Lamprey are a key component of the ecology of western rivers in the U.S. because they: make up a large portion of the biomass in streams therefore, making them an important component in processing nutrients and nutrient cycling; contribute considerable amounts of marine-derived nutrients in freshwater streams when they return from the ocean; and act as a buffer to predation (in the freshwater and marine environment) for many commercially valuable salmon species (Wang and Schaller 2015). Given Pacific Lamprey's persistence over time and vital role in the ecosystem, they have likely influenced the evolution of many aquatic species across the Pacific Rim from Japan to Mexico.

Currently, populations have declined in abundance and are restricted in distribution throughout Washington, Oregon, Idaho and California (Luzier et al. 2011; Goodman and Reid 2012; Clemens et al. 2017). Threats to Pacific Lamprey occur in much of their range and include restricted mainstem and tributary passage, reduced flows and dewatering of streams, stream and floodplain degradation, degraded water quality and changing marine and climate conditions (Luzier et al. 2011; Goodman and Reid 2012; Clemens et al. 2017). In light of these threats, partners including Native American tribes and federal, state and local agencies; developed the Pacific Lamprey Conservation Initiative (Initiative) to work collaboratively to conserve and restore Pacific Lamprey by reducing threats and improving their habitats (USFWS 2012; Wang and Schaller 2015).

The landscape level strategy of the Initiative is a three-part process which includes: an Assessment and Template for Conservation Measures (Assessment), a Conservation Agreement, and Regional Implementation Plans. The Assessment was completed in October 2011 (Luzier et al. 2011) and December 2012 (Goodman and Reid 2012), and the Conservation Agreement was signed by tribal, state and federal partners on 20 June 2012 (USFWS 2012). Through the Initiative, lamprey restoration efforts are coordinated with large-scale restoration activities for salmonids listed under the U.S. Endangered Species Act (ESA 1973). By evaluating the results of the risk assessments and the ongoing salmon and lamprey conservation measures, restoration gaps were identified for lamprey (Luzier et al. 2011; Goodman and Reid 2012; USFWS 2019). Restoration measures to fill these gaps are prioritized and implemented through ongoing assessments in an adaptive management framework (Wang and Schaller 2015).

One of the key areas of uncertainty identified through the Initiative was the impact of climate change on Pacific Lamprey and how these effects would influence the priorities for restoration actions (Luzier et al. 2011; Goodman and Reid 2012). Therefore, a consistent and thorough climate change vulnerability assessment is extremely important to inform how to address key threats by prioritizing restoration actions for rivers of the western U.S.

A pilot climate change vulnerability assessment to help illustrate the importance of informing Pacific Lamprey restoration activities was conducted using the NatureServe Climate Change Vulnerability Index (CCVI) (Schaller and Wang 2011; Young et al. 2011) by applying the currently available downscaled environmental changes for air temperature and moisture (Figure 1).



Figure 1. Pacific Lamprey NatureServe Climate Change Vulnerability Index results for mid and end-century time periods using the CMIP3 downscaled moisture and air temperature from ensemble model under the A1b and A2 carbon emission scenarios (Schaller and Wang 2011).

We concluded from the pilot study results and expert opinion (Bruce Young, NatureServe, personal communication) that incorporating specific hydrologic changes would greatly improve the assessment of climate change impacts for Pacific Lamprey. Therefore, we modified the CCVI to accommodate more specific information on changes in stream conditions. This modified tool provided a scoring system for indexing Pacific Lamprey vulnerability to the impacts of climate change and serves as a hybrid framework using trend and trait-based information. This is a model construct that performed relatively well in an evaluation of climate change vulnerability assessments (Wheatley et al. 2017). We applied this system to Pacific Lamprey with existing information provided by the downscaled climate predictions (Coupled Model Intercomparison Project 5 [CMIP5] 2013). We evaluated how climate change predictions shifted specific environmental indicators such as hydrologic timing and stream temperature. We then assessed how these environmental changes effect the vulnerability of Pacific Lamprey.

Pacific Lamprey, an anadromous species, has multiple life stages in the freshwater and marine environment. The life span of Pacific Lamprey ranges from about 4 to 13 years. Pacific Lamprey spends the majority of their life cycle in freshwater (3–7 years as larvae and 0–2 years as adult migrants) and up to 3.5 years in a marine parasitic stage (Beamish 1980; Clemens et al. 2017). Pacific Lamprey larvae undergo major physiological and morphological changes during their metamorphosis into their parasitic stage and transition to seawater. Peak outmigration of the metamorphosed juveniles or transformers occurs primarily during winter and spring freshets but some outmigration also occurs throughout the year (Goodman et al. 2015).

We use the life stage nomenclature of Clemens (2019) when characterizing the impacts of environmental change on lamprey. Changes in the hydrologic regime, as measured by the change in hydrograph timing, would affect larval, transformer, juvenile and adult life stages of Pacific Lamprey. Downstream movement in larval, transformer and juvenile Pacific Lamprey coincides with increases in stream discharge (Beamish and Levings 1991; Dawson et al. 2015). Earlier peak flows could prematurely move larval and transformer lamprey (prior to completing metamorphosis) to estuary and ocean environments. This could result in exposing these life stages to saline conditions prior to making the physiological changes needed to accommodate osmoregulatory function. Changes in outmigration timing in salmon and steelhead populations cause smolt mortality as well as delayed mortality at subsequent life stages (Budy et al. 2002; Scheuerell et al. 2009; Petrosky and Schaller 2010) and likely extends to other anadromous species. Changes in hydrologic timing affect the upstream migration and overwintering of the lamprey adult stage. In the Columbia River (at Bonneville Dam) lamprey run timing shifted progressively earlier from 1939 to 2007, coincident with decreasing Columbia River discharge and increasing water temperature; migration timing was earliest in warm, low-discharge years and latest in cold, high-flow years (Keefer et al. 2009).

Along with discharge, stream temperature is an important cue for initiation of downstream migration (Potter and Huggins 1973; Dawson et al. 2015). Increased water temperatures both in magnitude and timing affect multiple life stages of Pacific Lamprey. For example, increased stream temperatures could increase respiration rates for adult lamprey that are holding before spawning. These increased respiration rates come at an energetic cost that could cause increases in pre-spawning mortality or could decrease egg production and viability resulting in a reduction of reproductive rates for these populations (Moser et al. 2015).

Water temperature is a critical cue in the metamorphosis of lampreys transforming from the larval to the juvenile stage. Temperature influences the onset of metamorphosis, the rate of development during metamorphosis and the incidence of metamorphosis within a population (Dawson et al. 2015). Metamorphosing sea lamprey exposed to a large change in temperature (from 8 to 21 °C) were smaller than metamorphosing lamprey exposed to a smaller change in temperature (from 8 to 13 °C) possibly because of the energetic cost to maintaining body size in warmer temperatures (Holmes and Lin 1994; Holmes and Youson 1997; Dawson et al. 2015). In a study by Holmes and Youson (1998), the optimal temperature for metamorphosis was 21 °C when comparing to 9, 13, 17, 21 and 25 °C (Dawson et al. 2015). The incidence of metamorphosis is expected to decrease when the temperature is higher than 21 °C (Holmes and Youson 1998). Additionally, long-term studies show that low temperatures in the winter are necessary to ensure that physiological conditioning (increase in lipid concentration) occurs (Lowe et al. 1973; O'Boyle and Beamish 1977; Dawson et al. 2015) prior to rising temperatures in the spring and onset of metamorphosis. Studies on the effect of water temperature on rearing larval lamprey estimate the ultimate upper incipient lethal temperature to be 27.7-28.5 °C (Uh and Whitesel 2016). In a study by Meeuwig et al. (2005), survival of embryonic and newly hatched Pacific Lamprey pro-larvae was highest at 18 °C when compared to 10, 14 and 22 °C while survival at 22 °C was significantly lower than at the other temperatures. In summary, Clemens et al. (2017) identified temperatures of 20 °C or higher as being consistent with stress, tissue damage, and potential mortality for lamprey. In addition, changes to stream temperature regimes can obstruct with and create mismatches in the timing of the key seasonal activities of migration, spawning and embryonic development for Pacific Lamprey (Maitland et al. 2015; Clemens et al. 2017).

We evaluated the climate change vulnerability risk for Pacific Lamprey in 15 rivers of the west coast of the U.S. (Figure 2). These river basins ranged from Northern California to the Canadian border.



Figure 2. The 15 river basins and larger geographic groupings used for the Pacific Lamprey vulnerability assessment.

We evaluated this risk under two different greenhouse gas emission scenarios (which include greenhouse gas emission, carbon concentration and land use trajectories; van Vuuren et al. 2011) and for two time periods (mid-century 2040–2069 and end-century 2070–2099). We compared and contrasted climate change vulnerability risk for Pacific Lamprey across the 15 river basins to see if there were any geographic patterns in vulnerability and to inform restoration actions and monitoring and evaluation needs. We also evaluated whether climate change would have a greater impact on Pacific Lamprey vulnerability in highly altered rivers.

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# Methods

The NatureServe CCVI calculator is a tool that provides a categorical scoring system for indexing species vulnerability to the impacts of climate change. The general description of the CCVI approach for Pacific Lamprey was taken from NatureServe Guidelines (Young et al. 2011). The CCVI calculator divides the CCVI into two components: the exposure to climate change across the range of the species within the assessment area and the sensitivity of the species to climate change (Young et al. 2011). The index represents the consequences of species vulnerability (species sensitivity) to changing global patterns in precipitation and temperature. None of the sensitivity factors will influence the index score if the climate in an assessment area remains relatively stable, resulting in the species likely scoring at the less vulnerable end of the range. Conversely, a large change in temperature or precipitation will amplify the effect of any related sensitivity and will influence the index to score at the high end of vulnerability (Young et al. 2011).

Direct exposure is the magnitude or predicted temperature and moisture change (precipitation and the influence on stream flow) across the range of species within the assessment area (Young et al. 2011). The direct exposure is predicted by 10 General Circulation Models (GCM); under two future greenhouse gas emission scenarios (Representative Concentration Pathway (RCP) 4.5 optimistic and RCP 8.5 pessimistic).

As described in Young et al. (2011), sensitivities are composed of two categories: indirect exposure and species sensitivity. Indirect exposure characterizes the impact of sea level



Figure 3. Relation between exposure to local climate change and sensitivity factors (modified from Young et al. 2011, Figure 1).

rise, natural and anthropogenic barriers and land use changes from human response to climate change on the species of interest. Species sensitivities characterize how the biology and ecological preferences of a species influences how vulnerable a species is to environmental shifts from climate change projections. Following the approach of Luzier et al. (2011), we applied the assessment at the hydrologic unit code [HUC] 4 (Seaber et al. 1987)); because it provided the highest degree of specificity for demographics and threats, assessing vulnerability patterns, and to identify any relative strongholds or weak areas for Pacific Lamprey conservation . We calculated the CCVI for two time periods; mid-century (2040–2069) and end-century (2070–2099).

The NatureServe calculator integrates direct exposure and species sensitivities to generate a CCVI (Figure 3). The calculator combines information on exposure and sensitivity to produce a numerical sum. The sum or score is converted into a categorical index by comparing it to threshold values. The six possible indices are Extremely Vulnerable (EV; score >10), Highly Vulnerable (HV; score <10 and  $\geq$ 7), Moderately Vulnerable (MV; score <7 and  $\geq$ 4), Presumed Stable (PS; score <4 and  $\geq$ 0), Increase Likely (IL; score <0) and Insufficient Evidence (IE). Therefore, the CCVI outcomes can range from increasing lamprey vulnerability (extremely vulnerable) to decreasing lamprey vulnerability (increase likely) to climate change.

# Modification of CCVI technique to accommodate Pacific Lamprey

We made the following modifications to estimate vulnerability indices for lamprey:

- 1. For direct exposure inputs, we incorporated the most current downscaled air temperature data (CMIP5 2013) converted to stream temperature, and runoff and baseflow data routed via a stream network to produce estimates of average daily flow to calculate hydrologic timing (see details below in hydrologic timing section) (Taylor et al. 2012). In order to incorporate the stream temperature exposure input distributions into Section A of the NatureServe calculator, we conducted a sensitivity analysis on the method for creating distributions from downscaled temperature results and how this would affect the CCVI. Specifically, we analyzed how selection of the value for the most vulnerable end of the bin of exposure distribution affects the exposure score (using 0.7 or 0.8 as the upper end value) and how the starting point of the distribution (90th vs. 95th percentile of historical August mean stream temperature for the insignificant/low bin), also impacted the exposure score. We used August mean temperature because it typically represents the warmest period of the year (climate change scenario forecasts also exhibited the largest change from historical temperatures in August) and the time frame that would pose the most challenges to metabolic rates of larval, transforming and adult life stages. August temperatures were used in studies assessing the impacts of climate change on other aquatic species in rivers of the Pacific Northwest (Isaak et al. 2012, 2018).
- 2. In the sensitivity section, we did not apply sensitivity factors that were not applicable to lamprey (dependence on ice, ice-edge, or snow cover habitats; restriction to uncommon geological features; pollinator versatility [plants only]; and dependence on other species for propagule dispersal) and added historical thermal and hydrologic timing niches to the list of sensitivity factors. These sensitivity factors were applied to assess lamprey: dispersal and movements; thermal niche; hydrologic niche; dependence on specific disturbance regimes; dependence on other species to generate habitat;

dietary versatility; host parasite relationship that forms part of an interspecific interaction; and measured genetic variation.

- 3. Pacific Lamprey climate change vulnerability risk was assessed for 15 HUC 4 basins across much of the species range in the coterminous U.S. (Table 1). We selected these basins across the distribution of Pacific Lamprey in the U.S. to represent the ecological and environmental conditions experienced by lamprey. The 15 basins selected each had specific downscaled climate predictions to capture variation in exposure experienced by lamprey. In addition, we grouped the basins into Larger Geographic Groupings (LGG) to capture similar ecological and environmental conditions as compared to the full range of basins (Table 1). These geographic groupings helped to facilitate analysis of Pacific Lamprey climate change vulnerability.
- 4. We modified the CCVI model to run multiple basins and climate scenarios at once.

Table 1. Summary of CCVI risk scores by GCM in both RCP 4.5 and 8.5 greenhouse gas emission scenarios for mid and end-century time periods.

CSIRO-Mk3-6-0	4.5 mid	4.5 end	8.5 mid	8.5 end	NORESM1-M	4.5 mid	4.5 end	8.5 mid	8.5 end
Umpqua	11.02	12.17	12.17	13.66	Umpqua	8.00	12.17	10.64	13.66
Chehalis	4.84	5.50	4.84	6.00	Chehalis	4.16	5.34	4.84	6.00
Necanicum	5.42	5.01	5.01	5.75	Necanicum	3.50	5.01	5.01	5.75
Klickitat	2.66	2.66	3.34	3.34	Klickitat	2.66	2.66	2.66	3.34
Umatilla	5.99	5.99	5.99	5.99	Umatilla	4.33	4.67	5.00	5.00
Yakima	10.85	9.66	10.85	10.85	Yakima	7.98	10.02	8.83	10.85
Methow	7.66	7.66	7.16	8.85	Methow	6.65	7.16	7.16	8.85
Asotin	7.33	7.33	7.33	7.99	Asotin	5.66	6.65	7.33	7.99
Selway	7.32	7.32	7.32	8.68	Selway	6.99	7.32	7.32	8.68
MF Salmon	9.00	9.00	11.01	11.01	MF Salmon	7.98	9.00	9.00	11.01
Sandy	4.66	4.66	4.66	5.34	Sandy	3.33	4.33	3.67	4.66
Tualatin	3.67	4.66	4.66	4.66	Tualatin	3.33	3.67	3.67	4.00
Skagit	8.26	8.26	8.26	8.26	Skagit	6.75	8.26	7.49	8.26
Smith	4.34	4.26	4.26	5.17	Smith	3.33	4.34	4.26	5.17
SF Eel	6.01	6.01	6.01	7.25	SF Eel	4.66	5.93	6.01	7.25
Min	2.66	2.66	3.34	3.34	Min	2.66	2.66	2.66	3.34
Max	11.02	12.17	12.17	13.66	Max	8.00	12.17	10.64	13.66
Average	6.60	6.68	6.86	7.52	Average	5.29	6.43	6.19	7.36
Standard Dev.	2.48	2.45	2.69	2.78	Standard Dev.	1.95	2.60	2.29	2.93
bcc-csm 1-1-m	4.5 mid	4.5 end	8.5 mid	8.5 end					
bcc-csm 1-1-m Umpqua	4.5 mid 9.49	4.5 end 12.17	8.5 mid 11.02	8.5 end 12.17					
bcc-csm 1-1-m Umpqua Chehalis	4.5 mid 9.49 4.16	4.5 end 12.17 5.34	8.5 mid 11.02 4.84	8.5 end 12.17 6.00					
bcc-csm 1-1-m Umpqua Chehalis Necanicum	4.5 mid 9.49 4.16 4.66	4.5 end 12.17 5.34 5.42	8.5 mid 11.02 4.84 5.42	8.5 end 12.17 6.00 6.16					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat	4.5 mid 9.49 4.16 4.66 2.66	4.5 end 12.17 5.34 5.42 3.34	8.5 mid 11.02 4.84 5.42 2.66	8.5 end 12.17 6.00 6.16 3.34					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla	4.5 mid 9.49 4.16 4.66 2.66 4.99	4.5 end 12.17 5.34 5.42 3.34 4.99	8.5 mid 11.02 4.84 5.42 2.66 4.33	8.5 end 12.17 6.00 6.16 3.34 5.99					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 3.99	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 3.99 7.52	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit Smith	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52 3.41	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 3.99 7.52 4.26	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52 4.26	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26 4.26					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit Smith SF Eel	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52 3.41 3.50	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 3.99 7.52 4.26 6.01	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52 4.26 6.01	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26 4.26 6.01					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit Smith SF Eel Min	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52 3.41 3.50 2.66	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 3.99 7.52 4.26 6.01 3.34	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52 4.26 6.01 2.66	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26 4.26 6.01 3.34					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit Smith SF Eel Min Max	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52 3.41 3.50 2.66 9.49	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 7.52 4.26 6.01 3.34 12.17	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52 4.26 6.01 2.66 11.02	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26 4.26 6.01 3.34 12.17					
bcc-csm 1-1-m Umpqua Chehalis Necanicum Klickitat Umatilla Yakima Methow Asotin Selway MF Salmon Sandy Tualatin Skagit Smith SF Eel Min Max Average	4.5 mid 9.49 4.16 4.66 2.66 4.99 8.35 6.16 5.99 6.65 7.98 3.99 3.33 7.52 3.41 3.50 2.66 9.49 5.52	4.5 end 12.17 5.34 5.42 3.34 4.99 9.17 7.84 6.65 8.01 9.00 3.99 7.52 4.26 6.01 3.34 12.17 6.51	8.5 mid 11.02 4.84 5.42 2.66 4.33 9.17 7.84 5.66 8.35 9.00 4.33 3.67 7.52 4.26 6.01 2.66 11.02 6.27	8.5 end 12.17 6.00 6.16 3.34 5.99 10.85 8.85 7.99 8.68 9.00 4.66 4.00 8.26 4.00 8.26 6.01 3.34 12.17 7.08					

#### **Direct exposure**

The Intergovernmental Panel on Climate Change (IPCC) gathers and reviews global climate models (GCMs). The ensemble of the GCMs is called the Coupled Model Intercomparison Project (CMIP). The CMIP3 model ensemble was released in 2010 (Meehl et al. 2007). The CMIP5 model ensemble was released in 2013 (Taylor et al. 2012). Differences in global temperature projections are largely attributable to a change in greenhouse gas emission scenarios. In a previous pilot study, CMIP3 was employed (Schaller and Wang 2011). We used CMIP5 outputs to develop the downscaled stream temperature and hydrologic data for exposure inputs in this study.

GCMs project large-scale climate patterns (including precipitation, evaporation and temperature) for the earth under two different carbon emission scenarios (RCP 4.5 and RCP 8.5). The RCP 4.5 is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Smith and Wigley 2006; Clarke et al. 2007; Wise et al. 2009; van Vuuren et al. 2011). The RCP 8.5 scenario is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007; van Vuuren et al. 2011). The GCM model outputs are downscaled for hydrology and temperature for the CMIP5 multi-model dataset (CMIP5 2013). We were able to acquire downscaled hydrology and temperature data from 10 GCMs used in the CMIP5 ensemble. We used three of the model outputs (NorESM1-M, bcc-csm1-1-m and CSIRO-Mk3-6-0) to bound the potential future hydrologic and stream temperature conditions. The NorESM1-M GCM is the Norwegian Earth System model used for predicting climate under varying carbon emission scenarios (Bentsen et al. 2013). The bcc-csm1-1-m is a short-term climate prediction model system under varying carbon emission scenarios (Ding et al. 2000; CSMD 2005). The CSIRO-Mk3-6-0 climate system model is used for predicting climate under varying carbon emission scenarios (Gordon et al. 2002). We selected these three models out of the 10 possible GCMs in CMIP5 to represent the median (bcc-csm1-1-m), optimistic conditions (NorESM1-M) and pessimistic (CSIRO-Mk3-6-0) hydrologic conditions for future projections.

# Hydrologic timing

The vulnerability assessment for Pacific Lamprey requires estimates of daily historical and future flows. The CMIP5 downscaled runoff and baseflow data were routed via a stream network to produce estimates of average daily flow for each of the selected HUC 4 basins across the region (Table 1). This stream flow routing was produced by the Climate Impacts Group for the 15 basins using the Variable Infiltration Capacity (VIC) model (Climate Impacts Group 2015). Inputs were from three CMIP5 GCM projections (defined above) spanning the historical period 1951–2006, mid-century (2040–2069) and end-century (2070–2099) for both a low and high greenhouse gas emission scenario (RCPs 4.5 and 8.5, respectively).

In order to develop direct exposure for hydrologic timing, we compared future to historical distributions of hydrologic mean dates. The timing of migration of anadromous fish species, such as Pacific salmon (*Oncorhynchus* spp.), Atlantic salmon (*Salmo salar*), American shad (*Alosa sapidissima*) and alewives (*Alosa pseudoharengus*), at specific locations during the life cycle have been observed to vary with water temperature and river flow (Mundy and Evenson 2011). Changes in hydrologic timing affect the upstream migration and overwintering of the adult stage and earlier peak flows could prematurely move larval and transformer lamprey (prior to completing metamorphosis) to estuary and 38 🕢 C. J. WANG ET AL.

ocean environments (see introduction above). In order to capture how the hydrograph varies (including the effect of peak flows) within a basin, we used hydrologic mean date to consistently represent these changes that could impact a number of lamprey life stages (described above) across all of the 15 HUCs. Because of large variation in stream volume among the 15 HUCs, many other hydrologic indicators could not be standardized to evaluate the impacts to lamprey populations. The hydrologic mean date, for each year, represents the date when 50% of the volume of the river for the water year passes a downstream location in each of the 15 basins we evaluated. The yearly hydrologic mean date is calculated in the following steps: (1) for each day of the water year, calculate the water year; (2) multiply the proportion by the Julian date for each day of the water year; and (3) calculate the mean date by summing all daily results in step 2 (daily prop.×Julian date) over the water year.

To accomplish this for the three selected GCMs and for both RCP 4.5 and RCP 8.5 climate change scenarios, we conducted the following steps:

- 1. Calculated hydrologic mean dates for each year in the historical period 1951-2006.
- 2. Calculated historical grand mean of the annual hydrologic mean dates from 1951 to 2006.
- 3. Calculated how many days the yearly hydrologic mean date (for years 1951–2006) deviates from the historical grand mean. This is termed the days of deviation. The days of deviation each year for 1951–2006, constitutes the historical distribution for days of deviation.
- 4. Created bins, using the historical days of deviation, to bound what lamprey have historically experienced in each of the 15 basins.
  - a. Bin 1 Low/Insignificant Days of deviation from grand mean within or equal to two standard deviations from historical distribution of deviation days (1951–2006) for each basin.
- 5. Bin 2 Medium Low Days of deviation from grand mean (by HUC) outside of two standard deviations from historical distribution of deviation days (1951–2006) or equal to the 5th or 95th percentile for the HUC.
- 6. Bin 3 Medium High Days of deviation from grand mean (by HUC) outside of the 5th or 95th percentile for historical distribution of deviation days (1951–2006) or equal to 5th or 95th percentile in the LGG.
- Bin 4 High Days of deviation from grand mean (by HUC) outside of the 5th and 95th percentile for historical distribution of deviation days (1951–2006) in the LGG or equal to the 5th and 95th percentile in the U.S. geographic range of lamprey (range).
- 8. Bin 5 Very High Days of deviation from grand mean (by HUC) outside 5th and 95th percentile for historical distribution of deviation days (1951–2006) over the range.
- From the downscaled GCM average daily flow, we calculated the projected future hydrologic mean date for each year of the mid-century 2040–2069 and end-century 2070–2099. Next, we calculated how many days the yearly hydrologic mean date (for years 2040–2099) deviates from the historical grand mean. This is termed the days of deviation. The days of deviation for each year 2040–2069 constitutes the mid-century future projected distribution for days of deviation. The days of deviation for each year 2070–2099 constitute the end-century future projected distribution for days of deviation.

The future projected distribution was constructed by placing annual days of deviation (for mid-century and end-century) into the historical bins developed in Step 4 above. These distributions are used as the exposure inputs into the NatureServe CCVI model.

# Stream temperature

The vulnerability assessment for Pacific Lamprey requires estimates of daily historical and future August stream temperatures. For this direct exposure, we focused on August stream temperatures because they historically represent the warmest monthly temperatures recorded annually for the 15 basins we assessed.

We calculated August mean air temperatures from downscaled daily August air temperatures derived from CMIP5 GCM projections (defined above) for each of the selected basins across the region (Figure 2). These mean temperatures are from the mouth of each basin. Using CMIP3 downscaled air temperature, the NorWeST group developed a stream temperature data base and models for characterizing changes from historical conditions to those for projected climate scenarios. The NorWeST group provided parameters to convert the change in air temperatures to stream temperatures (https://www.fs.fed.us/rm/ boise/AWAE/projects/NorWeST.html). They accomplished this by building a temperature model that is fit to all the stream data within each domain (approximating an LGG) to produce an air temperature conversion parameter that represents historical climate runs (Hostetler et al. 2011). Figure 4 provides the conversion parameters from air to stream temperature (Dan Isaak, NorWest group, personal communication). Using these parameters (for the appropriate basins), we converted (multiply air temperature by conversion parameter) the August mean air temperatures to August mean stream temperatures for the 15 basins using outputs from the three CMIP5 GCM projections (defined above) spanning the historical period 1951-2006, mid-century (2040-2069) and end-century



NorWest Model Domain

Figure 4. The air/stream temperature relations to convert CMIP5 air temperature to stream temperature for Climate Change Vulnerability Index estimates (D. Isaak NorWeST 2015).

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(2070-2099) for both a low and high greenhouse gas scenario (RCPs 4.5 and 8.5, respectively).

In order to develop direct exposure for stream temperatures, we needed to compare future to historical distribution of August mean stream temperature. To accomplish this for the three selected GCMs and for both RCP 4.5 and RCP 8.5 scenarios, we conducted the following steps:

- 1. Calculated August mean stream temperature for each year of the projected historical dataset (1951–2006).
- 2. Calculated historical grand mean for August stream temperature from the annual August mean temperatures from 1951 to 2006.
- 3. Calculated how many degrees the August mean each year (1951–2006) deviates from historical grand mean. This is termed the degrees of deviation. The degrees of deviation calculated for August in the years 1951–2006, constitutes the historical distribution for the degrees of deviation.
- 4. In order to inform the criteria for constructing the bins to develop historical and future distributions for temperature exposure inputs we ran a sensitivity analysis. We ran the simulations for bcc-csm 1-1-m evaluating the effect of the criteria for the upper end of temperature exposure score (0.7 and 0.8 values) to the CCVI. And the starting point for the bins, 90th percentile versus 95th percentile. We ran simulations to evaluate these sensitivities for RCP 4.5 and 8.5 mid-century and end-century. For

CSIRO-Mk3-6-0	4.5 mid	4.5 end	8.5 mid	8.5 end	NORESM1-M	4.5 mid	4.5 end	8.5 mid	8.5 end
Umpqua	EV	EV	EV	EV	Umpqua	HV	EV	EV	EV
Chehalis	MV	MV	MV	MV	Chehalis	MV	MV	MV	MV
Necanicum	MV	MV	MV	MV	Necanicum	PS	MV	MV	MV
Klickitat	PS	PS	PS	PS	Klickitat	PS	PS	PS	PS
Umatilla	MV	MV	MV	MV	Umatilla	MV	MV	MV	MV
Yakima	EV	HV	EV	EV	Yakima	HV	EV	HV	EV
Methow	HV	HV	HV	HV	Methow	MV	HV	HV	HV
Asotin	HV	HV	HV	HV	Asotin	MV	MV	HV	HV
Selway	HV	HV	HV	HV	Selway	MV	HV	HV	HV
MF Salmon	HV	HV	EV	EV	MF Salmon	HV	HV	HV	EV
Sandy	MV	MV	MV	MV	Sandy	PS	MV	PS	MV
Tualatin	PS	MV	MV	MV	Tualatin	PS	PS	PS	PS
Skagit	HV	HV	HV	HV	Skagit	MV	HV	HV	HV
Smith	MV	MV	MV	MV	Smith	PS	MV	MV	MV
SF Eel	MV	MV	MV	HV	SF Eel	MV	MV	MV	HV
bcc-csm 1-1-m	4.5 mid	4.5 end	8.5 mid	8.5 end					
Umpqua	HV	EV	EV	EV					
Chehalis	MV	MV	MV	MV	-				
Necanicum	MV	MV	MV	MV					
Klickitat	PS	PS	PS	PS					
Umatilla	MV	MV	MV	MV	_				
Yakima	HV	HV	HV	EV	Most Vulnerable				
Methow	MV	HV	HV	HV	Most stable				
Asotin	MV	MV	MV	HV					
Selway	MV	HV	HV	HV					
MF Salmon	HV	HV	HV	HV					
Sandy	PS	PS	MV	MV					
Tualatin	PS	PS	PS	PS					
Skagit	HV	HV	HV	HV					
Smith	PS	MV	MV	MV					
	DC	N 41 /	N // /	N A) /					

 Table 2. Summary of CCVI risk categories by GCM in both RCP 4.5 and 8.5 greenhouse gas emission scenarios for mid and end-century time periods.

all combinations the majority of the 15 populations have no or small difference between 0.7 and 0.8 and 90th percentile to 95th percentile (Table 2). So we used 95th percentile and 0.7 for the resulting CCVI scores. Given the results of the sensitivity analyses, we ran all the remaining simulations at the temperature exposure score of 0.7 and at the 95th percentile of historical temperature.

- 5. Created bins, using the historical distribution for degrees of deviation, to bound what lamprey have experienced in the 15 basins (HUCs):
  - Bin 1 Low/Insignificant Degrees of deviation from grand mean (by HUC) is inside or equal to the HUC's 95th percentile of the historical distribution of degrees of deviation (1951–2006).
- 6. Bin 2 Medium Low Degrees of deviation from grand mean is greater than the HUC's 95th percentile or less than or equal to the HUC's 95th percentile of the historical distribution of degrees of deviation (1951–2006).
- Bin 3 Medium High Degrees of deviation from grand mean is greater than the HUC's 99th percentile or less than or equal to the highest 99th percentile (for a HUC) in the LGG of the historical distribution of degrees of deviation (1951–2006).
- 8. Bin 4 High Degrees of deviation from grand mean is greater than the LGG's 99th percentile or less than or equal to the highest 99th percentile (for a HUC) in the range of the historical distribution of degrees of deviation (1951–2006).
- 9. Bin 5 Very High Degrees of deviation from grand mean is greater than the highest 99th percentile (for a HUC) in the range of the historical distribution of degrees of deviation (1951–2006).
- From the three GCMs downscaled temperature datasets (air temperature converted to stream temperature), we calculated projected future August mean stream temperature for each year of the mid-century 2040–2069 and end-century 2070–2099. Next, we calculated how many degrees the yearly August mean (for years 2040–2099) deviates from the historical grand mean. This is termed the degrees of deviation. The yearly degrees of deviation for 2040–2069 constitute the mid-century future projected distribution. The yearly degrees of deviation for 2070–2099 constitute the end-century future projected distribution.
- The future projected distribution was constructed by placing annual degrees of deviation (for mid-century and end-century) into the historical bins developed in Step 4 above. These distributions are used as the exposure inputs into Section A of calculator tab in the NatureServe CCVI model.

# Sensitivities

Sensitivities are composed of two categories; indirect exposure and species sensitivity (Figure 3). Indirect exposure characterizes the impact of sea level rise, natural and anthropogenic barriers, and land use changes from human response to climate change on the species of interest (Young et al. 2011). Species sensitivities characterize how biology and ecological preferences of Pacific Lamprey could influence how vulnerable a species is to environmental shifts from climate change. Historical thermal and historical hydrological niche sensitivity factors are directly influenced by downscaled temperature and hydrologic timing model projections to characterize species vulnerability.

To define the sensitivity of Pacific Lamprey we used research, monitoring and evaluation data from Luzier et al. (2009, 2011). The 2009 publication describes regional differences in Pacific Lamprey biology, population structure, habitat preferences and threats. 42 🔄 C. J. WANG ET AL.

Luzier et al. (2011) outline the population demographics, threats and overall risk for Pacific Lamprey throughout the U.S. range. In addition to these documents, we used professional judgment from lamprey experts on the Lamprey Technical Workgroup and the Initiative Conservation Team. We used this information to inform the answers to questions for section B (indirect exposure) and section C (sensitivities) that are inputs to the NatureServe CCVI. These inputs are placed into categories: greatly increase vulnerability, increase vulnerability, somewhat increase vulnerability, neutral, somewhat decrease vulnerability and decrease vulnerability.

# Indirect exposure

Exposure to sea level rise – For each basin we chose the level of vulnerability from Greatly Increase to Somewhat Decrease based on percentage of range subject to sea level rise (see Section B1 for bin definition; Young et al. 2011, p. 16)

Distribution relative to natural barriers – For each basin we chose the level of vulnerability from Greatly Increase to Neutral based on the status of natural barriers and lamprey's ability to shift for climate change (see Section B2 for bin definition; Young et al. 2011, p. 18–19).

Distribution relative to anthropogenic barriers – For each basin we chose the level of vulnerability from Greatly Increase to Neutral based on the status of anthropogenic barriers and lamprey's ability to shift for climate change (see Section B2 for bin definition; Young et al. 2011, p. 18–19).

Predicted impact of land use changes from human response to climate change – For each basin we chose the level of vulnerability from Increase to Decrease based on the natural history requirements of lamprey and compatibility with mitigation (see Section B3 for bin definition; Young et al. 2011, p. 20–21).

# Species sensitivity

Dispersal and movements – For each basin we chose level of vulnerability from Greatly Increase to Somewhat Decrease based on ability of lamprey to disperse and move (see Section C1 for bin definition; Young et al. 2011, p. 22–24)

Historical Thermal Niche – Historical thermal niche measures large-scale temperature variation that a species has experienced in recent historical times (Young et al. 2011). We scored this sensitivity (Figure 3 – Temperature Regime) using the following steps:

- 1. Used converted August air temperature to stream temperatures for years 1951–2006 (historical).
- 2. Calculated the difference between historical August 95th percentile stream temperature and August 5th percentile stream temperature.
- Created equal bins using August stream temperature 20th percentile and August maximum stream temperature to bound what lamprey have experienced in the 15 basins.
   a. Greatly Increase: <1.17° of temperature variation</li>
- 4. Increase: equal to 1.17 or less than or equal to 1.50
- 5. Somewhat Increase: equal to 1.51 or less than or equal to 1.83
- 6. Neutral: equal to 1.84 or less than or equal to 2.15
- 7. Somewhat Decrease: >2.15
- For each basin, the level of vulnerability was determined based on how much temperature variation lamprey have experienced historically (1951–2006) (see Section C2ai for bin definition; Young et al. 2011, p. 24–25).

Physiological Thermal Niche – For each basin we chose level of vulnerability from Greatly Increase to Somewhat Decrease based percentage of occurrences or range restricted to cold environments (see Section C2aii for bin definition; Young et al. 2011, p. 25)

Historical Hydrologic Niche – Historical hydrological niche measures large-scale hydrologic timing variation that a species has experienced in recent historical times. We modified this sensitivity (Figure 3 – Hydrologic Regime) from precipitation (described in Young et al. 2011) to hydrologic timing to accommodate more specificity of impacts to aquatic species. We scored this sensitivity using the following steps.

- 1. Calculated the standard deviation for days of deviation from mean Julian date for the historical period 1951–2006. We calculated two sets of bins to incorporate uncertainty concerning the historical hydrologic niche scores.
- 2. Create bins using both 5th and 95th percentile
  - a. Greatly Increase: <5.25 days of deviation from mean
- 3. Increase: equal to 5.25 or less than or equal to 16
- 4. Somewhat Increase: equal to 16.1 or less than or equal to 26
- 5. Neutral: equal to 26.1 or less than or equal to 35.84
- 6. Somewhat Decrease: >35.85
- Create bins using both 1st and 99th percentile
- a. Greatly Increase: <5.09 days of deviation from mean
- Increase: equal to 5.09 or less than or equal to 17.49
- Somewhat Increase: equal to 17.5 or less than or equal to 29.9
- Neutral: equal to 29.91 or less than or equal to 42.29
- Somewhat Decrease: >42.29
- For each basin two levels of vulnerability were used (one score for each set of bins) based on how much variation in hydrologic timing lamprey have experienced historically (1951–2006) (see Section C2bi for bin definition pg 26; Young et al. 2011).

Physiological Hydrologic Niche – For each basin we chose level of vulnerability from Greatly Increase to Somewhat Decrease based percentage of occurrences or range dependent on specific hydrologic timing regime (see Section C2bii for bin definition; Young et al. 2011, p. 27–28).

Dependence on specific disturbance regime likely to be impacted by climate change – For each basin we chose level of vulnerability from Increase to Decrease based on level of response by lamprey to disturbance regime and climate change interaction (see Section C2c for bin definition; Young et al. 2011, p. 28–29).

Dependence on other species to generate habitat – For each basin we chose level of vulnerability from Greatly Increase to Neutral based on lamprey's dependence on another species or multiple species to generate habitat (see Section C4a for bin definition; Young et al. 2011, p. 31–32).

Dietary versatility – For each basin we chose level of vulnerability from Increase to Somewhat Decrease based on lamprey's dietary versatility (see Section C4b for bin definition; Young et al. 2011, p. 32).

Forms part of another interspecific interaction – For each basin we chose level of vulnerability from Increase to Neutral based on how lamprey need to be involved in interspecific relationships (see Section C4e for bin definition; Young et al. 2011, p. 33).

Measured genetic variation – For each basin we chose level of vulnerability from Increase to Somewhat Decrease based on level of genetic variation in lamprey compared to other aquatic species (see Section C5a for bin definition; Young et al. 2011, p. 33).

# Simulations

Once we parameterized the NatureServe calculator based on the description of steps above for direct exposure and sensitivities (indirect exposure and species), we ran simulations to capture a range of future conditions. Each simulation provides an estimate of CCVI, which captures future conditions based on the GCM and RCP scenario used to develop the exposure inputs to the NatureServe calculator. These simulations estimate CCVIs for each of the 15 basins (that span the selected geographic range for Pacific Lamprey in the U.S.) and for two time periods. These simulations, over the range of future conditions and geographic range, were performed to represent uncertainty in biology, ecology, and environmental conditions for Pacific Lamprey. The following are the steps we implemented:

For calculating CCVIs, we limited our simulations to three GCMs representing median, optimistic, and pessimistic projected downscaled exposure (see description above). The simulation results are contrasted across GCMs to capture model uncertainty.

The GCMs project climate patterns under two different greenhouse emission scenarios; both a low and high greenhouse gas scenario (RCPs 4.5 and 8.5, respectively; van Vuuren et al., 2011). We calculated CCVIs for each of the 15 HUCs at both the mid-Century (2040–2069) and end-century (2070–2099) time frame, using the GCM inputs described above for RCP 4.5 and 8.5. These results are presented by GCM to capture the uncertainty in projected greenhouse gas emission scenarios.

# Results

#### **Results by GCM**

#### CSIRO-Mk3-6-0

For RCP 4.5 mid-century, the CCVI scores averaged 6.60 (MV). The most vulnerable basin was the Umpqua (EV; 11.02) and the least vulnerable was the Klickitat (PS; 2.66). For end-





Figure 6. Pacific Lamprey Climate Change Vulnerability Index simulations using downscaled bcc-csm1-1-m model exposure.



century the CCVI scores averaged 6.68 (MV). The Umpqua was the most vulnerable (EV; 12.17) and the least vulnerable was the Klickitat (PS; 2.66) (Tables 1 and 2; Figure 5).

For RCP 8.5 mid-century, the CCVI scores averaged 6.86 (MV). The most vulnerable was the Umpqua (EV; 12.17) and the least vulnerable was the Klickitat (PS; 3.34). For the end-century the CCVI scores averaged 7.52 (HV). The most vulnerable was the Umpqua (EV; 13.66) and the least vulnerable was the Klickitat (PS; 3.34) (Tables 1 and 2; Figure 5).



Figure 8. Pacific Lamprey Climate Change Vulnerability Index simulations. Comparison for three Global Climate Models for mid-century and Representative Concentration Pathway 4.5.

The results for all three GCMs (*CSIRO-Mk3-6-0, bcc-csm 1-1-m and NORESM1-M*) for RCP 4.5 and 8.5 and at mid and end of century consistently demonstrated that the most vulnerable basin was the Umpqua and the least vulnerable was the Klickitat (Tables 1 and 2; Figures 6–8).

The CCVI scores for CSIRO-Mk3-6-0 increase on average from mid-century to endcentury for both emission scenarios. The three exceptions are for the Necanicum, Yakima, and Smith HUCs, however, two of these are so minor they did not yield a change in the vulnerability index (Tables 1 and 2). The one exception was the Yakima, which was downgraded one category from EV to HV under the 4.5 RCP emission scenario.

The CCVI scores for the CSIRO-Mk3-6-0 also increased on average from RCP 4.5 to 8.5 for both time periods. The two exceptions occur under the RCP 4.5 scenario are for the Necanicum, and Smith HUCs, however, these exceptions are so minor they did not yield a change in the vulnerability index (Tables 1 and 2). The variation in CCVI scores among HUCs increases from mid-century to end of century, and also increases from RCP 4.5 to 8.5 emission scenarios.

#### bcc-csm 1-1-m

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For RCP 4.5 mid-century, the CCVI scores averaged 5.52 (MV). For end-century the CCVI scores averaged 6.51 (MV) (Table 1).

For RCP 8.5 mid-century, the CCVI scores averaged 6.27 (MV). For end-century the CCVI scores averaged 7.08 (HV) (Table 1).

The CCVI score results for the two time periods for bcc-csm 1-1-m on average increase from mid-century to end-century for both emission scenarios. When we evaluated the results by emission scenario, CCVI scores for bcc-csm 1-1-m increased on average from RCP 4.5 to 8.5 for both mid-century and end-century simulations. The two exceptions are the Umatilla and Asotin HUCs, however, these are so minor they did not yield a change in the vulnerability index (Tables 1 and 2). The variation in CCVI scores among HUCs increases from mid-century to end of century, and also increases from RCP 4.5 to 8.5 emission scenarios.

# NORESM1-M

For RCP 4.5 mid-century, the CCVI scores averaged 5.29 (MV). For end-century, the CCVI scores averaged 6.43 (MV) (Table 1).

For RCP 8.5 mid-century, the CCVI scores averaged 6.19 (MV). For end-century, the CCVI scores averaged 7.36 (HV) (Table 1).

The CCVI scores for NORESM1-M increase on average from mid-century to end-century for both emission scenarios. When we evaluated the results by emission scenario, the CCVI scores for NORESM1-M increased on average from RCP 4.5 to 8.5 for both midcentury and end-century simulations. The variation in CCVI scores among HUCs increases from mid-century to end of century, and also increases from RCP 4.5 to 8.5 emission scenarios.

# **Results across GCMs**

Overall, the three GCMs represented the median hydrologic conditions (bcc-csm1-1-m), optimistic conditions (NorESM1-M) and pessimistic conditions (CSIRO-Mk3-6-0). The results were consistent for RCP 4.5 mid-century and end-century and RCP 8.5 mid-century. However, for RCP 8.5 end of century, bcc-csm1-1-m the CCVI scores where slightly more optimistic than NorESM1-M. The CCVI results calculated from the selected models for the most part adhere to pessimistic and optimistic hydrologic designations (similar to temperature designations). We believe these three models provide reasonable contrast to bound projected future exposure conditions for anadromous lamprey and salmonids.

For RCP 4.5 mid-century, the CCVI scores averaged 5.29 (MV) for NorESM1-M; 5.52 (MV) for bcc-csm 1-1-m and 6.60(MV)(for CSIRO-Mk3-6-0 Tables 1 and 2; Figure 8). For RCP 4.5 end-century, the CCVI scores averaged 6.43 (MV) for NorESM1-M; 6.51 (MV) for bcc-csm 1-1-m and 6.68 (MV) (for CSIRO-Mk3-6-0 Tables 1 and 2; Figure 9). For RCP 8.5 mid-century, the CCVI scores averaged 6.19 (MV) for NorESM1-M; 6.27(MV) for bcc-csm 1-1-m and 6.86 (MV) for CSIRO-Mk3-6-0 (Tables 1 and 2; Figure 10). For RCP 8.5 end-century, the CCVI scores averaged 7.36 (HV) for NorESM1-M; 7.08 (HV) for bcc-csm 1-1-m and 7.52 (HV) for CSIRO-Mk3-6-0 (Tables 1 and 2; Figure 11).



Figure 9. Pacific Lamprey Climate Change Vulnerability Index simulations. Comparison for three Global Climate Models for end-century and Representative Concentration Pathway 4.5.

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Figure 10. Pacific Lamprey Climate Change Vulnerability Index simulations. Comparison for three Global Climate Models for mid-century and Representative Concentration Pathway 8.5.



Figure 11. Pacific Lamprey Climate Change Vulnerability Index simulations. Comparison for three Global Climate Models for end-century and Representative Concentration Pathway 8.5.

On average the CCVI scores increased from mid-century to end-century for all of the GCMs. In RCP 4.5 for bcc-csm 1-1-m and NORESM1-M, these score changes result in a category increase from MV to HV. However, in RCP 8.5 the CCVI scores are high starting in mid-century so the category remains in HV for the end-century. When we evaluated the results by emission scenario, on average the CCVI scores increased from RCP 4.5 to 8.5 for all of the GCMs. In mid-century on average, these score changes resulted in a category increase from MV to HV for bcc-csm 1-1-m and NORESM1-M. However, for CSIRO-Mk3-6-0 the CCVI scores are high starting in RCP 4.5 so the category remains in HV for RCP 8.5.

# Discussion

Pacific Lamprey abundance is well below historical levels and distribution has contracted within the U.S. range (Wang and Schaller 2015). One of the key areas of uncertainty was the impact of climate change on Pacific Lamprey and how these effects would influence the priorities for restoration actions (Luzier et al. 2011; Goodman and Reid 2012). The study demonstrated that lamprey populations generally became increasingly vulnerable when going from greenhouse emission scenario RCP 4.5 to RCP 8.5 in all three GCMs for both mid-century and end-century. If we continue to observe greenhouse gas emission levels associated with the RCP 8.5, Pacific Lamprey will be at greater risk to climate change impacts.

In the pilot study of Pacific Lamprey climate change vulnerability, the input data were from the CMIP3 ensemble GCM for the A1b and A2 emission scenarios. Since then, the IPCC generated new projections in the CMIP5 project for ten different GCMs. We were able to modify the NatureServe CCVI calculator to accommodate the more recent climate predictions from the IPCC. We used the downscaled information from their climate study and customized the calculator to more directly characterize hydrologic and stream temperature changes in 15 rivers occupied by Pacific Lamprey in the western U.S. These stream temperature and hydrologic factors were used in assessing climate change vulnerability because they typically influence survival and productivity of aquatic species (Holmes and Lin 1994; Holmes and Youson 1998; Scheuerell et al. 2009; Petrosky and Schaller 2010; Potter and Huggins 1973). We believe our modified tool for calculating CCVI provided an improvement over approaches that purely use professional judgment or indirect measures of environmental change such as air temperature and moisture indices. By evaluating basin specific changes in stream temperature and hydrologic conditions due to climate change, this approach more directly assessed the climate change impacts to Pacific Lamprey. Compared to the pilot study, we were able to assess climate change vulnerability at a basin scale that better matches with downscaled hydrologic information and is more spatially informative for identifying stream restoration actions.

We greatly improved the efficiency of the model by developing the capability to simultaneously run simulations for multiple basins, carbon emission scenarios and time periods. This allowed us to directly compare the CCVI results among basins over time under different carbon emission scenarios.

In order to modify the model from using air temperature to directly incorporating stream temperature, we conducted a sensitivity analysis to optimize model performance. The majority of the 15 basins had no or small difference in CCVI score for bcc-csm 1-1-m at the upper end of the temperature exposure score of 0.7 and at the 95th percentile of historical temperature; therefore, we used this more conservative model structure for all simulations and are confident that we did not overestimate the risk levels.

We believe the three GCMs used in this study provided reasonable contrasts to bound projected future exposure conditions over the range of basins we examined, because the results were generally consistent with NORESM1-M being the most optimistic and CSIRO-Mk3-6-0 being the most pessimistic. The CCVI scores increased from mid-century to end-century for all three GCMs. One exception occurred for CSIRO-Mk3-6-0 in the Yakima basin where the CCVI decreased in risk category from EV to HV under the RCP 4.5 scenario from mid-century to end-century (Table 2). This exception was due to the anomaly that hydrologic timing was more similar to that of the historical hydrologic timing for end-century than for the mid-century; resulting in a lower CCVI score for the Yakima basin only. Regardless of the GCM or geographic location of the HUC, Pacific Lamprey vulnerability to climate change exhibited increases from mid-century to end-

century. By the end of century, the projections of stream temperature and hydrologic change are large for all GCMs, therefore yielding similar vulnerability scores. Because we observe this consistent pattern of increasing risk over time, we recommend that restoration efforts should focus on actions that address key threats such as passage barriers and dewatering and floodplain degradation. In order to reduce this risk by end-century, these actions should be implemented early in the mid-century. These types of restoration actions could address passage barriers and dewatering threats in a shorter time span, than other types of actions that may take decades to restore channel or stream function.

In all three GCMs, the Umpqua and Yakima were the most vulnerable HUCs. Their CCVIs were in the EV risk category for the 8.5 emission scenarios by the end-century. The Umpqua had relatively low variation (compared to the other HUCs) in its historical stream temperature and hydrologic timing, which contributed to the high CCVI score. The impact of where anthropogenic barriers are located relative to historical lamprey distribution in the Yakima HUC appears to have played a large role in the high CCVI score.

The Skagit, Methow, Asotin and Selway were the next most vulnerable HUCs. In the majority of simulations for the three GCMs in the 8.5 emission scenarios, their CCVIs go to HV risk category by the end-century. The Skagit also had relatively low variation (compared to the other HUCs) in its historical stream temperature and hydrologic timing compared to projected values under climate change which contributed to the higher CCVI score. The impact of where anthropogenic barriers is located relative to historical lamprey distribution in the Asotin and Selway HUCs appears to have played a large role in their higher CCVI scores. The Methow had both low variation in historical hydrologic timing and impacts from anthropogenic barriers, which contributed to its higher CCVI score.

The most stable HUC is the Klickitat, where the CCVIs are PS for all GCMs, RCPs and time periods. The Klickitat had wide variation in historical stream temperature and relatively less impact from anthropogenic barriers. Additionally, there is not a lot of change predicted for hydrologic timing through the end-century for both RCP 4.5 and 8.5.

The next most stable HUCs are Sandy, Tualatin, Chehalis, Necanicum, Umatilla, Smith and Eel; where the CCVIs stay in MV from mid- century to end-century in both 4.5 and 8.5 emission scenarios for all three GCMs (Table 2). All of these HUCs have more historical variation in stream temperature and hydrologic timing compared to the HUCs showing more vulnerability to climate change. Even though the Umatilla has similar impact from anthropogenic barriers when compared to HUCs with higher CCVI scores, it is relatively less vulnerable due to high historical variation in stream temperature. If a lamprey population historically experienced a large variation in stream temperature, in the CCVI construct the population would be less sensitive to projected change than a population that historically experienced much smaller variation in stream temperature.

When we looked for a pattern of vulnerability scores from northern to southern latitudes, there was no obvious pattern. However, the results from this study suggest that climate change impacts to Pacific Lamprey vulnerability are magnified in highly altered rivers. Within the Columbia River Basin the least vulnerable HUCs (Klickitat, Sandy, Tualatin, Umatilla) were downstream of the majority of mainstem hydroelectric facilities. Lamprey in the upper basins need to navigate through 8–9 mainstem dams and reservoirs on their upstream and downstream migrations. Similarly, in coastal areas the least vulnerable HUCs (Smith, Eel and Necanicum) were located in rivers with fewer mainstem dams.

# How can CCVI information help inform restoration priorities?

Our results reveal that the Umpqua HUC consistently exhibited the highest level of climate change vulnerability for all three GCMs and both emission scenarios. The Umpqua HUC is included in the South Coast Oregon Regional Implementation Plan (RIP) of the Pacific Lamprey Conservation Agreement (Coates and Poirier 2017).

Here we provide an example of how the CCVI study can be coupled with RIP recommendations to identify priority and timing of restoration work and projects. In the RIP, the following key threats have been identified for the Umpqua:

# Dewatering and flow management

Water withdrawals for irrigation, municipal, or residential purposes leave many watersheds in the South Coast sub-region dewatered or with inadequate flow during summer and fall months. In recent years, early cessation of rains, below average snow packs, and above average air temperature have further contributed to reduced stream flows in much of the region. Low flow conditions may reduce spawning habitat availability, prevent access to backwater or side channel habitats, create low water barriers, and may contribute to mortality if incubating eggs or burrowing larvae are dewatered or exposed to a high temperature or low oxygen environment.

# Stream and floodplain degradation

Stream and floodplain degradation is widespread throughout the South Coast sub-region. Within lowlands, wetlands and side channels have been channelized, diked, diverted or drained to prevent flooding, create farmland or pastures and provide land for commercial and residential development. In upland areas, historical and ongoing timber practices, agriculture, road construction and urbanization have deforested or altered the function and diversity of riparian vegetation. Suction dredge mining is of particular concern in the South Umpqua, Umpqua and Illinois River. This practice may increase sedimentation and turbidity, alter stream channel topography, disturb and destabilize spawning and rearing habitat, kill incubating eggs and larvae, and may re-suspend contaminants such as mercury or other heavy metals in the water body.

Large-scale salmonid restoration programs are currently increasing instream physical structure and repairing riparian vegetation in rivers of the west where Pacific Lamprey inhabit (Budy and Schaller 2007; Wang and Schaller 2015). In order to mitigate the risk from climate change toward the end of century, additional actions that expeditiously address gaps in lamprey restoration will be prioritized. In the Umpqua, actions that can increase flow, create backwater habitat, restore riparian vegetation that increases stream shading (leading to decreased stream temperature) (Wondzell et al. 2019) and reduce stream and floodplain degradation may have a higher likelihood of mitigating the increasing risk from climate change impacts.

All 15 basins from the CCVI study have corresponding RIPs. A framework could be developed from the Umpqua example on how to couple CCVI results with RIPs to systematically and consistently inform restoration priorities and monitoring and evaluation needs.

The present CCVI modeling covers 15 basins of the western U.S., which represent a large geographic scope of Pacific Lamprey distribution. However, now that additional downscaled climate change information is available; the analysis can be expanded to

additional basins and may possibly change future CCVI scores for populations across the range.

We applied our modified Climate Change Vulnerability Index tool to consistently score the vulnerability of Pacific Lamprey to future climate change and found that if greenhouse gas emission levels associated with the RCP 8.5 are realized, Pacific Lamprey will be at greater risk to climate change impacts. Increases in heat trapping gases, from worldwide carbon emissions, accumulate in the ocean as increased ocean heat content (Lijing et al. 2019). Recent empirical information, from an expanded ocean monitoring system, has demonstrated a sharp increase in heat content over the last decade that is consistent with model projections from the RCP 8.5 scenario (Lijing et al. 2019). These changes also negatively impact inland stream temperatures and hydrologic conditions that affect Pacific Lamprey and other freshwater fishes. In order to reduce these risks to Pacific Lamprey, along with maintaining extensive long-term salmon restoration actions in these basins, additional restoration actions (that fill the gaps in lamprey restoration needs) that rapidly and effectively reduce the impact of existing threats should be given priority.

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# **Disclosure statement**

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# References

- Beamish RJ. 1980. Adult biology of the river lamprey (*Lampetra ayresi*) and the Pacific lamprey (*Lampetra tridentata*) from the Pacific coast of Canada. Can J Fish Aquat Sci. 37:1906–1923.
- Beamish RJ, Levings CD. 1991. Abundance and freshwater migrations of the anadromous parasitic lamprey, *Lampetra tridentata*, in a tributary of the Fraser River, British Columbia. Can J Fish Aquat Sci. 48(7):1250–1263.
- Bentsen M, Bethke I, Debernard JB, Iversen T, Kirkevåg A, Seland Ø, Drange H, Roelandt C, Seierstad I. A, Hoose C, et al. 2013. The Norwegian Earth System Model, NorESM1-M Part 1: description and basic evaluation of the physical climate. Geosci Model Dev. 6(3):687–720.
- Budy P, Schaller HA. 2007. Evaluating tributary restoration potential for Pacific salmon recovery. Ecol App. 17(4):1068–1086.
- Budy P, Thiede GP, Bouwes N, Petrosky CE, Schaller HA. 2002. Evidence linking delayed mortality of Snake River salmon to their earlier hydrosystem experience. North Am J Fish Manage. 22(1):35–51.
- Clarke LE, Edmonds JA, Jacoby HD, Pitcher H, Reilly JM, Richels R. 2007. Scenarios of greenhouse gas emissions and atmospheric concentrations. Sub-report 2.1a of Synthesis and Assessment Product 2.1. Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.
- Clemens BJ. 2019. A Call for Standard Terminology for Lamprey Life Stages. Fisheries. 44(5):243-245.
- Clemens BJ, Beamish RJ, Coates KC, Docker MF, Dunham JB, Gray AE, Hess JE, Jolley JC, Lampman RT, McIlraith BJ, et al. 2017. Conservation challenges and research needs for Pacific Lamprey of the Columbia River. Fisheries. 42(5):268–280.
- Climate Impacts Group. 2015. Data for downscaled hydrologic information from the new global model runs for 15 river basins in the western U.S. Climate Impacts Group. Seattle, WA: College of the Environment, University of Washington.
- [CSMD] Climate System Modeling Division. 2005. An introduction to the fist-generation operational climate model at National Climate Center. Adv Clim Syst Model. 1:14.
- Coates K, Poirier JP. 2017. Pacific Lamprey 2017 regional implementation plan for the Oregon Coast Regional Management Unit South Coast sub-region. Submitted to the Pacific Lamprey Conservation Initiative Conservation Team June 9, 2017; [accessed 2019 December 19]. https://www.fws.gov/pacific-lamprey/PLCI\_RIPs.cfm.
- Coupled Model Intercomparison Project 5 [CMIP5]. 2013. World Climate Research Programme-Program for Climate Model Diagnosis and Intercomparison. [accessed 2019 December 19]. https://pcmdi.llnl. gov/mips/cmip5/data-portal.html.
- Dawson HA, Quintella BR, Almeida PR, Treble AJ, Jolley JC. 2015. The ecology of larval and metamorphosing lampreys. In: MF Docker, editor. Lampreys: biology, conservation and control. Dordrecht, Germany: Springer; p. 75–137. (Fish and fisheries series 37; vol. 1).
- Ding Y, Ni Y, Zhang X, Li W, Dong M, Zhao Z-C, Li Z, Shen W, editors. 2000. Introduction to the short-term climate prediction model system. Beijing, China: China Meteorological Press; 500 pp.
- Docker MF, Hume JB, Clemens BJ. 2015. Introduction: surfeit of Lampreys. In: MF Docker, editor. Lampreys: biology, conservation and control. Springer; p. 1–34. (Fish and fisheries series 37; vol. 1).
- Goodman DH, Reid SB. 2012. Pacific Lamprey (*Entosphenus tridentatus*) assessment and template for conservation measures in California. Arcata, CA: U.S. Fish and Wildlife Service; 117 pp; [accessed 2019 December 19]. http://www.fws.gov/arcata/fisheries/reports/technical/PLCI\_CA\_Assessment\_Final.pdf.

- Goodman DH, Reid SB, Som NA, Poytress WR. 2015. The punctuated seaward migration of Pacific Lamprey (Entosphenus tridentatus): environmental cues and implications for streamflow management. Can J Fish Aquat Sci. 72:1–12.
- Gordon HB, Rotstayn LD, McGregor JL, Dix MR, Kowalczyk EA, O'Farrell SP, Waterman LJ, Hirst AC, Wilson SG, Collier MA, et al. 2002. The CSIRO Mk3 Climate System Model [Electronic publication]. Aspendale: CSIRO Atmospheric Research. (CSIRO Atmospheric Research technical paper; no. 60); 130 pp; [accessed 2019 December 19]. http://www.dar.csiro.au/publications/gordon\_2002a.pdf.
- Holmes JA, Lin P. 1994. Thermal niche of larval sea lamprey. *Petromyzon marinus*. Can J Fish Aquat Sci. 53:253-262.
- Holmes JA, Youson JH. 1997. Laboratory study of the effects of spring warming and larval density on the metamorphosis of sea lampreys. Trans Am Fish Soc. 126(4):647–657.
- Holmes JA, Youson JH. 1998. Extreme and optimal temperatures for metamorphosis in sea lampreys. Trans Am Fish Soc. 127(2):206–211.
- Hostetler SW, Alder JR, Allan AM. 2011. Dynamically downscaled climate simulations over North America: methods, evaluation and supporting documentation for users: U.S. Geological Survey Open-File Report 2011-1238, Dordrecht, Germany; 64 p; [accessed 2019 December 19]. http://regclim.coas.oregonstate.edu/index.html.
- Isaak D, Luce CH, Horan DL, Chandler GL, Wollrab SP, Nagel DE. 2018. Global warming of Salmon and Trout rivers in the Northwestern U.S.: Road to ruin or path through purgatory? Trans Am Fish Soc. 147(3):566–587.
- Isaak DJ, Wollrab S, Horan D, Chandler G. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. Clim Change. 113(2):499–524.
- Keefer ML, Moser ML, Boggs CT, Daigle WR, Peery CA. 2009. In migration timing of adult Pacific lamprety (*Lampetra tridentata*) in the Columbia River. Environ Biol Fish. 85(3):253–264.
- Lijing C, Abraham J, Hausfather Z, Trenberth K. 2019. How fast are the oceans warming? Science. 363 (6423):128-129.
- Lowe DR, Beamish FWH, Potter IC. 1973. Changes in the proximate body composition of the landlocked sea lamprey *Petromyzon marinus* (L.) during larval life and metamorphosis. J Fish Biol. 5(6):673–682.
- Luzier CW, Schaller H, Brostrom J, Cook-Tabor C, Goodman DH, Nelle RD, Ostrand K, Strief B. 2009. Proceedings of the Pacific lamprey conservation initiative work session, October 28–29, 2008. Portland, OR: U.S. Fish and Wildlife Service, Regional Office.
- Luzier CW, Schaller HA, Brostrom JK, Cook-Tabor C, Goodman DH, Nelle RD, Ostrand K, Streif B. 2011. Pacific Lamprey (*Entosphenus tridentatus*) assessment and template for conservation measures. Portland, OR: U.S. Fish and Wildlife Service; 282 pp.
- Maitland PS, Renaud CB, Quintella BR, Close DA, Docker MF. 2015. Conservation of native lampreys. In MF Docker, editor. Lampreys: biology conservation and control. Vol. 1, New York: Springer, Fish and Fisheries Monograph Series; pp. 375–428.
- Meehl GA, Covey C, Delworth T, Latif M, McAvaney B, Mitchell JFB, Stouffer RJ, Taylor KE. 2007. The WCRP CMIP3 multi-model dataset: a new era in climate change research. Bull Am Meteorol Soc. 88(9):1383–1394.
- Meeuwig MH, Bayer JM, Seelye JG. 2005. Effects of temperature on survival and development of early life stage pacific and Western Brook Lampreys. Trans Am Fish Soc. 134(1):19–27.
- Moser ML, Almeida PR, Kemp PS, Sorensen PW. 2015. In: MF Docker, editor. Lampreys: biology, conservation and control. Dordrecht, Germany: Springer; p. 215–263. (Fish and fisheries series 37; vol. 1).
- Mundy PR, Evenson DF. 2011. Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. ICES J Mar Sci. 68 (6):1155–1164.
- O'Boyle BN, Beamish FWH. 1977. Growth and intermediary metabolism of larval and metamorphosing stages of the landlocked sea lamprey *Petromyzon marinus* (L.). Environ Biol Fish. 2:103–120.
- Petrosky CE, Schaller HA. 2010. Influence of river conditions during seaward migration and ocean conditions on survival rates of Snake River Chinook salmon and steelhead. Ecol Freshwater Fish. 19: 520–536.
- Potter IC, Huggins RJ. 1973. Observations on the morphology, behavior and salinity tolerance of downstream migrating river lamprey (*Lampetra fluviatilis*). J Zool. 169(3):365–379.
- Riahi K, Grübler A, Nakicenovic N. 2007. Scenarios of long-term socio-economic and environmental development under climate stabilization. Technol Forecasting Social Change. 74(7):887–935.
- Schaller HA, Wang C. 2011. Consideration of climate change impacts for restoration of Pacific Lamprey a Pilot study of Pacific Lamprey climate change vulnerability. Presented at Investigating the World of

Lamprey Biology and Ecology symposium at the American Fisheries Society 141st Annual Meeting, Seattle, Washington.

- Scheuerell MD, Zabel RW, Sandford BP. 2009. Relating juvenile migration timing and survival to adulthood in two species of threatened Pacific salmon (*Oncorhynchus* spp.). J Appl Ecol. 46(5):983–990.
- Seaber PR, Kapinos FP, Knapp GL. 1987. Hydrologic Unit Maps: U.S. Geological Survey Water-Supply Paper 2294; Reston, VA: U.S. Geological Survey; pp. 63.
- Smith SJ, Wigley TML. 2006. MultiGas forcing stabilization with minicam. Energy J Special Issue. 3: 373–392.
- Taylor KE, Stouffer RJ, Meehl GA. 2012. An Overview of CMIP5 and the experiment design. Bull Am Meteorol Soc. 93(4):485–498.
- Uh CT, Whitesel TA. 2016. The potential threat of a warming climate to Pacific Lamprey: thermal tolerance of larvae. Poster session presented at: American Fisheries Society 2016 Oregon Chapter 52nd Annual Meeting, Seaside, OR.
- van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F, et al. 2011. The representative concentration pathways: an overview. Clim Change. 109(1-2):5-31.
- Wang C, Schaller HA. 2015. Conserving Pacific Lamprey through collaborative efforts. Fisheries. 40(2): 72–79.
- Wheatley CJ, Beale CM, Bradbury RB, Pearce-Higgins JW, Critchlow R, Thomas CD. 2017. Climate change vulnerability for species assessing the assessments. Glob Change Biol . 23(9):3704–3715.
- Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S.J, Janetos A, Edmonds J. 2009. Implications of limiting CO<sub>2</sub> concentrations for land use and energy. Science. 324(5931): 1183–1186.
- Wondzell SM, Diabat M, Haggerty R. 2019. What matters most: are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? J Am Water Resour Assoc. 55(1): 116–132.
- Young B, Bayers E, Graves K, Hall K, Hammerson G, Reader A. 2011. Guidelines for using NatureServe Climate Change Vulnerability Index. Release 2.1. NatureServe 2011, Arlington, VA; [accessed 2019 December 19]. https://connect.natureserve.org/science/climate-change/ccvi.
- [USFWS] U.S. Fish and Wildlife Service. 2012. Pacific Lamprey Conservation Agreement. Portland, OR: U.S. Fish and Wildlife Service; 57 pp; [accessed 2019 December 19]. http://www.fws.gov/pacific/ Fisheries/sphabcon/Lamprey/lampreyCI.html.
- [USFWS] U.S. Fish and Wildlife Service. 2019. Pacific Lamprey (*Entosphenus tridentatus*) assessment. Portland, OR: U.S. Fish and Wildlife Service.