



EPA/600/R-17/052 November 2017 www.epa.gov/ord









Predicting patterns of vulnerability to climate change in near coastal species using an algorithmbased risk assessment framework





Office of Research and Development National Health and

Environmental Effects Research Laboratory Western Ecology Division THIS PAGE INTENTIONALLY BLANK.

Predicting Patterns of Vulnerability to Climate Change in Near Coastal Species Using an Algorithm-Based Risk Assessment Framework

By

Henry Lee II, U.S. EPA, Western Ecology Division Christina Folger, U.S. EPA, Western Ecology Division Deborah A. Reusser, USGS (Emeritus) Patrick Clinton, U.S. EPA, Western Ecology Division Rene Graham, CSS

Environmental Protection Agency Office of Research and Development National Health and Environmental Effects Research Laboratory Western Ecology Division

Disclaimer

This document has been reviewed by the U.S. Environmental Protection Agency, Office of Research and Development, and approved for publication. Any mention of trade names, products, or services does not imply an endorsement by the U.S. Government or the U.S. Environmental Protection Agency. The EPA does not endorse any commercial products, services, or enterprises.

Recommended Citation

Lee II, H., Folger, C.L. Reusser, D.A., Clinton, P. and Graham, R. 2017. Predicting Patterns of Vulnerability to Climate Change in Near Coastal Species Using an Algorithm-Based Risk Framework. EPA/600/R-17/052. 299 pages.

Contents

Disclaimer		ii
Contents		iii
Change Lo	g	xi
Acronyms a	and Abbreviations	xiii
Acknowled	gements	xvi
Executive S	Summary	xvii
Section 1. 1.1 1.2 1.3 1.4 1.5	Introduction and Overview Problem Statement Goals and Objectives Scope of Document Geographic and Taxonomic Scope 1.4.1 Geographic Scope 1.4.2 Taxonomic Scope and Standardization Algorithm-Based Approach to Climate Risk Assessment	1 6 7 8 8 9 11
Section 2. 2.1 2.2 2.3	Risk Categories and Overall Vulnerability Individual Risk Values Resilience Traits Overall Risk - "One Way to Live, A Thousand Ways to Die"	16 16 19 20
Section 3. 3.1 3.2 3.3 3.4 3.5	Relative Abundance Estimates Background Abundant or Rare? Hierarchical Relative Abundance Classification Schema Importance of Habitat Area Data Sources - Quantitative Data 3.5.1 Dominance Normalized Relative Abundance (DNRA) 3.5.2 Quantitative Cut Points for Abundance Classes	
3.6 3.7	Data Sources – Online Biodiversity Databases.Data Sources – Text-Based Information3.7.1Parsing Natural History Texts.3.7.2Negative Evidence: The Dog That Didn't Bark.	34 34 34 35
3.8	 Hybrid Approach to Estimating Ecoregion Abundances	
Section 4. 4.1	Baseline/Status Risks Introduction 4.1.1 Observed versus Preferred Habitats and Environmental Ranges	
4.2	Baseline/Status Traits – Biogeographic Distributions	50

	4.2.1	Introduction	50
	4.2.2	Relationship of Range Size to Vulnerability	50
	4.2.3	Endemics – Vulnerability Trait	51
	4.2.4	Restricted Distribution – Vulnerability Trait	52
	4.2.5	Wide Distributions – Resilience Trait	53
	4.2.6	Arctic Endemics – Vulnerability Trait	58
	4.2.7	Small Island Distributions – Resilience Trait	59
	4.2.8	Nonindigenous Species – Resilience Trait	61
4.3	Baselir	ne/Status Traits – Relative Abundance Patterns	62
	4.3.1	Background on Relative Abundance Metrics	62
	4.3.2	Hyper-Rare Species – Vulnerability Trait	63
	4.3.3	Abundant Someplace/Rare Everywhere – Vulnerability and Resilience Traits	63
	4.3.4	Population Trends – Vulnerability and Resilience Traits	64
	4.3.5	Southern Ecoregion Rare and Ecoregion to North Abundant – Vulnerability Trait	t 67
	4.3.6	Northern Transients – Resilience Trait	68
4.4	Baselir	ne/Status Traits – Life History	69
	4.4.1	Introduction	69
	4.4.2	Symbiotic Relationships – Vulnerability Trait	69
	4.4.3	Habitat Specialization	71
	4.4.4	Trophic Specialization	73
	4.4.5	Anadromous/Catadromous	77
	4.4.6	Growth and Productivity	78
4.5	Climate	e-Adjusted Baseline/Status Risks - Linking Baseline/Status & Climate Risks	82
Section 5.	Tempe	erature Predictions	84
5.1	Introdu	iction	84
5.2	Future	Temperature Predictions	85
5.3	Ecoreg	jional Thermal Windows Approach	87
	5.3.1	ETW Approach	87
	5.3.2	Conceptual Framework	90
	5.3.3	Within-Ecoregion Temperature Risks ("Worst-Case Scenario")	91
	5.3.4	Abundance-Normalized Temperature Risks ("Ecosystem Services Risks")	92
	5.3.5	Evaluation of ETW Thermal Thresholds	93
	5.3.6	Data Source and Analysis	94
5.4	Biogeo	graphical Thermal Limit Approach	97
	5.4.1		97
	5.4.2	BTL Approach	97
	5.4.3	Comparison of ETW and BTL	103
5.5	Northe	rn Colonization	104
Section 6.	Ocean	/Coastal Acidification	106
6.1	Backo	round	106
6.2	Backgi	round and Projected pH and Aragonite Saturation State (Ω a) Values	107
	6.2.1	pH Values	107
	6.2.2	Aragonite Saturation State (Ωa) Values	108
6.3	Toxico	logy Approach to Establishing pH Effects Thresholds	111
	6.3.1	Introduction	111
	6.3.2	Use of Maximum Acceptable Toxicant Concentrations (MATCs) to Generate	
		Comprehensive Effects Thresholds	111

	6.3.3 Ocean Acidification Population Viability Effects Thresholds	146
6.4	Biotic Traits Modifying Sensitivity and Temperature-Adjusted Ocean Acidification Risks	149
6.5	Risk Type and Risk Algorithm	153
	6.5.1 Risk Type	153
	6.5.2 Risk Algorithm and Assignment of Sensitivity Classes	154
Section 7.	Sea Level Rise	. 155
7 1	Introduction	155
7.2	Overview of SLR Approach	156
7.3	Eustatic Rates.	157
7.4	Regional Isostatic Rates	158
7.5	Duration	161
7.6	Constrained Versus Unconstrained Habitats	161
7.7	High and Low Exposure Habitats	162
7.8	Habitat Thresholds	162
	7.8.1 Introduction	162
	7.8.2 Rocky Intertidal and Mussel Beds	165
	7.8.3 Open Coastal Beaches, Backshore Beach Zones and Algal Beach Wrack	172
	7.8.4 Emergent Marsh	172
	7.8.5 Submerged Aquatic Vegetation	185
	7.8.6 Tide Flats - Unvegetated Sand/Mud & Ovster Beds & Macroalgal Mats	191
	7.8.7 Mandroves	200
7.9	Sea Level Rise Risks for Invertebrate and Fish Species	205
	7.9.1 Depth Preferences	206
	7.9.2 Habitat Preferences	207
	7.9.3 Final SLR Risk	207
Section 8.	Uncertainty Analysis and Quality Assurance/Quality Control	209
8.1	Uncertainty Analysis - Overview	209
8.2	Sources and Levels of Uncertainty	209
8.3	Reporting of Uncertainty	214
8.4	EPA/ORD's Quality Assurance/Quality Control	214
Appendix A	Under The Hood – Hardware, Software, Access Levels, & Backups	
A-1	Servers	217
A-2	Software	218
A-3	Access Levels	218
A-4	Backup Strategy	219
Appondix E	Quitnutting Dick Accomment Results	222
	Vula arability Summary Output	222
B-1	Vulnerability Summary Output	ZZZ
D-2 B 3	Outputting Results for Northern Colonization	224
D-3		229
Appendix C	2. Near-Coastal Habitat Areas and GIS Metadata	231
C-1	Introduction	231
C-2	Near-Coastal Habitat Areas – Patterns of Offshore and Estuarine Habitats	231
C-3	Near-Coastal Habitat Areas – Geospatial Analysis	237
C-4	Calculation and Metadata for Computing Habitat Thresholds for West Coat Intertidal Roc	жy
	Habitats due to Sea Level Rise using LiDAR Topobathy	239

Appendix D	D. Evaluation of Temperature as Determinant for Warm-Edge Range Limits	of Marine
	Species243	
D-1	Physiological	
D-2	Range Shifts	
D-3	Impaired Fecundity/Recruitment	
D-4	Trophic Dynamic Shifts	
Appendix E		250
E-1	Aragonite Saturation State Projections by MEOW Ecoregion GIS Process	
E-2	NOAA Climate Projections by MEOW Ecoregion GIS Process	
Glossary of	Terms	
Bibliograph	у	

List of Tables

Table 1-1. Approaches used to predict effects of climate change on aquatic species and habitats	4
Table 1-2. Objectives of the current risk analysis framework and risk analysis of near-coastal species.	7
Table 2-1. Potential climate change effects on individuals and populations within an ecoregion	19
Table 3-1. Hypothetical example of species' abundances at an ecoregion scale.	27
Table 3-2. Definitions and quantitative cut points for the three-level relative abundance classifications.	31
Table 4-1. Baseline/status climate rules derived from biogeographic distributions, relative abundance, history traits, and population trends.	life 41
Table 4-2. Baseline/status risks derived from productivity index parameters for fish	45
Table 4-3. Guidelines to distinguish between observed versus preferred habitats and environmental conditions.	48
Table 4-4. Number of species with endemic, restricted, or wide distributions	51
Table 4-5. MEOW provinces in the four major temperature regimes.	56
Table 4-6. Arctic Ecoregions	58
Table 4-7. Number of Arctic endemics, small island colonizers, and nonindigenous species	59
Table 4-8. Small island ecoregions	61
Table 4-9. The number of species identified by each of the relative abundance rules	63
Table 4-10. Population trend classes based on percent change in population size within an ecoregion.	. 65
Table 4-11. Number of species with symbiotic relationship, habitat specialization, trophic specialization and anadromous/catadromous reproduction.	ו 71
Table 4-12. Unique habitats of limited distribution.	72
Table 4-13. Guidelines for assigning levels of trophic specialization for single and multiple feeding modes.	75
Table 4-14. Productivity index parameter thresholds for fishes	78
Table 4-15. Sebastes productivity parameters.	79
Table 4-16. Climate-adjusted baseline/status risk values	83
Table 5-1. CMIP5 annual mean surface air temperature anomalies (°C) from the 1986–2005 reference period to 2081-2100 for the four RCPs.	; 84
Table 5-2. Temperature ranges (°C) associated with different risk levels for ecoregion mean annual SSTs.	88
Table 5-3. Temperature ranges (°C) associated with different risk levels for ecoregion mean summer SSTs.	88
Table 5-4. Temperature ranges associated with different risk levels for ecoregion mean winter SSTs (JanFebMarch).	89
Table 5-5. Predicted increases in annual, summer, and winter SSTs for 2050-2099 based on the RCP 8.5 scenario (°C).	90

Table 5-6.	Number of exceedances of the moderate and high risk thresholds for annual SST based on ETW approach.	the 96
Table 5-7.	Historical and projected mean annual SSTs (°C)	. 99
Table 5-8.	Historical and projected mean annual air temperatures (°C)	100
Table 5-9.	Historical and projected mean summer air temperatures (°C)	100
Table 5-10). Historical and projected mean winter air temperatures (°C)	101
Table 5-11	. Historical and projected mean 30-m temperatures (°C)	102
Table 5-12	. Historical and projected mean 100-m temperatures (°C)	102
Table 5-13	B. Comparison of risk predictions using the ETW versus the BTL approaches.	103
Table 6-1.	Historical and projected annual pH	109
Table 6-2.	Historical and projected summer pH. `	109
Table 6-3.	Historical and projected winter pH	110
Table 6-4.	Historical and projected aragonite saturation state values	110
Table 6-5.	Summary of pH exposure experiments with decapods.	114
Table 6-6.	MATCs for pH for each decapod species based on all endpoints (comprehensive analysis).	144
Table 6-7.	Comprehensive pH thresholds for high, moderate, and low sensitivity decapods using most sensitive MATCs.	146
Table 6-8.	MATCs for pH based on the population viability endpoints for each decapod species	148
Table 6-9.	Population viability pH thresholds values for high, moderate, and low sensitivity decapods	149
Table 7-1.	Eustatic sea-level rise scenarios used as default values for ecoregion SLR risk analysis	158
Table 7-2.	Derivation of ecoregion-specific isostatic rates.	160
Table 7-3.	Habitat thresholds associated with different levels of percent habitat loss	163
Table 7-4.	Habitat threshold classes based on the percentage of habitat lost to sea level rise	165
Table 7-5.	Studies predicting percentage loss of rocky intertidal habitat due to sea level rise	167
Table 7-6.	Summary of low marsh percent habitat change under different SLR rates	174
Table 7-7.	Submerged Aquatic Vegetation (<i>Zostera marina</i>), summary of seagrass percent habitat change under different SLR values.	188
Table 7-8.	Summary of tide flat percent habitat change under different SLR rates	192
Table 7-9.	Summary of mangroves percent habitat change under different SLR values and rates	202
Table 7-10). Risk values assigned to each combination of depth, habitat and exposure classes for each habitat threshold.	ı 206
Table 8-1.	Preliminary analysis of the major sources of uncertainty in the climate risk framework	210
Table 8-2.	Level of confidence adapted from the IPCC	213

Table A-1.	Summary of the privileges associated with each level of access in CBRAT	220
Table D-1.	Summary of studies supporting the assumption that temperature sets the warm-edge range limits of marine species	∍ 246
Table E-1.	Historical climate (1956-2005) and Anomaly (2050-2099) data	251
List of Fig	gures	
Figure 1-1	. Study area and MEOW ecoregions comprising the Northeast Pacific and U.S. Arctic	11
Figure 2-1	. Conceptual view of increased likelihood of adverse impacts with increasing risk level	18
Figure 3-1	. Three-level relative abundance schema for use at regional scales	25
Figure 4-1	. Example of an endemic species, defined as occupying only one MEOW ecoregion	52
Figure 4-2.	Example of a species with a restricted distribution, defined as species occupying two MEO ecoregions.	W 53
Figure 4-3	Example of a species occupying multiple ecoregions but not classified as having a wide distribution	54
Figure 4-4	Example of a species with a wide distribution, defined as occupying three MEOW provinces.	55
Figure 4-5	. Example of an Arctic endemic, defined as a species that occurs only in Arctic ecoregions	59
Figure 4-6	. Default levels of trophic specialization based on single and two feeding modes	76
Figure 5-1	Distribution of Chionoecetes bairdi illustrating WOE, NWUE, COE, and NCUE ecoregions.	86
Figure 5-2.	Abundance pattern of <i>Hemigrapsus nudus</i> as example for calculation of abundance- normalized temperature risks.	93
Figure 5-3	. Schematic of the derivation of thermal risk values with the BTL approach	98
Figure 6-1	. Cumulative distribution of the MATCs for each decapod species based on all endpoints	146
Figure 6-2.	Cumulative distribution of the MATCs based on population viability endpoints for each decapod species.	149
Figure 6-3	Temperature-Adjusted Ocean Acidification Risks	151
Figure 7-1	Generalized sea level rise approach to calculating relative risk	157
Figure 7-2	Low marsh habitat – Constrained	185
Figure 7-3	. Tide flats – Unconstrained	199
Figure 7-4	. Tide flats - Constrained.	200
Figure B-1	. Output Vulnerability Summary screen	223
Figure B-2	. Portion of Vulnerability Summary CSV - Output for climate risks	225
Figure B-3	. Portion of Vulnerability Summary CSV - Output for baseline/status risks	226
Figure B-4	. Outputting vulnerability summary limited to species with a specific risk or resilience factor.	227
Figure B-5	. Screen for outputting risks associated with a specific climate stressor.	228
Figure B-6	. Portion of the output from an individual climate risk output.	229

Figure B-7	Northern Colonization Test screen	230
Figure B-8	. Portion of the output from Northern Colonization Test.	230
Figure C-1	. Total estuarine area in the Southern California Bight, Northern California, Oregon, Washington, Vancouver Coast and Shelf, and Puget Trough/Georgia Basin ecoregions2	233
Figure C-2	. Areas of major estuarine habitats from Puget Trough/Georgia Basin to Southern California Bight ecoregions	234
Figure C-3	. Areas of offshore versus total estuarine unconsolidated habitats by ecoregion	235
Figure C-4	. Area of major habitat types from 0-200 m offshore in the Southern California Bight Ecoregion	235
Figure C-5	. Area of major habitat types from 0-200 m offshore in the Oregon, Washington, Vancouver Coast and Shelf Ecoregion	236
Figure C-6	. Area of major habitat types from 0-200 m offshore in the Northern California Ecoregion $\!$	236
Figure C-7	. Calculation of habitat thresholds by ecoregion for rocky intertidal habitats	242

Change Log

11/22/2017: 508 compliant version.

11/22/2017: Because of its resolution, the CMIP5 model was mixing terrestrial and ocean air temperatures in the Puget Trough/Georgia Basin Ecoregion. Therefore, the Puget Trough/Georgia Basin Ecoregion air temperatures and projections were approximated by taking the average of the values in ecoregions to the north and south (North American Pacific Fjordland and Oregon, Washington, Vancouver Coast and Shelf ecoregions). The likelihood of northern colonization was recalculated using these average air values, and Tables 5-8, 5-9, and 5-10 were modified to include these new air temperatures.

THIS PAGE INTENTIONALLY BLANK

Acronyms and Abbreviations

Ωa	Aragonite saturation state
ACE	Air, Climate and Energy (EPA/ORD research program)
AOO	Area of occupancy
AVHRR	Advanced Very High Resolution Radiometer (remote sensing)
BTL	Biogeographic Thermal Limit approach
°C	Degrees Celsius
CBRAT	.Coastal Biodiversity Risk Analysis Tool
cm	.Centimeter(s)
CMIP5	Coupled Model Intercomparison Project Phase 5
COE	Coolest occupied ecoregion
DEM	Digital elevation model
DNRA	Dominance normalized relative abundance
EOO	Extent of occurrence
EIS	Environmental impact statement.
EMAP	Environmental Monitoring and Assessment Program
EPA	Environmental Protection Agency
ESLR	Eustatic sea level rise.
ESRI	Environmental Systems Research Institute
ETP	Eastern Tropical Pacific

ETW	Ecoregional Thermal Window approach
FAO	Food and Agriculture Organization of the United Nations
GAM	Generalized additive models.
GBIF	Global Biodiversity Information Facility
GIS	Geographic information system
GLM	General linear model
hr	Hour
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
k	von Bertalanffy growth coefficient
km	Kilometer(s)
Lat. & Long	Latitude and Longitude
LIDAR	Light Detection and Ranging
LME	Large Marine Ecosystems
LOAEL	Lowest observed adverse effect level
m	Meter(s)
MATC	Maximum acceptable toxicant concentration
MEOW	Marine Ecoregions of the World
MHHW	Mean higher high water

MLLW	Mean lower low water
mm	.Millimeter(s)
MTP	Mexican Tropical Pacific Ecoregion
NCUE	Next coolest unoccupied ecoregion
ND	No data
NEP	Northeast Pacific
netCDF	Network Common Data Form
NIS	Nonindigenous species
NOAA	National Oceanic and Atmospheric Administration
NOAEL	No observed adverse effect level
NWI	National Wetlands Inventory
NWP	Northwest Pacific
NWUE	Next warmest unoccupied ecoregion
OA	Ocean acidification
OBIS	Ocean Biogeographic Information System
Ра	Pascal
PaCOOS	Pacific Coast Ocean Observing System
PDF	Portable Document Format
PFMC	Pacific Fishery Management Council
pH _F	Free pH scale

рН _{NBS}	National Bureau of Standards pH scale
pHsws	Seawater pH scale
pH⊤	.Total pH scale
PICES	North Pacific Marine Science Organization
PSU	Practical salinity units
r	Intrinsic rate of increase
RACE	Resource Assessment and Conservation Engineering (NOAA)
RCP	Representative concentration pathways
RSLR	Relative sea level rise
SAV	Submerged aquatic vegetation
SCAMIT	Southern California Association of Marine Invertebrate Taxonomists
SDMs	Species distribution models
SLAMM	Sea Level Affecting Marsh Model
SLR	Sea level rise
sp	Single species
spp	Multiple species
SST	Sea surface temperature
TLS	Terrestrial laser scanning
тос	. Total organic carbon
TSCA	Toxic Substances Control Act

- USFWSUnited States Fish and Wildlife Service
- USGSUnited States Geological Survey
- WOE.....Warmest occupied ecoregion
- WoRMS......World Register of Marine Species

Acknowledgements

Special thanks to the following people who have provided programming support and design of CBRAT: Dylan McCarthy, Rachel Nehmer, Marshall Hanshumaker and Robert Reusser. Emily Saarinen, Melanie Frazier and Katie Marko provided insights into the early development of the framework. Thanks to all the students and contractors who helped populate CBRAT including Rebecca Loiselle, Summer Maga, Tracy Hoblit, Anthony Pham, Rochelle Regutti, Micaela Edelson, Alma Meyer, Erin Horkan and Maya Kaup. Carol DeLong, our technical editor, assisted with data entry and editorial reviews. The authors would also like to acknowledge Tim Counihan and Jill Hardiman of the USGS Western Fisheries Research Center for their assistance in collating the abundance and distributions of rockfish and for coordinating interagency cooperation through an EPA-USGS Interagency Agreement. Dayy Lowry of Washington Dept. Fish and Wildlife provided helpful insights on Puget Sound rockfish. Workshops with the Southern California Association of Marine Invertebrate Taxonomists (SCAMIT) provided expert information on several taxa and usability of CBRAT; Don Cadien, Paul Valentich-Scott, Gene Coan, Doug Eernisse, Nora Foster, Greg Jensen, Ron Velarde, Mary Wicksten, Rick Brusca, and Roger Clark all shared their time and expertise. Mary Mahaffy of the U.S. Fish and Wildlife Service helped co-sponsor a workshop on trait-based risk assessment, which provided key insights into the design of CBRAT. Maggie Dutch and Valerie Partridge (Washington Dept. Ecology) reviewed an earlier version of this document and hosted a Biotic Matrix Workshop with expert taxonomists and ecologists, resulting in improvements for CBRAT. We would especially like to thank our taxonomic contractor Dancing Coyote Environmental under the leadership of Larry Lovell and Dean Pasko, for their efforts to synthesize and manage data contributions from colleagues John Chapman, María del Socorro García-Madrigal, Kenneth Coyle, Doug Diener, Francisco Solis-Marin, Rich Mooi, Phil Lambert, Megan Lilly, Sandy Lipovsky, Leslie Harris, Jerry Kudenov, and Tony Phillips, who all made valuable contributions to the project. The following peer reviewers provided insightful suggestions that improved both the document and the risk assessment approach: Rebecca Flitcroft, Thomas Hurst, Walter Nelson, Tony Olsen, Steve Rumrill, and James Markwiese. Finally, Dr. Lee would like to acknowledge the continued support of EPA's Air, Climate, and Energy (ACE) research program.

Executive Summary

Goals and Objectives

With increasing temperatures, ocean acidification, and sea level rise (SLR), climate change is arguably the greatest threat facing near-coastal ecosystems (0-200 m depth). For management to respond in a scientifically-sound fashion, it is critical to have a basic knowledge of the extent and pattern of risk to near-coastal species. To address these needs, we developed a rule-based framework to predict the relative risk of near-coastal species to climate change at regional scales. The framework synthesizes risks from biotic traits (baseline risks) and population status (trends) with risks predicted from increasing ocean temperatures, ocean acidification, and sea level rise.

Within this overall goal, key objectives were to develop a framework capable of predicting: a) climate risks for rare species as well as for better studied species; b) identifying major climate stressor(s) affecting each species within each region; c) geographic patterns of the importance of different climate stressors; and d) how risk changes under different climate scenarios. We developed an ecoinformatics website, the Coastal Biodiversity Risk Analysis Tool (CBRAT), to conduct the climate risk analyses and to serve as a practical tool for managers and researchers to address climate and species inquiries. As detailed in this document, over thirty rules were used to predict a species risks due to temperature, ocean acidification, or sea level rise. As discussed under "Uncertainty," we contend that the present framework is able to identify high risk vs. low risk species and regional risk patterns but does not have the resolution required for fisheries management.

Geographic and Taxonomic Scope of Current Framework

The Marine Ecoregions of the World (MEOW) is used as the biogeographic schema for evaluating regional distributions and climate risks. The present effort focuses on species in the twelve MEOW ecoregions that make up the Northeast Pacific (NEP) and U.S. Arctic, ranging from the Gulf of California through the Beaufort Sea, however the main focus was from Southern California north. To evaluate the efficacy of the framework, the current effort focuses on calculating preliminary risks for brachyuran and lithodid crabs (417 species), rockfish (71 species), and bivalves (892 species) that occur within 200 m depth.

Risk Categories and Overall Vulnerability

In the current framework, each risk rule generates one of four risk levels for each species: minor, low, moderate, or high risk. As the risk level increases, the likelihood, severity, and types of adverse impacts increase, as does the ability to detect such changes especially with the more abundant species. Climate impacts may range from physiological changes to population impacts and while it is not possible to predict the specific effects under each scenario, population declines are expected with high risk scenarios. We attempted to standardize the risks across different traits and climate stressors so that a high risk for one climate stressor is approximately equivalent to a high risk for another stressor. However, this proved difficult for ocean acidification because of the predominance of laboratory exposures using physiological

and behavioral endpoints not readily related to population viability. Even with this limitation, the overall risk value for a species within an ecoregion is calculated as the single greatest risk among the climate adjusted baseline/status risks and the risks calculated for temperature, ocean acidification, and sea level rise.

Expert Opinion Versus Algorithm-Based Approaches

Most risk assessments of marine and freshwater organisms incorporating multiple climate stressors have used expert opinion to determine risk. While useful when there is limited knowledge, relying on experts is prone to a number of disadvantages including: a) experts are subject to at least nine types of cognitive biases; b) lack of transparency; c) need to reconvene experts to evaluate new climate scenarios, taxa, or locations; d) lack of consistency among experts; and e) limitations of human experts being able to evaluate hundreds to thousands of species across wide geographical areas. To address these limitations, we developed an algorithm approach where the risk is automatically generated from a centralized knowledgebase stored in CBRAT and a set of explicit rules.

CBRAT – Web-Based Risk Analysis Tool

A distinguishing feature of the current effort is that the risk framework is implemented in an online ecoinformatic tool, the "Coastal Biodiversity Risk Analysis Tool" (<u>http://www.cbrat.org/</u>). CBRAT serves as the platform to calculate the climate risks using the associated knowledge base of biotic traits and rule sets along with the user input climate values. A key feature is that managers and researchers are able to easily evaluate different climate scenarios and assumptions by changing the baseline or future climate values and/or the effects thresholds for temperature, ocean acidification, and sea level rise. CBRAT outputs all the biotic trait information for each species (e.g., depth preferences) as well as the risk associated with each rule for each species by ecoregion. This output allows users to evaluate the details of risk patterns as well as use the synthesized biotic trait for other types of analyses.

Ecoregion-Scale Relative Abundances

Biogeographic distributions identify where a species can survive while abundances help elucidate preferred versus marginal environmental conditions. Because of the insights abundances provide, we developed an approach to classifying the relative abundances of each species at an ecoregion scale using a hierarchical abundance schema. A "hybrid" approach integrating regional and local quantitative survey data, natural history texts, expert opinion, and online biodiversity databases was used to estimate relative abundances. Using this synthesis of data types, it was possible to estimate relative abundances for essentially all the crabs, rockfish, and bivalves in each ecoregion from Southern California through the Beaufort Sea.

Baseline/Status Risks

The first method to identify species at risk was a set of rules using "baseline" biotic traits, such as a species' range, and status metrics, such as population trends, which are associated with increased climate vulnerability or resilience. Such baseline/status indicators are widely used in conservation and have the advantage that the data are available for most species The main disadvantage is the difficulty of predicting how the risk associated with a specific baseline/status trait changes under different specific climate

scenarios, though it is possible to link the overall baseline/status risk to the overall level of climatic risk. We generated 17 rules predicting vulnerability or resilience to climate change that can be applied to both well-studied and lesser known species. Because abundance is an indicator of a population's viability, relative abundance is used to modify the risk level for many of these rules. The baseline/status risks most frequently indicating high vulnerability are endemicity, habitat specialization, symbiotic relationships, current population declines, and population growth metrics, though the importance of these traits varies geographically and among taxa.

Temperature Risks and Northern Colonization

The core method developed to predict risks associated with increased temperatures was the Ecoregional Thermal Windows approach (ETW) that compares the projected sea surface temperature (SST) in each ecoregion to the historic range of SST values in the "warmest occupied ecoregion" or WOE. Temperatures in the WOE represent the warm range limit of a species and are assumed to represent the upper ecological thermal limit for a species to maintain a viable population. For this analysis, the ecoregion-scale historic SSTs were derived from an analysis of 28 years of "advanced very high resolution radiometer" (AVHRR) remote sensing data while the future projections were extracted from the CMIP5 model used by the IPCC served through NOAA's Climate Change Web Portal. The level of risk is determined by comparing the projected SST in each ecoregion to the historic mean plus a number of standard deviations (SD) in the WOE. Moderate risk is defined as a projected SST in a northern ecoregion greater than the WOE mean + 2 SDs while high risk is defined as a projected temperature greater than the WOE mean + 3 SDs. The "representative concentration pathway" (RCP) 8.5 is used as the default in CBRAT but users are able to input ecoregion-specific temperatures associated with any climate scenario.

To evaluate risks for species occurring at different depths, we developed the Biogeographical Thermal Limit (BTL) approach that predicts risks for intertidal species using projected air temperature, shallow subtidal species using projected temperatures at 30 m depth, and deep subtidal species using projected temperatures at 100 m depth. For this analysis, both the baseline temperatures and future projections were based on the CMIP5 model. The BTL approach compares the projected temperatures in the target ecoregion to temperature thresholds for each depth based on four bins between the historic temperatures in the WOE and the "next warmest unoccupied ecoregion" (NWUE). The NWUE is usually immediately to the south of the WOE, and is assumed to be too warm to maintain a viable population of the target species, with high risk defined as a projected temperature greater than the 3rd bin between the WOE and NWOE. The BTL approach generated the same risks as the ETW over 87% of the time with the brachyuran crabs when compared from the Beaufort Sea to Southern California. When there was a deviation, the BTL was less sensitive. Because of this difference, the moderate and high risks generated by the BTL were combined as "at risk species".

A geographic pattern emerging from a preliminary analysis of brachyuran crabs with both the ETW and BTL approaches is that high thermal risks are primarily limited to the southernmost occupied ecoregion of a species. The lack of substantial thermal impacts in the more northern range of a species assumes either that warm-tolerant genotypes occur in the ecoregions north of the WOE or that warm-genotypes from southern ecoregions migrate northward. To assess the "worst-case" scenario assuming no warm-

tolerant genotypes, CBRAT also calculates risks by comparing the projected temperature in the target ecoregion to the historic temperate range within ecoregion. A third view of risk is to compare the target ecoregion to the southern ecoregion where the abundance declines, presumably because it is too warm, and is most applicable to evaluating impacts on commercial species. This approach is discussed in the document but not implemented in the current version of CBRAT.

Climate change may also result in sufficient warming of cooler ecoregions to allow northern range expansion. To evaluate this potential, we reversed the logic of the BTL approach and derived temperature thresholds based on the bins derived between the "coolest occupied ecoregion" (COE) and the "next coolest unoccupied ecoregion" (NCUE), which is usually immediately to the north of the COE. CBRAT outputs the "suitability" for colonization in the unoccupied northern ecoregions based on the future projected temperatures, while recognizing that other factors could limit a species' expansion.

Ocean Acidification

Though the least well understood of the climate stressors, it is possible to conduct a first-order regionalscale risk assessment of ocean acidification by treating it like other contaminants. Specifically, we propose deriving "maximum allowable toxicant concentrations" (MATCs) for pH and aragonite saturation state from a synthesis of exposure experiments. MATC is the geometric mean of the "no observed adverse effects level" (NOAEL) and the "lowest observed adverse effects level" (LOAEL), and in the present context is the lowest "allowable" pH for a particular species. Because of the limited number of exposure experiments, the proof-of-concept with the decapods takes a comprehensive approach and uses the single most sensitive MATC for each species regardless of the specific endpoint or life history stage. To generate ocean acidification risks more similar to the population associated risks for temperature and sea level rise, we conducted a similar analysis just using endpoint directly related to population viability; however, the number of studies is too limited to currently to generate reliable effects thresholds.

Because species within a taxon vary greatly in their sensitivity, a cumulative frequency distribution curve is generated from the most sensitive MATC for each species within a taxon. This frequency distribution is then used to generate high, moderate, and low sensitivity thresholds to pH and aragonite saturation state. After assigning a sensitivity class to a species, its risk is calculated by overlaying the specific pH effects thresholds on ecoregion-scale projected values. Because of the reported interaction between elevated temperatures and reduced pH, moderate ocean acidification risks are elevated to high acidification risk under moderate to high temperature risk. Baseline and projected pH values for surface waters were presented in the document and CBRAT from the CMIP5 model served through NOAA's Climate Change Web Portal, using RCP 8.5 as the default. Baseline and projected aragonite saturation state values were presented based on projections developed by Cao and Caldeira based on the University of Victoria Earth System Climate Model version 2.8.

Based on a preliminary risk assessment with decapods, assignment of the high, moderate, or low sensitivity threshold to a species has a major effect on its ocean acidification risk assignment. Which raises the question on how to assign sensitivity classes for species lacking experimental studies. Ideally, it will be possible to assign sensitivity classes based on readily available physiological or life history traits;

to date the single example is that species with brood protection and/or lecithotrophic larvae have low sensitivities. Another approach is to classify species by their ecological and taxonomic similarity to experimentally tested species. Alternatively, moderate sensitivities could be used a "restrained" analysis and the high sensitivity thresholds as a "high risk" analysis.

Sea Level Rise

The objective of the sea level rise component is to estimate the population decline in the invertebrate and fish species inhabiting intertidal habitats based on the assumption that population declines are proportional to the extent of habitat loss. Predicting SLR risk species integrates four steps. The first is to estimate a net ecoregion sea level rise value (mm) for each ecoregion from the global eustatic rate and regional rates of isostatic adjustment. The second step is to generate "habitat thresholds" for each of the major intertidal habitat types from the literature and SLR models; models included SLAMM for wetlands and mangroves and a LIDAR/topobathy model we developed for the rocky intertidal. These thresholds classify the percent loss of each habitat type as minor, low, moderate, or high based on the extent of net SLR within each ecoregion. To account for inland migration of habitats, habitat thresholds were developed for both "unconstrained" and "constrained" (coastal squeeze) scenarios with the constrained thresholds used for Puget Sound through Southern California and the unconstrained thresholds used for the less developed ecoregions. The proportion of a species' population at risk due to loss of intertidal habitats depends upon its depth distribution. Thus, the third step is to generate risk values for the target species based on the habitat thresholds and species' depth preferences. Because many near-coastal species occupy multiple habitats, the final step is to assign the greatest SLR risk across all observed and preferred habitats occupied by the species.

In a preliminary analysis with brachyuran crabs and an "intermediate-high" eustatic SLR rate of 12 mm/yr, moderate and high SLR risks were limited to primarily intertidal crabs from Puget Sound south through the Cortezian ecoregion. The lack of risk in the northern ecoregions is due to high isostatic uplift countering SLR in much of Alaska and the paucity of intertidal crabs in the Arctic.

Uncertainties and Limitations

Climate change predictions are subject to a number of uncertainties, and the current document lays out a strategy for qualitative uncertainty analysis. The components of such an analysis are: 1) identification and characterization of uncertainty sources; 2) estimates of the direction and relative magnitude the uncertainty is likely to have on results; and 3) reporting of qualitative uncertainties in a non-technical summary. In addition to the qualitative analysis, it is possible to conduct a quantitative uncertainty analysis on the key climate projections and effects thresholds by changing input values in CBRAT.

A preliminary uncertainty analysis indicates that: 1) predictions from the current framework are sufficient to identify the scope and patterns of risk and for regional-scale adaptation planning; 2) predictions are sufficient to flag high risk commercial species but not for fisheries management; 3) lack of sufficient spatial resolution in the current regional-scale climate models limits the ability to predict temperature and pH changes within estuaries, increasing the uncertainty for estuarine organisms; and 4) the greatest uncertainty appears to be associated with ocean acidification. It is not unsurprising that there are a number of uncertainties in predicting the effects of multiple climate stressors on hundreds of species over the

entire U.S. Pacific Coast. But with higher resolution climate models and additional effects research it should be possible to reduce these uncertainties over time.

1.1 Problem Statement

Climate change is arguably the greatest threat facing near-coastal ecosystems (0-200 m depth) in recent history. Over the last 100 years, climate change has resulted in documented increases in ocean temperatures, reduced pH, and increased sea levels (Doney et al., 2009; Pörtner et al., 2014; Blunden and Arndt, 2016). These climatic alterations have, or will, result in a host of ecological impacts, ranging from species' range shifts to a loss of ecosystem functions to regional/global extinctions (Harley et al., 2006; Hannah, 2012). The nature and extent of these impacts can vary substantially among species according to their exposure to specific climate stressors as well as their life history, physiological, and population traits. As a simple example, a 2-meter sea level rise (SLR) would have major effects on many intertidal species but a trivial effect on continental shelf species. Besides these species differences, the ecological impacts of climate change will vary regionally, both in response to geographical differences in the extent of climate alterations as well as latitudinal differences in biodiversity and species composition.

For management to respond in a scientifically-sound fashion to climate change, it is critical to have a basic knowledge of what species are at the greatest risk, what climate stressors represent the largest threats, where risk is the greatest, and how risk varies with different climate scenarios. Understanding the relationship between the nature and extent of risks with different climate scenarios informs policy makers of the potential benefits to reducing emissions while a knowledge of the geographical patterns of risk helps set regional adaptation priorities. Knowledge of the vulnerability of rare species is important both because of their contributions to ecological functions and genetic diversity (Bálint et al., 2011; Prather et al., 2013) as well as their central role in conservation and adaptation efforts (Raphael and Molina, 2007; Angulo et al., 2009). However, a major challenge in addressing the full breadth of species along the U.S. coast is the diversity of near-coastal species. Almost 1500 species of fish occur along the U.S. West Coast (Love et al., 2005) and over 1000 bivalve species have been reported from Alaska through northern Mexico (Coan et al., 2000; Coan and Valentich-Scott, 2012).

Not surprisingly for a threat of this scope and complexity, a number of different approaches are being applied to identify vulnerable species and habitats (Table 1-1). Each has benefits and limitations – some are better at revealing underlying mechanisms while others are better at generating predictions for a large number of species. Some require massive amounts of quantitative survey data, while others can be applied via data mining. While all the approaches in Table 1-1 are complementary, only three potentially address our objectives of assessing multiple species at regional scales: 1) species distribution models; 2) evaluation of species' "climate velocities"; and 3) trait-based approaches.

Species distribution models (SDMs) include a suite of statistical approaches based on associating records of where a species occurs, or its abundance, with the environmental parameters at each occurrence (Elith and Leathwick, 2009). They have been used to evaluate nonindigenous species (e.g., Reusser and Lee, 2008; Herborg et al., 2009), native species for conservation purposes (Pearson, 2010), and to evaluate distributional changes in response to climate change (e.g., Mellin et al., 2012; Reusser et al., 2016). Advantages are that SDMs can predict the potential response of target species at a relatively fine-scale resolution and can evaluate species' responses to different temperature scenarios, assuming the data set used to construct the model encompasses all or most of the species' temperature range.

A disadvantage of SDMs is the number of samples required to generate robust models; based on the "one in ten" rule of thumb, a minimum of 10 samples ("observations") containing the targeted species ("event") is required for each predictor variable in the model (see Harrell et al., 1996; Babyak, 2004), while other authors suggest at least 20 observations per variable is required to avoid overfitting (Steyerberg et al., 2000). The sampling requirement generally limits SDMs to more abundant species, though in one case the SDM was linked into online databases (FishBase and SeaLifeBase) allowing an evaluation of over 1000 exploited fish and invertebrates (Cheung et al., 2008, 2009). Besides the sample size limitations, we are unaware of any cases where SDMs have been used with ocean acidification or sea level rise.

A novel approach is the evaluation of "climate velocity", or shifts in population centroids across the landscape which are presumably in response to recent temperature changes (Pinsky et al., 2013). These authors evaluated 360 marine taxa. However, even more than with the SDMs, the large number of quantitative samples needed is a major limitation; the Pinsky et al. analysis used a database of 128 million individuals primarily from the NOAA's RACE groundfish trawl surveys. Molinos et al. (2016) expanded upon this technique by linking into modeled species distributions from AquaMaps (http://www.aquamaps.org/main/home.php) combined with projections of future sea surface temperatures (SSTs), resulting in predictions for over 12,000 near-coastal and oceanic species. While this approach provides important insights into regional and global responses to ocean warming, it is not suitable for rare species, many of which have no or very few records in the AquaMaps. Additionally, assessments of climate velocity do not appear to be suitable for evaluating either ocean acidification or sea level rise.

The last of the three potential approaches, trait-based analyses, have been used to address a number of conservation issues. Among marine fishes, traits have been used to evaluate the effects of overfishing (e.g., Musick, 1999; Dulvy et al., 2004; Reynolds et al., 2005). Reynolds et al. (2005) concluded, "Simple life history traits can be incorporated directly into quantitative assessment criteria, or used to modify the conclusions of quantitative assessments, or used as preliminary screening criteria for assessment of the 95% of marine fish species whose status has yet to be evaluated either by conservationists or fisheries scientists."

Trait-based approaches have also been applied to assess climate vulnerability. In a simulation study with amphibians and reptiles, Pearson et al. (2014) inferred, "extinction risk due to climate change can be predicted using a mixture of spatial and demographic variables that can be measured in the present day without the need for complex forecasting models." With freshwater and marine species, the IUCN evaluated 797 coral species globally, Moyle et al. (2013) evaluated all the native and nonindigenous freshwater fishes in California while Hare et al. (2016) evaluated 82 marine fishes and invertebrates on the Northeast U.S. continental shelf. These studies indicate that trait-based risk assessments can be successfully conducted for a large number of species over wide geographical locations. Further, combining risks derived from projections of future temperatures, SLR, and pH with the trait analysis, as did Hare et al. (2016), strengthens the predictions.

In reviewing these methodologies, we concluded the most rigorous approach to predicting effects of multiple climate stressors, evaluating species with limited data, evaluating geographical patterns of risk and conducting assessment on different climate scenarios was to integrate a trait-based approach with climate effects thresholds. As discussed in Sections 5-7, effects thresholds are numerical values indicating different levels of risk for temperature, pH and sea level rise that are overlain on projected climate values. The analysis of biotic traits augments the climate thresholds by identifying at risk species potentially missed by the comparison of regional climate values with general impact levels. There are, however, a number of differences between our framework and the previous trait-based efforts, including use of an algorithm-based risk assessment versus expert solicitations (Section 1.5) and integrating relative abundance into the analysis (Section 3). Another key difference is that the climate risk analysis and associated data are available via an online tool, the Climate Biodiversity Risk Analysis Tool (CBRAT, http://www.cbrat.org), allowing managers and researchers to review the information and conduct their own risk assessments.

Table 1-1. Approaches used to predict effects of climate change on aquatic species and habitats. # Species Analyzed = Number of species analyzed within a study. SDM = species distribution model. GLM = generalized linear model. GAM = generalized additive models. NIS = nonindigenous species.

Approach	Primary Climate Stressors Evaluated	# Species Analyzed	Comments	Examples
Laboratory exposures	Temperature, Ocean acidification or both	Few	Variations in exposure conditions and response variables make it difficult to compare studies; best used as inputs into predictive models.	Johansen and Jones, 2011; Waldbusser et al., 2013; Long et al., 2016
Biochemical responses	Temperature, Ocean acidification	Few	Utility as predictive vs. monitoring approach is unclear. Extrapolation to other species unclear.	Helmuth and Hofmann, 2001; Tomanek, 2010
Field experiments	Primarily temperature	Few	Bias towards intertidal species. Usually at local scale. Extrapolation to other species unclear.	Yamane and Gilman, 2009; Jones et al., 2012
SLAMM	Sea level rise	Wetland habitats	Site specific SLR model for wetland habitats, not the associated species. Moderately high data requirements. Primarily at local scale.	Glick et al., 2007; Craft et al., 2009; Lee et al., 2014
Mechanistic population models	Temperature or Ocean acidification	Few	High data requirements, largely limited to well- studied commercial species. Potentially can model temperature, ocean acidification, and/or SLR.	Buckley et al., 2010
SDM - Presence only or with abundance data (GLMs & GAMs)	Primarily temperature and Habitat	One to dozens	Reasonably high data requirements, not suitable for rare species. Can elucidate geographic patterns of risk if sampled at appropriate scale and covers adequate temperature range.	Brown et al., 2011; Jones et al., 2013; Reusser et al., 2016
SDM - Abundance drawing on global databases	Temperature	1066 fishes and invertebrates	Special case of linking into global databases. Not suitable for rare species. Temperature only.	Cheung et al., 2008, 2009
Climate velocity – NOAA RACE data	Temperature	360 fishes and invertebrates	High data requirement for quantitative samples - linked into NOAA RACE data. Not suitable for rare species. Temperature only.	Pinsky et al., 2013
Climate velocity – AquaMap modeled distributions	Temperature	12,796 fishes and invertebrates	Links to modelled probability distributions, modeled geographic patterns of risk. Not suitable for rare species. Temperature only.	Molinos et al. 2016
Trait-based: IUCN	Temperature and Ocean acidification	797 corals	Based on expert solicitation with climate projections. Included rarer species.	Foden et al., 2008, 2013
Trait-based: Freshwater fishes	Climate in general	121 native & 43 NIS freshwater fish	Not geographically specific (all of CA). Based on expert solicitation. Included rarer species	Moyle et al. 2013

Approach	Primary Climate Stressors Evaluated	# Species Analyzed	Comments	Examples
Trait-based & Climate projections: NE Atlantic shelf	Temperature, Ocean acidification, Sea level rise, Precipitation, Salinity, Currents	82 coastal fishes & invertebrates	Included greater range of climate stressors, based on expert solicitation. Focused on common species. Did not elucidate geographic patterns of risk.	Morrison et al., 2015; Hare et al., 2016
Trait-based & climate effects thresholds: Pacific Coast	Temperature, Ocean acidification, Sea level rise	387 crabs, 71 bottom- associated rockfish, & 884 bivalves	Algorithm-based risk calculations. Included rare species. Modeled geographic patterns of risk.	Current study

1.2 Goals and Objectives

The overall goal of the current research is to predict the relative risk of near-coastal (0-200 m depth) species to climate change at regional scales. As detailed in this document, we approached this challenge by developing a climate risk assessment framework that synthesizes predictions based on biotic traits or attributes ("baseline/status risks", Section 4) and predictions based on overlaying effects thresholds on projected values for temperature, ocean acidification, and sea level rise (Section 5–Section 7). Both the baseline/status risks and the climate risks are generated via a set of rules that are detailed in the appropriate sections. The analysis is conducted and risks reported at the spatial scale of the "Marine Ecoregions of the World" (MEOW, Spalding et al., 2007), ranging across twelve ecoregions from the Gulf of California through the Beaufort Sea. The "Coastal Biodiversity Risk Analysis Tool" (CBRAT; <u>http://www.cbrat.org/</u>) is the platform used to calculate the climate risks using the associated knowledge base of biotic traits, climate projections, and rule sets. Programming details and metadata on CBRAT are given in Appendix A, while Appendix B provides an overview on how to conduct risk assessments in CBRAT.

Within the overall goal of predicting climate risk, there is a suite of more specific project objectives that are listed in the Table 1-2.

Table 1-2. Objectives of the current risk analysis framework and risk analysis of near-coastal species.

OBJECTIVES

Climate Risk Framework

- Develop a framework that predicts the relative risks associated with temperature, ocean acidification and sea level rise for species within each MEOW ecoregion as well as an overall climate risk for each ecoregion.
- Develop a framework that identifies the major climate stressor(s) affecting each species within each ecoregion.
- Develop a framework that predicts relative climate risks for rare species with limited data as well as for the better studied species.
- Develop approaches to integrating multiple climate stressors, especially temperature and ocean acidification

CBRAT - Web-Based Risk Analysis and Research Tool

- Develop an online system, CBRAT, as the tool to integrate biotic traits, historical and projected environmental values, and the rules to predict relative risk
- Design CBRAT such that approved managers and researchers, as well as the CBRAT administrators, can evaluate different climate scenarios.
- Synthesize biotic trait information for use in addressing non-climate management and research questions/issues
- To the extent practical, promote CBRAT as a public outreach tool for the informed public.

Geographical and Taxonomic Patterns of Risk

- Predict how climate risk varies regionally for each species.
- Predict the geographic patterns of the relative importance of different climate stressors from the Gulf of California through the Beaufort Sea.
- Evaluate how risk varies among major taxa as well as the relative importance of different climate stressors for different taxa.

Evaluate Different Climate Scenarios

• Evaluate the relative risks associated with different climate scenarios for temperature, ocean acidification, and sea level rise.

Transparency/Uncertainty analysis

- Provide transparency in the data used and in the rules to predict risk.
- Document each rule such that a user could calculate the risk manually.
- Document the major assumptions associated with each rule.
- In CBRAT, document the sources of information used to assign biotic traits along with any associated assumptions.
- Generate a qualitative uncertainty analysis.

1.3 Scope of Document

The focus of the current report is to document the climate risk framework we developed for nearcoastal species. The specific rules and key assumptions for the baseline/status risk, temperature increases, ocean acidification, and sea level rise are given in Section 4, Section 5, Section 6, and Section 7, respectively. The rules are described in sufficient detail that a user could evaluate the risk for a single species by hand. Examples of the types of data that are used in the risk assessment are presented to illustrate the types of required data and how they are analyzed. For example, a detailed review of the effects of pH on decapods is provided (Section 6) but a review is not provided for aragonite saturation since the methods are the same for both.

In addition to the conceptual framework, this report documents how the web-based Coastal Biodiversity Risk Analysis Tool (CBRAT; <u>http://www.cbrat.org/</u>) is used to conduct the risk analyses. This document is not a user's manual, though Appendix B provides a guide on how to conduct the risk assessments in CBRAT. For further information, the user is referred to the "User's Guide & Metadata to Coastal Biodiversity Risk Analysis Tool (CBRAT): Framework for the Systemization of Life History and Biogeographic Information" (Lee et al., 2015), which is available on CBRAT.

The results of the climate risk assessments will be detailed in a separate document (Lee et al., in progress). This initial risk assessment will analyze all the near-coastal brachyuran crabs (365 species), lithodid crabs (22 species), bottom-associated rockfish (71 species), and bivalves (884 species) reported from the Gulf of California through the Beaufort Sea.

1.4 Geographic and Taxonomic Scope

1.4.1 Geographic Scope

We use the "Marine Ecoregions of the World" (MEOW) (Spalding et al., 2007) as the biogeographic framework for evaluating the distributions and abundances of near-coastal species as well as for assessing climate risk. MEOW is a hierarchical schema for marine coastal waters down to a depth of 200 m. The original three levels of MEOW include ocean basin *realms* divided into smaller *provinces* and then smaller *ecoregions*. As defined by Spalding et al. (2007), ecoregions are "Areas of relatively homogeneous species composition, clearly distinct from adjacent systems. The species composition is likely to be determined by the predominance of a small number of ecosystems and/or a distinct suite of oceanographic or topographic features." To capture differences in the eastern and western sides of the Atlantic and Pacific, we previously modified the MEOW schema by adding a fourth level, the *region* which is between a realm and province (Reusser and Lee, 2011; Lee and Reusser, 2012). Detailed maps of the world's 232 ecoregions are available in CBRAT under the Documents tab; GIS shapefiles are available at http://maps.tnc.org/gis_data.html.

The present effort evaluates species' vulnerabilities in the 12 ecoregions that make up the Northeast Pacific (NEP) and U.S. Arctic (Figure 1-1). The three U.S. Arctic ecoregions (Eastern Bering Sea, Chukchi Sea, Beaufort Sea- continental coast and shelf) are in the Arctic Realm (Arctic is not broken into provinces). The Cold Temperate Northeast Pacific Province is composed of the six ecoregions ranging from Northern California up through the Aleutian Islands. The MEOW Warm Temperate Northeast Pacific Province is composed of the Cortezian, Magdalena Transition, and Southern California Bight ecoregions. We extend the study into Baja California and the Gulf of California so as to fully capture the Warm Temperate Northeast Pacific Province. Additionally, it is likely that many of the near-coastal species in these ecoregions will migrate northward with warming so their inclusion helps predict future colonists.

We chose the MEOW schema over the other existing biogeographic schema because it appears to best capture biological reality across the globe. It has been used in a variety of biodiversity and conservation studies, including a global assessment of human impacts on marine ecosystems (Halpern et al., 2008), wetland conservation Ramsar Convention (Ramsar, 2008), IUCN's assessment of global ocean protection (Toropova et al., 2010), assessing biogeographic patterns of marine invaders (Molnar et al., 2008; Lee and Reusser, 2012) and in analyzing global biodiversity patterns of various taxa (Piepenburg et al., 2011; Van Soest et al., 2012; Barboza and Defeo, 2015; Molinos et al., 2016). Additionally, species' distributions can be viewed by MEOW ecoregions in the online Ocean Biogeographic Information System (OBIS; http://iobis.org/mapper/).

In terms of the appropriateness of this spatial scale for risk analysis, the ecoregion level is large enough to capture population level responses to regional climate changes. Since population declines resulting in rarity is a potential impact of climate change, Gaston's conclusion (1994) that "the concept of rarity can be applied to almost any spatial scale, it is of primary interest and has been most extensively studied at regional or biogeographic scales" supports our focus on regional risk assessments. MEOW ecoregions are also large enough to incorporate both major and minor near-coastal habitat types along with their associated taxa. Conversely, the MEOW ecoregions are small enough to detect geographical patterns in risk. In contrast, with the commonly used Large Marine Ecoregions (LMEs) schema, the California Current LME extends from the entrance to Puget Sound to the entrance of the Gulf of California, an area that is divided into four MEOW ecoregions. Lastly, MEOW ecoregions are an appropriate scale to inform many management decisions, in particular those related to conservation and climate impacts on populations (e.g., Ramsar, 2008; Toropova et al., 2010).

1.4.2 Taxonomic Scope and Standardization

The risk framework described in this document should, in theory, apply to all near-coastal fishes and invertebrate taxa that occur within 200 m depth assuming the basic distributional and biotic trait data are available. Having said that, each major taxon may require modification of some of the rules or addition of new rules. As described in Section 4, the available information allows a set of baseline/status risk rules for fish based on productivity, but such rules are not currently available for invertebrates. Since many rules predicting risk are based on biogeographical patterns, the general approach should be modifiable for submerged aquatic vegetation (e.g., *Zostera* spp.), marsh plants, and macroalgae (e.g., kelp), though new rules would likely be

necessary to capture the physiology of primary producers (e.g., positive effect of increased CO₂). Lastly, relative abundances and the corresponding risk levels are generated for the portion of species' populations that occur at depths from 0-200 m. Thus, there is greater uncertainty in the risk predictions for oceanic species for which 0-200 m only constitutes a small portion of their total population.

Our strategy is to evaluate the species taxon by taxon rather than by habitat. The major conceptual reason for evaluating vulnerabilities by taxon is that we use relative abundance within an entire taxon as one of the attributes to assess risk (Section 3), thus promoting evaluations of an entire taxon for comparative purposes. A practical advantage is that much of the literature is taxon based, thus it is more efficient to synthesize biotic traits by major taxon.

While it is a common refrain that there are not enough taxonomists (e.g., Kim and Byrne, 2006), it has been our experience that there are more than enough to cause mischief for ecologists and biogeographers. Because of differing views on taxonomy, we standardize using the World Register of Marine Species (WoRMS, <u>http://www.marinespecies.org/index.php</u>, Costello et al., 2013). A downloaded version of the WoRMS database is incorporated into CBRAT so that every new species is checked against the WoRMS higher level taxonomy as it is added. Species in CBRAT and their synonyms are periodically compared against those in WoRMS using the WoRMS "Match taxa" to find updates in taxonomy and errors such as valid species being entered as synonyms. For a few taxa, we use regional authorities in lieu of WoRMS. In particular, we use the regional treatises of Coan et al. (2000) and Coan and Valentich-Scott (2012) for bivalves. Such species are identified in CBRAT on the species' taxonomy page as deviating from WoRMS.



Figure 1-1. Study area and MEOW ecoregions comprising the Northeast Pacific and U.S. Arctic. The U.S. Arctic consists of the Beaufort Sea - Continental Coast and Shelf, Chukchi Sea, and Eastern Bering Sea ecoregions. The remaining ecoregions constitute the Northeast Pacific Region, with the Aleutian Islands through the Northern California ecoregions making up the Cold Temperate Northeast Pacific Province and the Southern California Bight, Magdalena Transition, and Cortezian ecoregions making up the Warm Temperate Northeast Pacific Province. Hawaii is not part of the Northeast Pacific and is not assessed as part of this effort.

1.5 Algorithm-Based Approach to Climate Risk Assessment

Previous trait-based assessments of climate change on marine and freshwater organisms have used an expert opinion, or expert elicitation, approach (e.g., Foden et al., 2013; Moyle et al., 2013; Hare et al., 2016). Such expert opinion approaches are useful when there is very limited information and where there are no suitable models. An example is the evaluation of the combined effects of melting of the Greenland and Antarctic ice sheets, reorganization of the Atlantic Meridional Overturning Circulation, shift to a more permanent El Nino regime, and dieback of the Amazon rainforest on climate change (Kriegler et al., 2009). Although there was large uncertainty among the experts, the process was able to provide approximate bounds for

triggering events. As pointed out by Drescher et al. (2013; also see Sutherland, 2006), expert elicitations addressing ecological issues have gained momentum during the last two decades.

There are, however, a number of disadvantages with expert elicitations. Experts are subject to at least nine types of cognitive biases, ranging from overconfidence to "motivational biases when opinions are influenced for personal or research reasons" (O'Leary et al., 2008; also see Kynn, 2008). Other sources of uncertainty relate to issues such as linguistic differences in the understanding the specific meaning of terms and "translation confusion" in translating a response from one scale to another (e.g., categorical to numerical probabilities) (Kuhnert et al., 2009; Drescher et al., 2013). These unintentional biases can be mitigated through the use of carefully crafted expert elicitations such as the Delphi procedure (Rowe and Wright, 2011; Drescher et al., 2013) or the procedure detailed in the NOAA climate change risk analysis (Morrison et al., 2015). However, while such detailed procedures can mitigate the effects of these biases, they cannot eliminate them since such biases are often not obvious (Kuhnert et al., 2009) and thus are difficult to control.

There is also the question of the accuracy of expert elicitations compared to algorithm-based predictions. In a meta-analysis covering 136 research studies comparing expert opinion versus automated predictions, the experts were clearly better in only eight cases (Grove et al., 2000). A number of other studies have found that automated methods outperformed experts in predicting a variety of endpoints including medical diagnoses, psychiatric diagnoses of criminal behavior, job and school performance, and eradication of aquatic nonindigenous species (Dawes et al., 1989; Grove et al., 2000; Ægisdóttir et al., 2006; Kuhnert et al., 2009; Kuncel et al., 2013; Drolet et al. 2015). In some cases, the improvements over the experts were slight but in other cases the automated predictions were substantially better. In predicting job performance, the mechanical and holistic data combination methods displayed a 50% improvement compared to experts (Kuncel et al., 2013).

These results led McAfee (2013) in an article on the Harvard Business Review site titled "Big Data's Biggest Challenge? Convincing People NOT to Trust Their Judgement" to state, "The practical conclusion is that we should turn many of our decisions, predictions, diagnoses, and judgments—both the trivial and the consequential—over to the algorithms. There's just no controversy any more about whether doing so will give us better results."

Because of these limitations with expert solicitation, our objective was to design an algorithmbased (rule-based) approach to assessing risk. Specifically, our objective was to create a "turnkey" web-based tool by removing expert opinion from the final risk calculations. In designing our framework, we recognized that expert opinion could be used in three different phases of the risk analysis.
- Phase 1: Synthesizing biotic and environmental traits and estimating values for parameters with incomplete data (e.g., relative abundances, depth preferences).
- Phase 2: Generation of climate effects thresholds and rule sets used to predict risk.
- Phase 3: Calculation of climate risk from biotic and environmental traits, effects thresholds and rules.

In Phase 1 and Phase 2, we utilized extensive literature review and synthesis as well as expert opinion from several workshops with regional/national experts. However, by design, the experts were not questioned about the potential climate risks to any particular species or the geographical patterns of risk. Also, in most cases different experts were questioned regarding biotic traits and rule generation, thus separating these two phases of the analysis. In Phase 3, CBRAT was designed so that no expert intervention was required to calculate the risk from the synthesized information and rule sets. That is, the calculation of the individual climate risks is independent of user inputs and decisions other than to decide on a particular climate scenario. Additionally, we note that with hundreds to thousands of species analyzed across 12 ecoregions and the complexity of the rules, in most cases the calculated risk values were not apparent when synthesizing the information or generating the rules.

Besides circumventing the limitations of expert elicitations, algorithm-based approaches coupled with a web-based knowledge base offer a number of advantages:

- Transparency in the biotic trait values, climate exposure values, and effect thresholds used in the analysis for each species in each ecoregion.
 - Use of expert opinion in assessing biotic traits is documented in the comments associated with each species in CBRAT.
- Transparency in the logic and rules used to calculate risk.
 - The data and rules used to generate every risk estimate are explicitly defined.
 - Clarity of the rules allows future improvements.
- Application of the rules to generate the risks is unbiased.
- Consistency in predictions compared to predictions made by multiple experts over time or made by different groups of experts.
 - Straightforward to evaluate multiple geographic areas once biotic data on species are collected without need for different sets of regional experts.

- Straightforward to conduct scenario modelling to evaluate range of risks associated with different emission scenarios and uncertainty analysis to evaluate uncertainty associated with the effects thresholds.
- Straightforward for managers/researchers to evaluate different scenarios via unsupervised risk assessments.
- Linked database and rule sets capture institutional knowledge so it is not necessary to start anew each time a new taxon or location is evaluated or to assess different climate scenarios.
- Simple to incorporate new biological data or climate values as they become available.
- Practical to modify or generate new rules as new knowledge becomes available without the need to reassemble groups of experts, though it does require new programming.
- Synthesized biotic and climate data are potentially useful in addressing other research and management issues.
- Web-based systems can be used as an outreach tool for the informed public.

In addition to these advantages, it is tempting to argue that algorithm-based predictions for climate risks are more accurate based on the studies mentioned above. However, expert elicitation for climate and the algorithm-based approach in CBRAT are too new to compare accuracy, so this is an open question. Regardless, we suggest that algorithm-based systems will prove to be the more accurate approach as they are further developed and tested.

As with any approach, there are also some limitations to algorithm-based approaches. The two main disadvantages we found while implementing CBRAT:

- Initially it is more time consuming to create the knowledge base, corresponding rule sets, and web interface for an algorithm-based risk analysis than soliciting a panel of experts.
- Potentially, there is a greater time lag in incorporating the most recent information compared to gathering and soliciting a panel of experts.

Another possible advantage of expert solicitation is the ability to establish levels of uncertainty using self-estimated levels of confidence by the respondents or from estimates from other experts. However, McBride et al. (2012) showed that there was no consistent relationship between expert performance in predicting the outcome of scientific experiments and the expert's publication record, years of experience, or self-assessment of expertise. This result combined with the documented overconfidence of most experts suggests there may be substantial

uncertainty around expert-generated confidence estimates. In any case, a strategy to assessing uncertainty with CBRAT is discussed in Section 8.

Section 2. Risk Categories and Overall Vulnerability

2.1 Individual Risk Values

The present assessment uses a categorical approach to assigning climate risks. Other regional studies using a categorical approach to assessing environmental quality include the EPA's Environmental Monitoring and Assessment Program (EMAP) (e.g., Nelson et al., 2007, 2008) and National Aquatic Resource Surveys (NARS) (U.S. EPA, 2015; https://www.epa.gov/national-aquatic-resource-surveys/ncca). A categorical approach has also been used in several climate risk assessments (e.g., Morrison et al., 2015). In the current framework, the risk associated with each individual trait or climate stressor is assigned to one of four classes: minor, low, moderate, or high risk, with corresponding numerical values of 0 to -3. Risks are scored on a negative basis because of the inclusion of resilience traits (Section 2.2) that are scored with positive values. The negative scores can be considered a measure of the species' population viability. "Minor risk" is used instead of "no risk" to acknowledge the uncertainty in the predictions. Traits and stressors that do not apply to a particular species are assigned a null value. Species missing critical trait information for a particular rule set are also assigned a null value. For example, it is not possible to assign a sea level rise risk if the depth range of a species is unknown. Null values do not affect the overall risk score for a species (Section 2.3).

The climate risk factors inherently incorporate both exposure and sensitivity attributes. Projected changes in temperature (Section 5), pH/aragonite saturation state (Section 6), and sea level rise (Section 7) constitute the exposure component. The sensitivity component is formalized via the effects thresholds that associate minor to high risks to specific values of temperature, sea level rise and pH/aragonite saturation state. Overlaying the thresholds on the projected climate values for an ecoregion generates the risks associated with each climate stressor in the ecoregion, which may be modified by specific species traits. As discussed in Section 4, baseline/status risks capture species' inherent sensitivities or resiliencies to climate change. While individual baseline risks and status metrics are not directly coupled with climate change, the overall baseline/status risk based on or modified by a species' biogeographic distribution or abundance pattern likely incorporate indirect effects, such as trophic interactions, that affect a species' range or abundance.

The risk levels based on the climate effects thresholds are most simply viewed as resulting from the direct effects of a particular climate stressor on one or more life history stages. However, determination of the temperature risks incorporates biogeographic distributions and abundances, and thus are likely to capture indirect effects operating at an ecoregion scale (Section 5). Another issue is possibility of interactions among climate stressors. As a first step in addressing such interactions, we developed a simplified approach to approximate the interaction between risks associated with ocean acidification and elevated temperatures (Section 6.4).

The risk classifications are a relative ranking to help identify the species most and least vulnerable to climate change. As the risk level increases from minor to high, the likelihood of an adverse impact increases, severity of impacts increases, number of different types of impacts increases, as does the ability to detect such changes (Figure 2-1). A wide range of different effects have been reported as a result of climate change (Table 2-1) and the specific effects will depend upon the severity of the change, specific type of climate change, and attributes of the species. For example, ocean acidification is likely to result in a suite of physiological effects whereas sea level rise may result in increased population fragmentation through habitat loss but is not likely to result in major physiological changes. Though these risk levels are not meant to predict specific impacts, in many cases population declines are likely, especially at high risk levels. While in the worst cases, extirpation from an ecoregion is possible, a high risk should not be interpreted as implying regional extinction. Further, the risks are based on a long-term response to climate change and it is likely that population size and other indicators of ecological condition will show increased fluctuations with a changing environment, potentially including periods of positive growth. Finally, we note that while not an adverse impact, the likelihood of detecting physiological or ecological changes increases as the risk level increases, though the ability to detect changes in abundance will largely be limited to more abundant species because of number of samples needed to detect changes in rare species.

Minor Risk	Low Risk	Moderate Risk	High Risk	
				_ /
	Likeliho	ood of Population Reduction	n	
	Likelihood of C	other Ecologically Significant	: Impacts	
	Severity of	FEcologically Significant Imp	pacts	
	Number of	Ecologically Significant Imp	oacts	

Figure 2-1. Conceptual view of increased likelihood of adverse impacts with increasing risk level. Schematic of relationship between risk classes and the likelihood of adverse impacts on near-coastal species. Not every type of impact is necessarily expected in all cases (e.g., an increase in severity may not be accompanied by an increase in the number of impacts). The most likely types of effects are listed in Table 2-1.

Table 2-1. Potential climate change effects on individuals and populations within an ecoregion. "Major climate stressors" are the climate stressors most often associated with a particular type of effect. Effects are limited to those that occur within a single ecoregion, and the table does not include changes at a biogeographical scale such as range contractions or expansions.

Response	Major Climate Stressor(s)	Examples								
Ecoregion Population										
Population decline All Laffoley and Baxter, 2016										
Regional extirpation	All	Glynn, 2012; Maclean and Wilson, 2012								
Increased population fragmentation	Sea level rise, Temperature	Chu-Agor et al., 2012; Hubbard et al., 2014								
Increased population fluctuations	All	McLaughlin et al., 2002								
Increased susceptibility to "events"	All	Wethey et al., 2011								
Decreased genetic variability	All	Balint et al., 2011								
Deepening of species to cooler waters	Temperature	Dulvy et al., 2008								
Ecosystem Functions and Services										
Population falls below level to provide ecosystem functions	All	Bulling et al., 2010								
Population falls below economically viable level	All	Sumaila et al., 2011; Branch et al., 2013								
Biochem	ical and Physiological									
Increased susceptibility to disease	Temperature (elevated and/or fluctuation)	Eisenlord et al., 2016; Kohl et al., 2016								
Change in calcification rate	Ocean acidification	Chan and Connolly, 2013; Waldbusser et al., 2016								
Altered individual growth rate	Temperature & Ocean acidification	Thresher et al., 2007; Sheridan and Bickford, 2011								
Reproductive output	Temperature &	Lawrence and Soame, 2004;								
(fecundity, # reproductive events, hatching rate)	Ocean acidification	Swiney et al., 2016								
Reduction in maximum body size	Temperature & Ocean acidification	Sheridan and Bickford, 2011; Cheung et al., 2012								
Physiological/biochemical alterations	Temperature & Ocean acidification	Helmuth et al., 2010; Hofmann and Todgham, 2010; Hans et al., 2014								

2.2 Resilience Traits

Species may possess traits that provide an ability to cope with climate change and/or to recover after being impacted by a climate event. Some authors separate these into resistance and resiliency (e.g., McKinney, 1997), respectively, but we follow Bernhardt and Leslie (2013) and use resilience as a general term encapsulating both. We identified seven baseline traits that potentially indicate increased resilience to climate change in near-coastal species (see Table 4-1). These factors are assigned values of low (+1), moderate (+2) or high resilience (+3).

Resilience factors are not incorporated into the calculation of overall risk primarily because in most cases it is unclear whether the mechanisms conveying resilience directly offset the risks. For example, being a nonindigenous species someplace (Section 4.2.8) and the ability to colonize small island ecoregions (Section 4.2.7) both indicate good colonizing ability, which should help a population recover from a disruption. However, it is not clear how this colonizing ability would offset the physiological impacts of ocean acidification or the habitat loss resulting from sea level rise within a specific ecoregion. In some cases, there is a spatial mismatch between the resilience traits and the risk factors. Species having a wide distribution may insulate the species from global extinction (Section 4.2.5) but it is not apparent how this trait confers protection within an ecoregion could incorrectly reduce the threat to the species. Though not currently used, identification of these resilience traits allows them to be incorporated if future research identifies scientifically-sound principles on how resilience traits offset specific risk factors.

2.3 Overall Risk - "One Way to Live, A Thousand Ways to Die"

As detailed in the remainder of this document, over 30 different risk and resilience values are independently evaluated for each species in each occupied ecoregion. We attempted to standardize the risks across different traits and climate stressors. The goal is that a high risk for sea level rise would be approximately equivalent to a high risk for temperature in the sense that in both cases that there would be ecologically significant impacts on population viability (Figure 2-1). While such equivalence is extremely difficult to calibrate or to demonstrate, the temperature and SLR risks both evaluate changes to population viability. For ocean acidification, however, much of the data currently available to generate risks are not directly related to population viability (see Section 6.3.3). Even with this difference among the climate stressors, we posit that there is at least a general correspondence among the risk classes calculated via different rules. Because of this general correspondence, our approach to assigning an overall risk for a species within an ecoregion is to take the single highest risk; the calculation of the overall risk is not increased if there are multiple risk factors with the same value. Assuming that a moderate risk is the greatest risk, multiple moderate risk values do not result in a high risk, though multiple values can increase the confidence that the species is at some degree of risk. Similarly, a single high risk factor is sufficient to assign an overall high vulnerability to the species.

Basing the overall vulnerability on the greatest risk factor has a long history, dating back to the nineteenth century with Liebig's law of the minimum, where a species is impacted by the single most limiting constraint (see Jones et al., 2006). More recently, the same general approach has been used in EPA's regional-scale monitoring programs that use multi-metric indicators of ecological condition, with the component condition set to poor if any of the individual indicators are poor (e.g., U.S. EPA, 2015). It is also conceptually similar to the multiplicative versus additive approach of assessing habitat suitability in nonparametric multiplicative regressions

(HyperNiche[™]; McCune, 2011). As pointed out by McCune, "if any one factor is lethal then no level of any other independent factor can compensate for it."

A number of other climate risk assessments have used some type of summation or averaging of risks (e.g., Moyle et al., 2013; Hare et al., 2016). Of these approaches, we most strongly disagree with averaging individual factors especially if they include both risk and resilience factors. As pointed out by Morrison et al. (2015), averaging tends to minimize the influence of high risk factors, thus potentially underestimating the overall risk. Averaging risk and resilience values is especially problematic because, as mentioned above, the mechanism or scale of the resilience factor may be different than the risk factors impinging on the individuals or populations within an ecoregion.

A stronger case can be made for basing the overall vulnerability on some type of summation of the number of risk factors (e.g., Morrison et al., 2015; Hare et al., 2016). The summation of risk factors is analogous to the ranking of the ecological condition of sites for water quality, sediment quality, and fish tissue contamination by the number of component indicators rated as good, fair, or poor (U.S. EPA, 2015). Nonetheless, we did not pursue this approach for the following reasons:

Rules were developed with the objective of approximate equivalence in terms of risk. Thus, a single high risk is sufficient to identify the species is at peril and reducing the overall vulnerability based on lower risk factors would underestimate the threat.

We are unaware of any *a priori* ecological justification for choosing any particular methodology to sum different levels of risks.

The results are process dependent, with the overall risk dependent upon the number of risk factors incorporated into the analysis and how the different risk levels are weighted.

Certain baseline/status risk factors or resilience factors may be expressions of the same, or similar, attributes (e.g., colonization ability), and summing them could double account for these attributes.

The general lack of understanding of the interactions among different risk and resilience factors argues against combining them into a single risk score.

While we contend that using the single greatest risk is the most scientifically defensible approach, the vulnerability output from CBRAT (Appendix B) is designed to allow users to evaluate different approaches such as summing the number of risks.

Section 3. Relative Abundance Estimates

3.1 Background

Abundance data provide more insights into potential vulnerabilities than are provided by distributions alone. Distributions identify where a species can survive while abundances help elucidate preferred and marginal environmental conditions; and several studies have indicated that rare species are more susceptible to disturbances (e.g., Davies et al., 2000; Duncan and Young, 2000; Davies et al., 2004). However, because the majority of species in a community or a taxon are rare (e.g., Gray et al., 2005) we do not use rarity alone as an indicator of climate risk, with the exception of Hyper-rare species (Section 3.3). Rather, relative abundance is used as a modifier to the baseline rules predicting climate risk, as discussed in the next chapter.

As far as we are aware, estimating regional relative abundances for thousands of marine species for an entire coast has not been previously attempted. Thus, we had to develop approaches to generate such information. This section details: 1) an overview of some of the factors affecting abundance estimates; 2) a hierarchical abundance schema for classifying relative abundances; and 3) a hybrid approach to generating relative abundance estimates from a mix of quantitative and qualitative information.

3.2 Abundant or Rare?

Everyone knows what abundant and rare species are, but quantifying the concept proves elusive. A number of researchers, in particular Gaston and his colleagues (e.g., Gaston, 1994, 1997, 2011; Blackburn and Gaston, 1997) and conservation biologists (e.g., Hartley and Kunin, 2003; Flather and Sieg, 2007; Marcot and Molina, 2007; Hercos et al., 2012), have tackled defining population abundances. Nonetheless, no generally agreed upon set of definitions have emerged, largely because of the complexities associated with defining different types of abundance across multiple spatial scales and taxa. The major complexities include:

Scale Dependency: Assessment of species' abundances is strongly influenced by the spatial scale evaluated, from that of a single sample (point scale) to global population estimates. Species may be abundant at a small scale in a particular locality but rare at a regional scale.

Temporal Dependency: Most near-coastal species show seasonal patterns in abundance, and many are subject to strong short-term stochastic variations. Thus, when and over how long a population is sampled will affect its estimated abundance, with longer timeframes smoothing out the seasonal and short-term fluctuations.

Absolute Abundances: Absolute estimates of abundance can be expressed as a density, total number of individuals within some habitat or region, areal extent of the population (e.g., marshes and corals), or as the frequency of occurrence in a set of samples. Absolute abundance estimates are very sensitive to differences in sampling gear and sampling design.

Relative Abundances: Relative abundances are abundances normalized to some measure of the abundances of the other species in the taxon or guild. Relative abundances are often used when comparing studies with different sampling techniques or when comparing species across taxa or habitats. Values of relative abundances depend upon what taxon or guild is used to relativize the abundances. In general, relative abundances are larger the narrower the taxon or guild used to relativize the abundances. For example, a rockfish's relative abundance will likely be greater if its abundance is relative only to other rockfish rather than to all bottom fish.

Given that our spatial domain is the MEOW ecoregions, which includes multiple habitat types, assessing absolute abundances for hundreds of common and rare species is essentially impossible. It is possible, though challenging, to assess relative abundances within an ecoregion by integrating different types of information, including habitat areas. Our approach is to assess relative abundances within major taxonomic units for species either associated with the bottom or the water column. For example, the relative abundances of brachyuran crabs are determined by comparing them to other bottom-associated decapods. The rockfish are evaluated compared to other bottom-associated fishes, and not to water-column species. Operationally, these bottom-associated species are those normally captured in bottom trawls and grabs, while water-column associated species are captured in mid-water or surface trawls.

It is important to emphasize that we generate relative abundance for the entire ecoregion and not by habitat. Thus, the relative abundance of crabs in the rocky intertidal are compared to all offshore crabs. The only ecosystem split is that offshore and estuarine species are evaluated independently. To the extent practical, the relative abundances of estuarine crabs are relative to other estuarine crabs while offshore crabs are compared to offshore species. Final estimates are based on the adult stage.

3.3 Hierarchical Relative Abundance Classification Schema

To compare abundance estimates derived from quantitative surveys with those from natural history texts, we needed a classification schema to systematize the abundance estimates. An example of an early sample-scale schema is the ACFOR system (abundant, common, frequent, occasional, or rare; Crisp and Southward, 1958) to describe invertebrate abundances in the rocky intertidal. This system was then replaced with "ESACFOR" (Hawkins and Jones, 1992) that had seven classes (extremely abundant, superabundant, abundant, common, frequent, occasional, or rare). However, in evaluating such sample-scale schemas it became evident that they did not

accommodate classifications at different levels of information, a common occurrence when assessing multiple species at a regional scale. Additionally, these schemas, as well as others, mixed abundance with frequency of occurrence. While frequency is related to a species' abundance, we posit that abundance classes should not be defined by frequency of occurrence since the ecological factors resulting in high/low frequency may be different than those resulting in high/low population abundance.

To address the need for a regional-scale schema, we developed a three-tiered relative abundance schema (Figure 3-1) that is flexible enough to accommodate both quantitative and qualitative information, with the level of resolution determined by data availability. Level I classifications include Present, Not Reported, Error/Extinct, and Transient. Not Reported indicates that there are no records for the species in the ecoregion, and is the default, while Present indicates that there are valid records. Species designated as Present presumably have reproducing populations and are considered established. Present and Not Reported form the basis for describing species' biogeographic distributions (i.e., "presence/absence").

Two additional Level I classifications are necessary to address ecological and taxonomic complexities. The first are Transients, species that temporarily occur in an ecoregion due to climatic or oceanographic events, and are further discussed in Section 4.3.6. The second classification, Error/Extinct captures species that have been reported to occur in an ecoregion but do not actually occur either because they were incorrectly reported or went extinct in the ecoregion. Note that Error/Extinct was previously referred to as Absent (Lee et al., 2015). Incorrect attribution can be due to incorrect taxonomy, taxonomic revisions, mislabeling of samples, or incorrectly extending a species range. In our earlier assessment of coastal invaders in the North Pacific (Lee and Reusser, 2012), we found that such "problem children" occur with annoying regularity. One metric to evaluate the number of occurrences is the 'species X ecoregion' occurrences where, for example, Metacarcinus magister in the Northern California Ecoregion is one species X ecoregion occurrence. Of the 840 species x ecoregion occurrences of brachyuran crabs in the NEP and U.S. Arctic (see www.cbrat.org), 92 were classified as Error/Extinct. Most of these were due to incorrect attributions. Species are also classified as Error/Extinct when they previously occurred in the ecoregion but went extinct, such as nonindigenous species that were introduced but never became established or native species impacted by habitat loss or over exploitation (Dulvy et al., 2003). The Population Trends map in CBRAT identifies whether a species is a mistake or extinct (Lee et al., 2015).

Level II is an assessment of a species' general relative abundance (Abundant, Moderate, or Rare). Level III allows more detailed information to be captured, providing a higher resolution classification of a species' abundance. Basically, each of the Level II classes is divided into two subclasses at Level III plus one additional Hyper-rare class. We define Hyper-rare species as those that have not been reported for \geq 50 years within an ecoregion taking into account whether

there has been at least a minimal sampling effort. The 50-year criterion is in accordance with typical 53-year lag between the last sighting of a species and the reporting of a species' extinction (Dulvy et al., 2003).

As detailed below, a "hybrid" approach combining multiple lines of evidence is used to assign relative abundances. Because many species only have limited information, Level II rather than Level III relative abundances are used to modify the baseline rules (Section 4). As additional information on coastal species becomes available, it should be possible to generate Level III relative abundances for many if not most species, which in turn may provide higher resolution risk predictions.



Figure 3-1. Three-level relative abundance schema for use at regional scales. Level I is the basis for describing biogeographic distributions of species. Level II describes the geographical pattern of relative abundance of a species. Level III describes the relative abundance pattern with a greater resolution. Hyper-rare species have not been observed in >50 years assuming at least a minimal sampling effort.

3.4 Importance of Habitat Area

At an ecoregion scale, the total population size of a species is determined by the sum of its abundance across all the habitats within the ecoregion. This can be expressed as:

Eq. 1: Total population in ecoregion =
$$\sum_{i=1}^{n} (Habitat_i \times Density_i)$$

As illustrated by this heuristic formula, the size of a species' population at a regional scale is as dependent upon the total area of the occupied habitats as on the densities. Species that are abundant in only a single habitat of limited extent would have a low relative abundance when

averaged over the entire ecoregion. Conversely, a species that is moderately abundant in a very wide-spread habitat might be ranked relatively abundant compared to the other species within the ecoregion.

To illustrate the importance of habitat area, the total population size for a species is calculated as the product of habitat area times density for an approximate 1000-fold range in both area and density (Table 3-1). Using the simplifying assumption that a species only occupies a single cell, the relative abundance of each species (cell) is classified using the hierarchical abundance schema (Section 3.3) based on dominance normalized relative abundances (Section 3.5.1). The point of this exercise is to illustrate that most area and density combinations result in a classification of Rare. Of the 121 'area X density' combinations, 66 are classified as Moderately Abundant or Very Abundant. Even at the highest density, species are Rare if they occupy a habitat of limited extent and are classified as Abundant only if the species occupies a habitat of at least moderate spatial extent. The bottom line is that areas of the occupied habitats are as important in determining a species' total abundance at an ecoregion scale as the more commonly reported densities.

Table 3-1. Hypothetical example of species' abundances at an ecoregion scale.

Each species is represented by a single cell, with its abundance calculated as the product of the area of the habitat times the density in that habitat. Abundances are classified according to the hierarchical abundance schema that ranges from Very Rare to Very Abundant (Section 3.3) based on their dominance normalized relative abundance (Section 3.5.1) in each cell. There is a total of 121 species (cells) and a total of 4,190,209 individuals summed across all species. Both the median density and the median habitat area is 32; there are no Abundant species at the median density regardless of habitat area or Abundant species at median habitat area regardless of density.

			Species Density										
		1	2	4	8	16	32	64	128	256	512	1024	
	1	1	2	4	8	16	32	64	128	256	512	1024	
	2	2	4	8	16	32	64	128	256	512	1024	2048	
	4	4	8	16	32	64	128	256	512	1024	2048	4096	
t	8	8	16	32	64	128	256	512	1024	2048	4096	8192	
abita	16	16	32	64	128	256	512	1024	2048	4096	8192	16384	
of H	32	32	64	128	256	512	1024	2048	4096	8192	16384	32768	
Area	64	64	1024	2048	512	1024	2048	4096	8192	16384	32768	65536	
	128	128	256	512	1024	2048	4096	8192	16384	32768	65536	131072	
	256	256	512	1024	2048	4096	8192	16384	32768	65536	131072	262144	
	512	512	1024	2048	4096	8192	16384	32768	65536	131072	262144	524288	
	1024	1024	2048	4096	8192	16384	32768	65536	131072	262144	524288	1048576	
	Key	Very Rare		Moderately Rare		Low Moderate		High Moderate		Moderately Abundant		Very Abundant	

To provide guidance to the areas of different habitats, the total areas of the major estuarine and offshore habitats were determined using georeferenced marine/estuarine landscape data for Oregon, Washington, and California. As detailed in Appendix C, data sources included the National Wetland Inventory (NWI) and various offshore surveys. The major patterns described in Appendix C are:

- Estuarine habitat area is substantially less than offshore area to a depth of 200 m.
- Intertidal and subtidal unconsolidated sediment combined are the major estuarine habitats.

- Submerged aquatic vegetation (SAV) constitutes a relatively small percentage of the estuarine area from Puget Sound through Northern California, and a somewhat greater percentage in Southern California.
- Emergent marshes are moderately abundant in Oregon and Northern California, and relatively less abundant in Puget Sound and Southern California.
- Unconsolidated sediments are the major offshore habitat type from Oregon through Southern California. Rocks and boulders constitute the second largest offshore habitat but a minor habitat in estuaries.
- Kelp constitutes a relatively small proportion of the total area in Puget Sound through Southern California.

For other ecoregions, we assumed generally similar patterns of major habitats (e.g., predominance of unconsolidated sediments and relatively small estuarine area. Two specialized habitats, mangroves and corals, do not occur in the analyzed ecoregions. Mangroves appear to be moderately abundant at least in certain areas in the Magdalena Transition and Cortezian ecoregions (Glenn et al., 2006; Spalding et al., 2010). In comparison, isolated coral patches and coral reefs only occur in the Cortezian Ecoregion, where they constitute a minor area.

Though not used in a formal algorithm, these patterns of habitat area were considered when combining multiple sources of information in the "hybrid approach" to estimate relative abundance (Section 3.8).

3.5 Data Sources - Quantitative Data

Quantitative biotic studies are a key information source to estimate relative abundances, but the challenge is that these studies vary greatly in scale, from a single restricted location to regional surveys. They also vary in sampling design, from fixed sites to randomized surveys, and in sampling gear. This section describes how we mitigate the effects of these differences by normalizing abundances and setting thresholds to convert these normalized abundances to the relative abundance classes described in Section 3.3.

3.5.1 Dominance Normalized Relative Abundance (DNRA)

When quantitative data are available, the question becomes how to compare abundances across different studies. Our first attempt to compare relative abundances across studies was to normalize each species' abundance to the mean abundance of all the species of the target taxon in the sample set. While normalization of abundances to the mean is intuitive, it has the limitation that with increasing sample size new rare species are added to the species set relatively faster than the total number of individuals increases. This results in the average abundance of all

species decreasing since the denominator (number of species) increases faster than the numerator (sum of individuals), which in turn affects the relative abundances of the species. Use of the median abundance does not resolve this issue as it is even more sensitive to increasing sample size and inclusion of new rare species.

To minimize the problem of sample size dependency, we normalized individual species abundances to the mean abundances of the "numerical dominants," defined as those species constituting \geq 75% of the individuals. Use of 75% criterion is derived from Swartz's dominance index (Swartz et al., 1986), which is the minimum number of species required to account for 75% of the total individuals. Advantages of normalizing abundances to the numerical dominants are that, in most cases, their mean abundance stabilizes with a moderate number of samples and their mean abundance does not change monotonically with increasing sample size. Consequently, the relative abundances of non-dominant species do not change systematically as the number of rare species increases with increased sampling.

Dominance normalized relative abundance (DNRA) is calculated from a quantitative sample set according to the following procedure:

- 1. Determine the relative abundance (%) of all species within the target taxon in the total collection.
- 2. Determine the species that make up 75% of the total individuals of the taxon.
- 3. Calculate the average abundance of the species constituting 75% of the individuals. This is inclusive, so if the cumulative percentage of the first 4 species is 74.9% take the average abundance of the first 5 species.
- 4. Divide the abundance of each species by the average abundance of the numerically dominant species. This value is the "dominance normalized relative abundance" for that species.

Because of limitations in capturing the Very Rare species at the lower end of the abundance range (see Table 3-2), dominance normalized relative abundances should be calculated with sample sets with \geq 1000 total individuals and preferably \geq 5,000 individuals; otherwise the approach may fail to identify the Very Rare species.

3.5.2 Quantitative Cut Points for Abundance Classes

After calculating dominance normalized relative abundances for a taxon, the next step is to partition the species into the classes used in the hierarchical relative abundance schema, which requires generating quantitative cutpoints. As pointed out by Gaston (1994, 1997), there is no general theory to establish cutpoints for rare versus abundant species. While theory does not offer any easy answers, it does provide guidelines. In particular, there is strong theoretical and

empirical evidence that most species in assemblages are rare or moderate and only a few species within a taxon are abundant (e.g., Gray et al., 2005).

Using previously described species abundance distribution patterns as a guide, we evaluated various cutpoints within single datasets using quantitative abundances from two large databases. The first was the bottom trawl data from NOAA's RACE program (<u>www.afsc.noaa.gov/RACE/</u>) from which we summarized the bottom trawl data from 1977 to 2006 by MEOW ecoregion in an Access database (USGS_EPA RACE 1977-2006, 2013). The other large dataset was an Access database of EPA's EMAP benthic surveys on the West Coast combined with other benthic surveys (U.S. EPA, 2008). With the RACE data, we analyzed the relative abundance of all bottom fish in the Eastern Bering Sea, while with the benthic data we analyzed the bivalves in Puget Sound through Southern California. Additionally, we evaluated the breakout of Rare to Abundant species at an ecoregion scale with the brachyuran crabs.

The maximum value for a dominance normalized relative abundance is around 5 (i.e., a dominant species is 5-times as abundant as the average abundance of all the numerical dominants). Such high values tend to occur in extreme environments where a few species dominate the fauna. At the opposite extreme, the lowest value, 0.00000015, was derived for bottom fish in the Bering Sea based on the extensive RACE dataset. In most cases, however, the lower value is on the order of 0.001 to 0.00001 in a large dataset. After exploring the behavior of different cutpoints with these datasets, we finalized the values for Level II and Level III relative abundances given in Table 3-2. These cut points give ecologically realistic percentages of Rare to Abundant species from the quantitative survey data in the sense that few species are classified as Abundant and many as Rare as well as capturing the difference between high and low diversity regions.

Table 3-2. Definitions and quantitative cut points for the three-level relative abundance classifications.

Dominance normalized relative abundances (DNRA) are the values used with quantitative studies to assign relative abundance classes. Phrases commonly used in relation to the abundance class both in terms of abundance and frequency of occurrence are provided as a guide. Most of the phrases are not unique to a single level of abundance class; interpretation of these terms needs to be taken in context of scope and spatial scale of the study. The approximate range of the number of species in each abundance class is based on our analyses of the relative ecoregional abundances of brachyuran crabs and bivalves in the Southern California Bight, Northern California, Oregon, Washington, Vancouver Coast and Shelf, and Puget Trough/Georgia Basin ecoregions. (Table modified from Lee et al., 2015). NA = Not applicable.

Abundance Class	Qualitative Description	Qualitative DescriptionCommon Key Phrases - AbundanceCommon Key Phrases - 		Dominance Normalized Relative Abundance Cutpoints	Approximate Ranges of Percentage of Species in an Ecoregion
		Level I			
Present	Valid quantitative or qualitative records exist for a species within an ecoregion.	Present, Observed, Reported, Found, Occurs	Frequency >0	>0	95 - 100%
Not Reported	There are no records known for the species in an ecoregion. This is the default.	No mention of the species within the ecoregion.	Frequency = 0	NA	NA
Error/Extinct	Species that have been incorrectly reported as present in a region due to incorrect taxonomy or taxonomic revisions, or that have gone extinct within the ecoregion.	Misidentified, Taxonomic revision, Extinct, Extirpated	NA	NA	0-5%
Transient	Species that temporarily occur in an ecoregion due to unusual climatic or oceanographic events but do not establish a permanent population.	Transient, Extralimital, Temporary, Migrant, Not established, Outside normal range	Varies (Often low frequency)	>0	0-5%

Abundance Class	Qualitative Description	Common Key Phrases - Abundance	Common Key Phrases - Frequency of Occurrence	Dominance Normalized Relative Abundance Cutpoints	Approximate Ranges of Percentage of Species in an Ecoregion
		Level II			
Abundant	Numerous and usually observed in collections in suitable habitat(s). Often inhabit a habitat of wide spatial extent and/or multiple habitats.	Abundant, Common, Plentiful	Widespread, Frequently observed, High rate of capture	≥ 0.1	4-17%
Moderate	Includes both species that are abundant in habitats of small to moderate spatial extent as well as species that are regularly found at multiple sites but which do not normally constitute a major portion of the individuals.	Moderate, Relatively common, Not uncommon, Collected in reasonable numbers	Moderate rate of capture, Often observed	≥0.01 <0.1	18-45%
Rare	Species with low total population sizes. Often inhabit habitats of limited spatial extent. May be relatively abundant in a spatially limited habitat.	Rare, Uncommon, Specialized	Infrequently observed, Low frequency, Rarely observed, Low rate of capture, Not found very often	<0.01	39-66%
Hyper-Rare	Species that have not been observed within an ecoregion for 50+ years, with the caveat that there has been at least a moderate sampling effort.	Extremely rare, Possibly extinct	Not observed, Not seen for over 50 years	0	0-4%

Abundance Class	Qualitative Description	Common Key Phrases - Abundance	Common Key Phrases - Frequency of Occurrence	Dominance Normalized Relative Abundance Cutpoints	Approximate Ranges of Percentage of Species in an Ecoregion
		Level III			
Very Abundant	The most numerous species within an ecoregion, usually inhabit a habitat of large spatial extent and/or multiple habitats.	Numerical dominant, Very abundant	Ubiquitous, Very widespread, Nearly always collected	≥0.5	2-8%
Moderately Abundant	Abundant species within an ecoregion, but not numerically dominant.	Abundant, Very common	Widespread, Regularly captured	≥ 0.1<0.5	2-12%
High Moderate	Species frequently observed in one or several habitats though usually not among the most numerous species.	Common, Not uncommon, May be abundant in suitable habitats	Frequent, Often observed, Routinely collected	≥ 0.03<0.1	5-25%
Low Moderate	Species that occur in high abundances in relatively spatially limited habitats.	Common, Not uncommon, Common in one locality	Regularly observed, Not infrequent	≥ 0.01<0.03	5-25%
Moderately Rare	Uncommon species, but often observed in low numbers in large collections. May inhabit specialized habitats and/or habitats of limited area. May also include generalist species at the end of their biogeographic range.	Rare, Sparse	Infrequent	≥ 0.005<0.01	8-25%
Very Rare	The least abundant species in an ecoregion, often inhabit specialized habitats or habitats of limited area. Usually sparse even in suitable habitats. Can include species at the end of their biogeographic range.	Rare, Very rare, Unusual, Only one specimen found	Rarely observed, Seldom found	<0.005	10-50%

3.6 Data Sources – Online Biodiversity Databases

Online biodiversity informatics databases are becoming an increasingly important source of species' information (Edgar et al., 2016). Of the current databases, the Ocean Biogeographic Information System (OBIS; <u>http://iobis.org/mapper/</u>) and Global Biodiversity Information Facility (GBIF; <u>https://www.gbif.org/</u>) are particularly useful. Both sites plot individual georeferenced sample points from museum records and quantitative surveys, and can be used to fill in a species' distribution. OBIS maps occurrence data by MEOW ecoregion, making it easier to extract the records. These sites can also provide insights into a species' geographical pattern of abundance. A large number of reports within an ecoregion suggests a moderate or high relative abundance for that species. However, the converse has to be interpreted cautiously; few or no records do not necessarily indicate rarity as the site may not have captured the pertinent surveys. Caution also has to be exercised in comparing among species because differences in the number of occurrences may be a function of the surveys summarized rather than real differences in abundance.

Of the two sites, GBIF tends to have more species than OBIS, though it also tends to have more incorrect or suspicious records in our experience (see Robertson, 2008). Another caution is that GBIF may include fossil records that are not obvious unless the specific record is viewed. For suspicious records (e.g., a single report of a Pacific species in the Atlantic), it is important to backtrack the suspect records to their original sources.

3.7 Data Sources – Text-Based Information

3.7.1 Parsing Natural History Texts

"When *I* use a word," Humpty Dumpty said in rather a scornful tone, "it means just what I choose it to mean – neither more nor less."

-Lewis Carroll, Through the Looking-Glass.

The reality is that quantitative data are not available for many species, especially at regional scales. There is, however, a wealth of information from taxonomists and natural historians that date back over a 100 years on the Pacific Coast. For rare species not reported from quantitative surveys, taxonomic and natural history texts may be the only source of information. We initially developed a set of about 100 key words and phrases related to abundance (e.g., "dense," "not common," etc.) with the objective to standardize, and perhaps automate, the parsing of natural history texts are too context specific to use simple parsing of key words and phrases to generate relative abundances at an ecoregion scale.

Another issue is that natural historians tend to report species' abundances from the species' preferred habitats where they are most abundant. Thus, many species are referred to as

"common", "frequent" or the dreaded "not uncommon". In Hart's (1982) "Crabs and Their Relatives of British Columbia", "common" was used in association with 17 of the 35 brachyuran crabs and "widespread" was used in association with an additional 6 species. Based on these descriptors, one could conclude that 23 of the 35 crabs (65.7%) in British Columbia are abundant, a much higher percentage than can be reconciled with ecological theory. We refer to this tendency of natural historians to assign abundances based on the most favorable habitats as the "Panda Bear Syndrome" – there is a bamboo forest somewhere in south central China where Panda Bears are the most abundant mammal. If this is your point of reference, you view Panda Bears as numerical dominants.

Even with these challenges, taxonomic and natural history texts are treasure troves of information. We offer the following guidelines in using these texts to evaluate regional relative abundances:

Table 3-2 provides a list of the commonly used words and phrases in relation to abundance and frequency of occurrence in relation to Level I through Level III relative abundance classes. Most of the phrases are not unique to a single abundance class, and need to be interpreted in the context of the scope and spatial scale of the study (e.g., local habitat or regional scale).

Texts that describe species at a regional scale are given greater weight than texts describing only a local area.

Give greater weight to cases where several authorities describe similar abundances, with the caveat that the more recent authors are not repeating results from earlier authors.

Unless the text is exclusively focused on a local area, it is generally more straightforward to extrapolate a description of rarity to a regional scale than to extrapolate a report of high abundance to a region.

If possible, compare the text-based abundance to known quantitative estimates to help calibrate how the author uses various words and phrases.

3.7.2 Negative Evidence: The Dog That Didn't Bark

Sherlock Holmes in "Silver Blaze" (Sir Arthur Conan Doyle, 1892) observes there is much to be learned when something that is expected doesn't happen:

Gregory: "Is there any point to which you would wish to draw my attention?" Holmes: "To the curious incident of the dog in the night-time." Gregory: "The dog did nothing in the night-time." Holmes: "That was the curious incident."

Negative evidence has a long history in ecology and evolution, at least as far back as Darwin in 1854 (Darwin, 1854). While it needs to be used judiciously, negative evidence can help identify

rare species. If a species has been reported from an ecoregion in a taxonomic treatise or a species checklist but is not reported from a large dataset, its absence is suggestive that the species is rare. One caveat is that the dataset is based on surveys using appropriate sampling methods and in appropriate locations. Another caution is that if there are only one or two reports of a species in an ecoregion, the accuracy of the identification should be evaluated.

3.8 Hybrid Approach to Estimating Ecoregion Abundances

3.8.1 Synthesizing Multiple Data Types

Recognizing that not all data are equal or that all data types are available for all species, we developed a hybrid approach to assigning relative abundance classes at an ecoregion scale. The following guidelines were used in weighting different types of information:

The most useful data are those from regional scale, randomized surveys such as the previous EMAP surveys (e.g., Nelson et al., 2004, 2007, 2008) and the current National Aquatic Resource Surveys (NARS, U.S. EPA, 2015; <u>https://www.epa.gov/national-aquatic-resource-surveys</u>). Consideration needs to be given to any potential effects of habitat biases or any sampling gear limitations. For example, neither EMAP nor NARS sampled the rocky intertidal. These quantitative data can be converted into dominance normalized relative abundance values in a csv file which allows the relative abundance classifications for all the species in the survey to be automatically mapped into CBRAT with an accompanying PDF for documentation. This functionality saves considerable time compared to entering relative abundances species by species when a survey contains hundreds to thousands of species.

Regional-scale, non-randomized quantitative surveys, such as NOAA's RACE surveys (<u>https://www.afsc.noaa.gov/RACE/default.php</u>), are given second priority. Besides the limitations mentioned above, non-random surveys are subject to nonrandom sampling and spatial biases. As with the randomized surveys, the relative abundances can be automatically mapped into CBRAT if the data are converted to dominance normalized relative abundances in a CSV file.

Expert opinion specifically addressing the ecoregional abundance of a taxon, such as occurred during EPA's "extreme natural history" workshops with SCAMIT (Cadien and Lovell, 2012; Lovell and Cadien, 2013), is usually given third priority. The expert opinion may be given higher priority if the experts can identify limitations with the quantitative surveys or provide more up-to-date information. A key component of working with experts is to provide adequate background information and training to help standardize relative abundances across experts. To the extent practical, the experts should explain their conclusions, especially any that deviate from quantitative surveys.

Local randomized and non-randomized surveys are, in general, given fourth priority. Their weight depends upon the scale of the study and whether there are additional local studies with similar results. Consideration needs to be given to the effects of strong spatial and habitat biases on the results. As with the randomized surveys, the relative abundances can be automatically mapped into CBRAT if the data are converted to dominance normalized relative abundances, though in these cases the abundances only apply to a portion of the ecoregion.

Natural history and taxonomic texts are given fourth or fifth priority. They are given more weight when several texts give similar independent answers or when there is no or very limited quantitative data. In addition to the eccentricities of natural history texts, an additional challenge is standardizing across the experts interpreting the text-based information. Working directly with experts reduces differences among individual interpretations as does initial training.

OBIS and GBIF, and frequency of occurrence data in general, are given the lowest priority and are generally used as a supplement to other data types. A large number of records in an ecoregion from OBIS or GBIF suggest a moderate or high abundance; however, absence of records does not necessarily indicate absence of the species.

Combining these various information types is not formulaic, but several guidelines are possible:

Level III abundance classes should be used if the source(s) give sufficient resolution and there is reasonable certainty in the results. If the sources do not provide sufficient resolution or there is uncertainty (e.g., two authoritative sources disagree), the abundances should be classified at Level II. The CBRAT comment function should be used to document the reasoning and sources, especially for the more problematic cases.

As mentioned, the area of the habitat potentially occupied by the species needs to be incorporated into assigning abundance estimates at an ecoregion scale. It's been our experience that it takes some training to have experts "scale up" their view from local habitats to ecoregions.

Species may only occupy the very northern or southern portion of an ecoregion (e.g., Alijos Rocks which is located at the edge of the southern border of the Southern California Bight ecoregion); in such cases they would be considered rare or very rare when averaged over the entire ecoregion.

One approach to assigning relative abundances with species that have limited or no quantitative data is to initially define a set of "anchor species" that have sufficient information to allow assigning relative abundances with reasonable confidence. Then, by comparing the data-poor species to various upper and lower anchor species, it is often possible to assign a Level II or even Level III relative abundance.

One initial step is to partition the species into abundance bins based on whatever information is available. In most cases, the abundant species will be limited to the 1st bins while the fourth bin will consist of rare species. The 2nd bin will primarily consist of

species with moderate relative abundances. The 3rd bin likely will be a mix of moderate and rare species. This approach is a guide and each species should then be evaluated independently. Nonetheless it can make evaluating a large set of species less daunting.

Our experience is that trained interpreters are generally within a single Level III class (e.g., moderately rare versus very rare).

3.8.2 Checking Abundance Classifications at an Ecoregion Scale

A useful check after classifying a majority of the species is to evaluate the percentages of abundant, moderate, and rare species within each ecoregion. In general, the percentages should follow the order Rare > Moderate >> Abundant. Additionally, the ecoregion-specific percentages can be compared to the ranges in Table 3-2. This table summarizes the percentages of brachyuran crabs and bivalves based on our initial analysis of the four ecoregions from Puget Sound to Southern California. Approximately 98-100% of the species in these taxa are classified to a Level II relative abundance in each of the ecoregions. Percentages for the Level III classes had to be extrapolated as only 31-61% of the crabs and bivalves are currently classified at this level of resolution. The percentages in Table 3-2 are presented as general examples, but distributions that deviate greatly should be examined. However, as noted earlier, percentages may deviate from those in Table 3-2, in particular in stressed or extreme environments and when there is very low diversity of a taxon. An example is the Beaufort Sea-continental coast and shelf Ecoregion which has only three brachyuran crabs, of which two (66%) are classified as abundant and the third as high moderate (33%) based on their numbers.

Also, the distributions should be examined if adjoining ecoregions have substantially different breakouts. If such deviations are noted, examine whether the differences were driven by results from different experts or by a reliance on a particular study in one ecoregion. Another possibility is that an ecoregion has a large number of species classified only as Present, which may artificially reduce the percentage of rare species.

Section 4. Baseline/Status Risks

4.1 Introduction

In their analysis of climate change effects on freshwater fish, Moyle et al. (2013) defined baseline vulnerabilities as species traits, or indicators of such traits, that identify which species are most vulnerable to current environmental stressors other than climate change. Biotic traits, such as life span and spatial distributions as well as measures of population trends, have been used frequently in conservation research (e.g., Sodhi and Ehrlich, 2010), in predicting climate risks with freshwater, and terrestrial species (e.g., Olden et al., 2008; Galbraith and Price, 2009; Diamond et al., 2011; Chown, 2012; U.S. EPA, 2012; Moyle et al., 2013; Pearson et al., 2014) and in predicting climate risks with marine species (Foden et al., 2013; Hare et al., 2016).

In the current analysis, we slightly modify the concept of baseline risks. While other authors have included population trends with baseline risks (e.g., Moyle et al., 2013), we limit baseline risks to inherent biotic traits of species. "Status" is used to capture changes in a species' viability due to exogenous factors such as overfishing or non-climate related habitat loss. The combination of these two is referred to as "baseline/status risks". The second difference is that baseline/status risks are used herein to capture *increased risk under climate stress*. While endemicity is an indicator of population vulnerability under current conditions, we evaluate it as an indicator of increased vulnerability to climate change (e.g., Malcolm et al., 2006; Loarie et al., 2008; Morueta-Holme et al., 2010). Specifically, the risk levels associated with the baseline/status risks identified below are the risks under increased temperatures, reduced pH, and/or sea level rise. Section 4.5 discusses how baseline/status risks are linked to different levels of climatic stress.

A total of 17 baseline/status traits were identified that could be applied to both well-studied and lesser known near-coastal species, with the rules are summarized in Table 4-1 and Table 4-2. These rules are divided into three categories: biogeographic distributions, relative abundances, and life history traits. The rules are further classified as either global or ecoregion specific. Global rules are those that apply the same risk for a species across all ecoregions while ecoregion-specific rules incorporate some ecoregion-specific trait, such as relative abundance, that modify the risk geographically. The baseline/status rules in CBRAT assign a risk value ranging from -3 (high risk) to 3 (high resiliency) depending on whether they increase vulnerability or increase resiliency, respectively. It is not currently possible to change the risk levels associated with particular traits in CBRAT, but users can change the values in the vulnerability summary spreadsheet (see Appendix B).

In the following sections, we list the number of crabs, rockfish, and bivalve species at risk due to the various traits. These provide an assessment of the general applicability of the rules. Rules that identify risk in a very small number of species have limited general utility while rules that predict high risk in most species do not have sufficient resolution to differentiate taxonomic or geographical patterns. These risks are based on a preliminary analysis, and may change with the formal risk analysis (Lee et al., in progress).

Table 4-1. Baseline/status climate rules derived from biogeographic distributions, relative abundance, life history traits, and population trends. Rules are classified as Vulnerability or Resilience depending upon whether the trait results in increased or reduced risk from climate change, respectively. Rules are also classified by the type of trait: biogeographical distributions, regional abundance patterns, or life history traits. A rule that applies to all ecoregions is referred as "global", while geographically specific rules are referred to as "ecoregion specific". Risk is scored from -3 (high risk) to 3 (high resilience).

Trait	Risk / Resilient	Туре	Global or Ecoregion Specific	Baseline/Status Rule	Comments & Exceptions
Endemic	Vulnerability	Distribution	Ecoregion	If species present in only one ecoregion AND NOT Abundant \Rightarrow -3 If species present in only one ecoregion AND Abundant \Rightarrow -2 If species present in more than one ecoregion \Rightarrow 0	
Restricted Distribution	Vulnerability	Distribution	Ecoregion	If species present in only two ecoregions AND Hyper-rare in one or both \Rightarrow -3 If species present in only two ecoregions AND Rare in both \Rightarrow -2 If species present in only two ecoregions AND Present or Moderate or Abundant in one or both \Rightarrow -1 If species present in more than two ecoregions \Rightarrow 0	Do not include ecoregions where the species is Transient.
Wide Distribution	Resilience	Distribution	Global	If species occurs in Arctic/Southern Ocean realm & Cold Temperate & Warm Temperate Provinces $\Rightarrow 2$ If species occurs in Cold Temperate & Warm Temperate & Tropical Provinces $\Rightarrow 2$ If species does not occur in three Provinces with different temperature regimes $\Rightarrow 0$	Do not include ecoregions where the species is Transient or Hyper-rare. See Table 4-5 for MEOW provinces by temperature regime.
Arctic Endemic	Vulnerability	Distribution	Global	If species present only in Arctic ecoregions \Rightarrow -2 If species present in any ecoregion outside the Arctic \Rightarrow 0	Do not include ecoregions where the species is Transient or Hyper-rare. See Table 4-6 for Arctic ecoregions.

Trait	Risk / Resilient	Туре	Global or Ecoregion Specific	Baseline/Status Rule	Comments & Exceptions
Small Island Distribution	Resilience	Distribution	Global	If species occupies a "Small Island Ecoregion" \Rightarrow 2 If species does not occupy a "Small Island Ecoregion" \Rightarrow 0	Do not include ecoregions where the species is Transient or Hyper-rare. See Table 4-8 for Small Island Ecoregions.
Nonindigenous Species (NIS)	Resilience	Distribution	Global	If species has a Master NIS classification anywhere globally with a Master Established value $\Rightarrow 2$ If species has a Master NIS classification but establishment is Not Established OR Unknown OR only Stocked $\Rightarrow 0$ If species does not have a Master NIS classification anywhere $\Rightarrow 0$	
Hyper-Rare	Vulnerability	Abundance	Ecoregion	If species is Hyper-rare \Rightarrow -3 If species is not Hyper-rare \Rightarrow 0	
Rare Everywhere	Vulnerability	Abundance	Global	If species is Rare or Hyper-Rare in all ecoregions \Rightarrow -1 If species is Present, Moderate, OR Abundant in one or more ecoregions \Rightarrow 0	Do not include ecoregions where the species is Transient.
Abundant Somewhere	Resilience	Abundance	Global	If species is Abundant in any ecoregion \Rightarrow 1 If species is not Abundant in any ecoregion \Rightarrow 0	

Trait	Risk / Resilient	Туре	Global or Ecoregion Specific	Baseline/Status Rule	Comments & Exceptions
Population Trend	Vulnerability	Abundance	Ecoregion	If Population Trend is "No Apparent Trend" $\Rightarrow 0$ If Population Trend is "Unknown" \Rightarrow Null If Population Trend is "Moderate Decrease" (-30% to -49% decline) \Rightarrow - 1 If Population Trend is "Substantial Decrease" (-50 to -79% decline) AND abundance is Present, Moderate, or Abundant \Rightarrow -2 If Population Trend is "Substantial Decrease" (-50 to -79% decline) AND abundance is Rare \Rightarrow -3 If Population Trend is "Extreme Decline" (\geq -80% decline) \Rightarrow -3 If Population Trend is "Moderate Increase" (30% to 49% increase) \Rightarrow 1 If Population Trend is "Substantial Increase" (50 to 100% increase) \Rightarrow 2 If Population Trend is "Major Increase" (>100% increase) OR "Order of Magnitude" (\geq 10-fold increase) \Rightarrow 3	Do not include ecoregions where the species is Transient.
Southern ecoregion Rare - Northern ecoregion Abundant	Vulnerability	Abundance	Ecoregion	If a Rare ecoregion abuts an Abundant ecoregion to the north AND there are no Present, Moderate, OR Abundant ecoregions to the south of the Rare ecoregion \Rightarrow -2 All ecoregions to the south of the Rare ecoregion abutting the Abundant ecoregion are also Rare \Rightarrow -2 If not one of the above cases \Rightarrow 0	Limited to 12 ecoregions in U.S. Arctic and NEP, and the ecoregions of the Tropical East Pacific Province.
Northern Transient	Resilience	Abundance	Ecoregion	If a Transient ecoregion occurs to the north of an occupied ecoregion with an abundance of Present, Rare, Moderate, or Abundant AND there are no other occupied ecoregions to the north of the Transient ecoregion \Rightarrow 3 If not a Transient to the north of an occupied ecoregion \Rightarrow 0	Does not apply to Transient ecoregions to the south of an occupied ecoregion.

Trait	Risk / Resilient	Туре	Global or Ecoregion Specific	Baseline/Status Rule	Comments & Exceptions	
				If "Strength of Relationship" (Symbiotic) is Incidental \Rightarrow 0		
				If "Strength of Relationship" (Symbiotic) is Facultative \Rightarrow -2		
Symbiotic Specialization	Vulnerability	Life History	Global	If "Strength of Relationship" (Symbiotic) is Obligate AND abundance is Present, Moderate, or Abundant \Rightarrow -2	Do not include ecoregions where the	
Specialization				If "Strength of Relationship" (Symbiotic) is Obligate AND abundance is Rare or Hyper-Rare \Rightarrow -3	species is Transient.	
				If no symbiotic relationship \Rightarrow 0		
				If no Specialized Habitats \Rightarrow 0		
				Vulnerable Specialized Habitats		
				Obligate & Preferred Habitat \Rightarrow -3		
				Facultative & Preferred Habitat \Rightarrow -2		
				Incidental & Preferred Habitat \Rightarrow Data error		
				Obligate & Observed Habitat \Rightarrow Data error	If multiple aposiblized	
				Facultative & Observed Habitat \Rightarrow -1	habitats, take the	
Habitat	Vulnerability	Life History	Global	Incidental & Observed Habitat \Rightarrow 0	greatest risk. See Table 4-12 for	
Specialization				Resistant Specialized Habitats	vulnerable & resistant	
				Obligate & Preferred Habitat \Rightarrow -2	specialized habitats.	
				Facultative & Preferred Habitat \Rightarrow -1		
				Incidental & Preferred Habitat \Rightarrow Data error		
				Obligate & Observed Habitat \Rightarrow Data error		
				Facultative & Observed Habitat \Rightarrow -1		
				Incidental & Observed Habitat \Rightarrow 0		

Trait	Risk / Resilient	Туре	Global or Ecoregion Specific	Baseline/Status Rule	Comments & Exceptions
Trophic Specialization	Vulnerability	Life History	Global	If Specialist Trophic Specialization \Rightarrow -3 If Moderate Trophic Specialization \Rightarrow -1 If Generalist Trophic Specialization \Rightarrow 0 If Unknown Trophic Specialization \Rightarrow Null	
Anadromous / Catadromous	Vulnerability	Life History	Global	If species is anadromous or catadromous AND Rare \Rightarrow -3 If species is anadromous or catadromous AND Present, Moderate, OR Abundant \Rightarrow -2 If species is not anadromous or catadromous \Rightarrow 0	
Productivity parameters	Vulnerability & Resilience	Life History	Global	See Table 4-2.	Currently only applies to fish

Table 4-2. Baseline/status risks derived from productivity index parameters for fish.

Thresholds for "high" (green), "moderate" (yellow), "low" (orange), and "very low productivity" (red) productivity parameters are from Musick et al., 2000. We combine two of the productivity parameters listed by Musick et al., maturation age of females (age of first reproduction) and maximum life span, to generate a climate risk that is modified by the species' relative abundance in the ecoregion. These rules are for fish only. Risk is scored from -3 (high risk) to 3 (high resiliency).

Maturation - Min. Age (Female only)	Max. Life Span	Relative Abundance	Risk
<12 months	0 to 36 months	Abundant	3
<12 months	0 to 36 months	Present, Rare, Moderate	2
<12 months	37 to 102 months	All	2
12 to 48 months	0 to 36 months	All	2
12 to 48 months	37 to 102 months	All	1
12 to 48 months	103 to 360 months	All	0
49 to 120 months	37 to 102 months	All	0

Maturation - Min. Age (Female only)	Max. Life Span	Relative Abundance	Risk
12 to 48 months	>360 months	All	-1
>120 months	37 to 102 months	All	-1
49 to 120 months	103 to 360 months	All	-1
49-120 months	>360 months	All	-2
>120 months	103 to 360 months	All	-2
>120 months	>360 months	Abundant	-2
>120 months	>360 months	Present, Rare, Moderate	-3
If missing \Rightarrow Null	If missing \Rightarrow Null	All	Null

4.1.1 Observed versus Preferred Habitats and Environmental Ranges

Several of the baseline/status rules (Table 4-1) as well as the SLR rules (Section 7) are modified by whether a species occupies a "preferred" or "observed" habitat or environmental condition. This section provides guidelines for distinguishing between the two (also see Lee et al., 2015).

Many marine and estuarine species are found across a wide range of habitats and environmental conditions, yet the majority of the population occurs within a much more restricted range. For example, several estuarine species are found in low abundances on the continental shelf but the preferred habitat is intertidal estuarine soft bottoms. Classifying these species simply as estuarine and oceanic is misleading about where the species primarily occurs, yet ignoring the oceanic portion of the population truncates the species' environmental range. To address such cases, we developed a natural history topology where many of the species' traits are classified as either "observed" or "preferred" values. Observed and preferred classifications are used for regime, habitat, salinity, depth, substrate, wave & current energy, adult & reproductive temperatures, feeding type, and hosts for symbionts.

Preferred habitats or environmental ranges are those that the species "normally" occurs in. Observed indicates that the species has been collected in a particular habitat or within an environmental range but these condition may represent marginal conditions. All species have a preferred habitat and environmental range though not all occur in marginal conditions or at least have not been reported from marginal conditions. The preferred range can be conceptualized as encompassing approximately 80% of the population while 20% of the population occurs under the observed environmental conditions. In reality, such quantitative data are rarely available and in lieu of such data we developed a set of guidelines to distinguish between the two (Table 4-3). Note that observed is the default classification when there is insufficient information to decide on the relative suitability of the habitat or environmental range for a species. Table 4-3. Guidelines to distinguish between observed versus preferred habitats and environmental conditions.

Observed indicates that the species has been collected within a particular environmental range and may represent marginal conditions. Preferred indicates environmental conditions under which the species normally occurs. Observed is the default classification in absence of sufficient data. The guidelines are listed in their approximate order of utility. The examples are for depth, which is classified as neritic (>0 to 200 m) with shallow subtidal (>0 - 30 m) and deep subtidal (>30 - 200 m) subclasses.

Order utility	Indicators of Preferred Environment	Indicators of Observed Environment	Comments
1	Experts classify environment as preferred (e.g., usually found, typically found, normally occurs at, mostly found, common)	Experts classify environment as marginal (e.g., rarely found, atypical, uncommon)	Such information often given in natural history texts.
2	Moderate to high frequency of occurrence	Low frequency of occurrence	Relative to the specific species, requires quantitative data.
3	Moderate to high abundance	Low abundance	Relative to the specific species, requires quantitative data.
4	Environmental range reported multiple times across multiple papers and databases	A particular environmental range is not or only rarely reported in papers and databases	Multiple reports of depths between 30 and 200 m would indicate that the "deep subtidal" was a preferred depth class. A caution is that the same data are often repeated in different sources.
5	Species is observed in only in subclasses of an environmental class, then the more general class is preferred.	If species is observed in more than the two higher level environmental classifications	If a species is observed in shallow subtidal and deep subtidal, but nowhere else, the neritic is classified as preferred.
6	If a species' observed quantitative range spans two environmental subclasses and the occupied space in one is \ge 80% of the subclass and \le 20% in the other, make the former preferred and the latter observed	If a species' observed range does not follow these criteria (i.e. more than 20% and/or less than 80% in a subclass)	Shallow Subtidal: 20% of 30 m range = 6 m; 80% of 30 m range = 24 m. Deep Subtidal: 20% of 170 m range = 34 m; 80% of 170 m range = 136 m If a species range is 27-180 m, it has a 3 m overlap in shallow subtidal which is < 6 m, complies with the 20% rule. The 150 m in the deep subtidal is > 136 m, complies with the 80% rule. Therefore, shallow subtidal is classified as observed and the deep subtidal as preferred.
7	If only the mean environmental value is given, use as indicator of preferred level	No mean environmental value is given	Can indicate preferred environmental class but not range.
Order utility	Indicators of Preferred Environment	Indicators of Observed Environment	Comments
------------------	--	---	--
8	Suitable for breeding, presence of gravid females, breeding pairs, healthy nests	Marginal or unsuitable for breeding	Breeding can occur in marginal habitats, though not as frequently.
9	Juveniles often found, juveniles present	Juveniles rarely found	
10	Organisms found are normal to large in size	Evidence for stunted growth	Relative to the specific species.
11	Low levels of biochemical / physiological stress markers	High levels of biochemical / physiological stress markers	For example, HSP70 for temperature ranges.

4.2 Baseline/Status Traits – Biogeographic Distributions

4.2.1 Introduction

While it is recognized that a species' vulnerability is related to its biogeographic distribution, there is no uniform approach to defining ranges, and Gaston (1997) summarized 14 different metrics used to describe geographic ranges. Our approach is to characterize distributions by using the number of MEOW ecoregions occupied. This is a measure of the extent of occurrence (EOO), or the "distance or area between the outermost limits to the occurrence of a species" (Gaston, 1994, 1997; IUCN, 2001, 2016). We propose six distributional metrics, of which three are based on the size of a species' range and three are based on where a species occurs (Table 4-1).

4.2.2 Relationship of Range Size to Vulnerability

There is considerable literature indicating that both marine (e.g., Roberts and Hawkins, 1999; Musick et al., 2000; Polidoro et al., 2012) and terrestrial species (e.g., Cooper et al., 2008) with smaller ranges are at a greater extinction risk. Similarly, paleontological evidence indicates that taxa with small ranges were at greater extinction risk than those with wider ranges (see McKinney, 1997 for review). In their simulation study, Pearson et al. (2014) found that the "occupied area", defined as the total area of all occupied patches (= area of occupancy, AOO), was the single most important variable predicting extinction due to climate change. Finally, the IUCN uses both the AOO and EEO as key components of their Red List criteria (IUCN, 2016).

Lower risks associated with larger ranges result from a suite of non-exclusive factors. A wide biogeographic distribution generally indicates that the species has wide physiological tolerances to temperature and perhaps other environmental factors as well. Occupation of multiple regions can mitigate the impact of local or regional perturbations by spreading of risk across a species' geographical distribution (IUCN, 2016). Species with wide ranges often have a greater genetic diversity than species with narrow ranges, suggesting a greater adaptability to environmental changes. Conversely, a narrow range may indicate that the species has poor dispersal ability, is a poor competitor, and/or is highly susceptible to predation, factors potentially increasing a species' vulnerability to new stressors. Finally, species with small ranges often have low abundances, though there are exceptions (see Gaston, 1994; Hobbs et al., 2011).

There are two cautions in interpreting the risks associated with small ranges. First, inadequate sampling in certain regions may give the appearance of a limited distribution while, in fact, the species extends over multiple ecoregions. Such overestimation of species with limited distributions will be less pronounced for well-studied taxa like crabs, bivalves and fish than for lesser studied taxa. Second, is the presence of cryptic species, "two or more distinct species classified as a single species" (Bickford et al., 2006). Thus, what appears to be a widely distributed species may consist of a number of localized, distinct species, potentially

underestimating the number of species with limited distributions. Cryptic species will be most prevalent among polychaetes (e.g., Nygren, 2014) and other taxonomically challenging taxa. While it is not possible to generate rules to catch such errors, it is straightforward to modify species' distributions as taxonomic revisions become available.

4.2.3 Endemics – Vulnerability Trait

As the smallest unit of occupancy in our analysis, we define endemic species as those occupying a single MEOW ecoregion (e.g., *Bonita mexicana*, Figure 4-1). Based on the evidence discussed above, endemic species are considered to be particularly vulnerable to both natural and anthropogenic threats. However, as pointed out by Hobbs et al. (2011), "high abundance of marine endemic species may buffer them from intrinsic characteristics that increase the probability of extinction". Incorporating the potential for buffering, we generated the following rules (see Table 4-1):

If an endemic species is abundant in the ecoregion \Rightarrow -2

If an endemic species has a moderate or rare abundance or is classified as present \Rightarrow -3

Approximately 13% of the brachyuran crabs are endemic (Table 4-4). Many of these endemics occur in the Gulf of California (Cortezian Ecoregion), and the percentage of endemics is reduced to 4.3% if this ecoregion is excluded. The other taxa range from 0 to 4.2% endemics, again with many of the endemics in the Gulf of California. While a commonly used indicator of risk, endemicity only identifies a relatively small number of at risk species.

Table 4-4. Number of species with endemic, restricted, or wide distributions. The number of occupied ecoregions is evaluated globally. The values for the brachyuran crabs are also calculated excluding the Cortezian Ecoregion because of the concentrations of endemics in the Gulf of California. These values are preliminary and the bivalve results are based on incomplete trait analysis.

Taxon	# Species	Average # Ecoregions Occupied	Median # of Ecoregions Occupied	# Endemic (%)	# Restricted (%)	Wide Distribution (%)
Brachyuran crabs	365	7.02	6	45 (12.57%)	29 (7.95%)	29 (7.95%)
Brachyuran crabs - wo/ Cortezian ecoregion	210	7.66	7	9 (4.29%)	22 (10.47%)	26 (12.38%)
Lithodid crabs	21	7.33	7	0 (0%)	1 (4.76%)	6 (28.57%)
Rockfish	71	4.94	5	3 (4.22%)	11 (15.49%)	12 (16.90%)
Bivalves	892	8.45	6	35 (3.92%)	48 (5.38%)	172 (19.28%)

4.2.4 Restricted Distribution – Vulnerability Trait

Most coastal species have wide distributions. Crab, bivalve and rockfish species occupy an average of about 5 to 8.5 ecoregions (Table 4-4). Based on these wide distributions, we created a second metric, species with restricted distributions, defined as species occurring in only two MEOW ecoregions (e.g., *Lophopanopeus leucomanus* (Figure 4-2). Species with restricted distributions are subject to the same vulnerabilities as endemics, though not to the same severity because of their wider span in temperature and other environmental conditions as well as a greater spreading of risk. We apply analogous rules for restricted species as with the endemics but the risk is reduced by one risk class based on the assumption of a lesser vulnerability (Table 4-1):

Species present in only two ecoregions and Hyper-rare in one or both \Rightarrow -3

Species present in only two ecoregions and Rare in both \Rightarrow -2

Species present in only two ecoregions and Present or Moderate or Abundant in one or both \Rightarrow -1

Species present in more than two ecoregions $\Rightarrow 0$



Figure 4-1. Example of an endemic species, defined as occupying only one MEOW ecoregion. The pinnotherid crab *Bonita mexicana* has only been reported from Tortugas Bay, Mexico, which puts it in the Southern California Bight Ecoregion. The color key is used in CBRAT to symbolize the ecoregion relative abundance classes.



Figure 4-2. Example of a species with a restricted distribution, defined as species occupying two MEOW ecoregions. The mud crab *Lophopanopeus leucomanus* has been reported only from the Northern California and Southern California Bight ecoregions. The color key to the ecoregion relative abundance classes is given in Figure 4-1.

The risk is increased if one of the ecoregions is classified as Hyper-rare since these populations are so small that such species are functionally endemics. As with the endemics, risks are modified by abundance, with a greater risk when the species is rare in both of the ecoregions. Based on these rules, 29 brachyurans have restricted distributions or 22 if the Cortezian Ecoregion is excluded. In comparison, 1 lithodid crab, 11 rockfish, and 48 bivalves have restricted distributions (Table 4-4).

4.2.5 Wide Distributions - Resilience Trait

Wide biogeographic distributions indicate that a species has wide environmental tolerances, and thus should be less vulnerable to climate change. Wide distributions may also reduce vulnerability by spreading of risks and indicate a larger total population size. One possible metric for wide distributions is the number of ecoregions occupied compared to the average (or median) for the taxon (Table 4-4). The limitation is that if all the ecoregions occur in regions with similar temperatures, the number of ecoregions occupied may not accurately identify species with wide environmental tolerances. For example, a number of the warm-water brachyuran crabs that reach their northern limit in the Magdalena or Cortezian ecoregions. The coral gall crab, *Hapalocarcinus marsupialis*, occurs in the Cortezian Ecoregion and twenty Indo-Pacific ecoregions. Similarly, many Arctic species extend over multiple Arctic and cold temperate ecoregions, such as the Arctic lyre crab, *Hyas coarctatus* that occupies 27 ecoregions (Figure

4-3). Although these two distribution patterns exceed the average number occupied for brachyuran crabs, all the ecoregions tend to have broadly similar temperature regimes.

To better identify species with broad environmental tolerances, we define wide distributions as those that encompasses at least three MEOW provinces with different temperature regimes. For a species limited to the NEP and U.S. Arctic, it would be considered to have a wide distribution if it occurred in the Arctic, Cold Temperate Northeast Pacific Province and the Warm Temperate Northeast Pacific Province. Alternatively, a species would be considered widespread if it occurred in the Cold Temperate Northeast Pacific, Warm Temperate Northeast Pacific, and the Tropical Eastern Pacific provinces. An example is the sandflat elbow crab, *Latulambrus occidentalis,* that occurs from the Northern California Ecoregion to the Guayaquil Ecoregion, encompassing three MEOW provinces (Figure 4-4).

Analysis for wide distributions is based on global distributions of the species, with a list of provinces in polar regions (Arctic/Southern Ocean), cold temperate, warm temperate, and tropical temperature regimes in Table 4-5. We assign a moderate resilience level to species with wide distributions, as defined by the following rules (Table 4-1):

Species occurs in Arctic & Cold Temperate & Warm Temperate Provinces $\Rightarrow 2$ Species occurs in Cold Temperate & Warm Temperate & Tropical Provinces $\Rightarrow 2$ Species does not occur in three Provinces with different temperature regimes $\Rightarrow 0$

A total of 29 brachyuran crabs, 6 lithodid crabs, 12 rockfish, and 172 bivalves have wide distributions (Table 4-4).



Figure 4-3. Example of a species occupying multiple ecoregions but not classified as having a wide distribution.

The crab *Hyas coarctatus* occupies 27 MEOW ecoregions in the Arctic and Cold Temperature provinces, which have broadly similar temperature regimes. The color key to the ecoregion relative abundance classes is given in Figure 4-1.



Figure 4-4. Example of a species with a wide distribution, defined as occupying three MEOW provinces.

The elbow crab *Latulambrus occidentalis* has been reported from cold temperate, warm temperate, and tropical provinces. The color key to the ecoregion relative abundance classes is given in Figure 4-1.

Arctic and Southern Ocean	Cold Temperate	Warm Temperate	Tropical
Arctic	Amsterdam-St Paul	Agulhas	Andaman
Continental High Antarctic	Black Sea (Ponto-Caspian)	Benguela	Arabian
Scotia Sea	Cold Temperate Northeast Pacific	East Central Australian Shelf	Bay of Bengal
Subantarctic Islands	Cold Temperate Northwest Atlantic	Lord Howe and Norfolk Islands	Central Indian Ocean Islands
Subantarctic New Zealand	Cold Temperate Northwest Pacific	Mediterranean Sea	Central Polynesia
	Juan Fernández and Desventuradas	Northern New Zealand	Easter Island
	Lusitanian	Southwest Australian Shelf	Eastern Coral Triangle
	Magellanic	Warm Temperate Northeast Pacific	Galapagos
	Northern European Seas	Warm Temperate Northwest Atlantic	Guinea Current
	Southeast Australian Shelf	Warm Temperate Northwest Pacific	Gulf of Guinea
	Southeast Australian Shelf	Warm Temperate Southeastern Pacific	Hawaii
	Southern New Zealand	Warm Temperate Southwestern Atlantic	Java Transitional
	Tristan Gough	West Central Australian Shelf	Java Transitional
			Marquesas
			Marshall, Gilbert and Ellis Islands
			North Brazil Shelf
			Northeast Australian Shelf
			Northwest Australian Shelf
			Red Sea and Gulf of Aden
			Sahul Shelf
			Somali/Arabian
			South China Sea
			South Kuroshio
			Southeast Polynesia

Table 4-5. MEOW provinces in the four major temperature regimes. The Arctic does not have provinces and is listed at the MEOW realm level.

Arctic and Southern Ocean	Cold Temperate	Warm Temperate	Tropical	
			St. Helena and Ascension Islands	
			Sunda Shelf	
			Tropical East Pacific	
			Tropical Northwestern Atlantic	
			Tropical Southwestern Atlantic	
			Tropical Southwestern Pacific	
			West African Transition	
			West and South Indian Shelf	
			Western Coral Triangle	
			Western Indian Ocean	

4.2.6 Arctic Endemics – Vulnerability Trait

Species limited to one or more of the 19 ecoregions comprising the MEOW Arctic Realm (Table 4-6) are defined as Arctic endemics. Limitation to the Arctic indicates that the species has a narrow temperature range and would be vulnerable to temperature increases as well as having limited opportunity to migrate northward. Limitation to the Arctic is considered a moderately strong indicator of risk, with the following rules (Table 4-1):

Species present only in Arctic ecoregions \Rightarrow -2

Species present in any ecoregion outside the Arctic $\Rightarrow 0$

This is not a common distribution (see Josefson and Mokievsky, 2013). None of the brachyuran crabs, lithodid crabs or rockfish are limited to the Arctic though six bivalves that occur in U.S. Arctic ecoregions are so limited (Table 4-7). An example is *Boreacola maltzani* (Figure 4-5) that occurs in the Chukchi Sea, Beaufort Sea, and in Europe and Russia Arctic ecoregions.

Table 4-6. Arctic Ecoregions.

The High Arctic ecoregion was not included in the MEOW schema, but was added to capture species that occur in the highest portion of the Arctic.

Arctic Ecoregions
Eastern Bering Sea
Chukchi Sea
Beaufort Sea - continental coast and shelf
Beaufort-Amundsen-Viscount Melville-Queen Maud
High Arctic Archipelago
Lancaster Sound
Baffin Bay - Davis Strait
Hudson Complex
Northern Labrador
West Greenland Shelf
East Greenland Shelf
North Greenland
North and East Iceland
North and East Barents Sea
White Sea
Kara Sea
Laptev Sea
East Siberian Sea
High Arctic

Taxon	# Species	Arctic Endemic (%)	Small Island Colonizer (%)	Nonindigenous Species (%)
Brachyuran crabs	365	0 (0)	106 (29.04)	5 (1.36)
Lithodid crabs	21	0 (0)	0 (0)	1 (4.76)
Rockfish	71	0 (0)	0 (0)	0 (0)
Bivalves	892	6 (0.67)	118 (13.23)	10 (1.12)

Table 4-7. Number of Arctic endemics, small island colonizers, and nonindigenous species. The values are preliminary for the bivalves.



Figure 4-5. Example of an Arctic endemic, defined as a species that occurs only in Arctic ecoregions. The clam *Boreacola maltzani* is limited to the Chukchi and Beaufort Sea - Continental Coast and Shelf ecoregions and to Eurasian Arctic ecoregions. The color key to the ecoregion relative abundance classes is given in Figure 4-1.

4.2.7 Small Island Distributions - Resilience Trait

There is a set of MEOW ecoregions that are surrounded by water with no direct contact with the mainland, which we refer to as island ecoregions. Mainland species that occur on these island ecoregions possess three key traits indicating a lower vulnerability to environmental change (see Whittaker and Fernandez-Pelacios, 2007 for a discussion of traits associated with island colonizers). First, they have good dispersal ability to initially colonize island ecoregions. Second, they are able to establish a population with a relatively small number of initial colonizers. Third, island colonizers are able to maintain populations in a relatively limited area. These traits should reduce vulnerability by enhancing the species' ability to recover from environmental perturbations. Note that this increased resilience refers only to species occurring both on the mainland and island ecoregions; island endemics are considered to be especially vulnerable to anthropogenic perturbations (e.g., Whittaker and Fernandez-Palacios, 2007).

While there is a debate about how population dynamics on small islands differs from those on larger islands ("small island effect"; see Lomolino and Weiser, 2001; Triantis et al., 2012), we assume that the biotic traits associated with colonization and small population viability are more pronounced with species able to occupy small islands. For this analysis, we use the Revillagigedos, the largest of the three island ecoregions in the Tropical Eastern Pacific, as the upper limit. The Revillagigedos have a land area of approximately 158 km², which we round to 200 km² as our upper threshold. In comparison, Hawaii has an area of 28,311 km². Based on this threshold, there are 29 small island ecoregions globally, three of which occur in the Tropical Eastern Pacific (Table 4-8).

The upper size threshold of only 200 km² is a stringent criterion and, accordingly, species that occur in small ecoregions are assigned a moderate resilience. The specific rules (Table 4-1) are:

If species occupies a "Small Island" Ecoregion $\Rightarrow 2$

If species does not occupy a "Small Island" Ecoregion" $\Rightarrow 0$

A total of 106 brachyuran crabs and 118 bivalve species occupy small island ecoregions (Table 4-7). The majority of these are reported from the Gulf of California presumably reflecting the subtropical/tropical nature of Revillagigedos, Clipperton, and Cocos Islands as well as the lack of island ecoregions off more northern ecoregions. In comparison to the bivalves and brachyurans, no lithodid crabs or rockfish occupy small island ecoregions.

Table 4-8. Small island ecoregions.

Island ecoregions are defined as ecoregions surrounded by water with no direct contact with the mainland, while small island ecoregions are defined as those with a land area of 200 km² or less.

ECOREGION	PROVINCE
Amsterdam-St Paul	Amsterdam-St Paul
Bermuda	Tropical Northwestern Atlantic
Bounty and Antipodes Islands	Subantarctic New Zealand
Bouvet Island	Subantarctic Islands
Campbell Island	Subantarctic New Zealand
Cargados Carajos/Tromelin Island	Western Indian Ocean
Chagos	Central Indian Ocean Islands
Clipperton	Tropical East Pacific
Cocos-Keeling/Christmas Island	Java Transitional
Cocos Islands	Tropical East Pacific
Easter Island	Easter Island
Fernando de Naronha and Atoll das Rocas	Tropical Southwestern Atlantic
Juan Fernández and Desventuradas	Juan Fernández and Desventuradas
Kermadec Island	Northern New Zealand
Lord Howe and Norfolk Islands	Lord Howe and Norfolk Islands
Macquarie Island	Subantarctic Islands
Marshall Islands	Marshall, Gilbert and Ellis Islands
Ogasawara Islands	Tropical Northwestern Pacific
Peter the First Island	Subantarctic Islands
Phoenix/Tokelau/Northern Cook Islands	Southeast Polynesia
Rapa-Pitcairn	Southeast Polynesia
Revillagigedos	Tropical East Pacific
Sao Pedro and Sao Paulo Islands	Tropical Southwestern Atlantic
Snares Island	Southern New Zealand
South China Sea Oceanic Islands	South China Sea
Southern Cook/Austral Islands	Southeast Polynesia
Three Kings-North Cape	Northern New Zealand
Trindade and Martin Vaz Islands	Tropical Southwestern Atlantic
Tristan Gough	Tristan Gough

4.2.8 Nonindigenous Species – Resilience Trait

Nonindigenous species (NIS) is another group that has demonstrated both good dispersal ability and the ability to establish populations with a small inoculant. Similar to the small island occupants, these traits should reduce their vulnerability to environmental changes, and NIS may

actually increase with climate change (e.g., Walther et al., 2009a). Because invaders may undergo substantial declines after an initial "boom" (e.g., Delefosse et al., 2012) as well as being potentially susceptible to climatic events themselves (McDowell et al., 2017), we consider invasion of a non-native ecoregion a moderate rather than high resilience trait. To reduce uncertainty about the population status of the invaders, we only include invaders that are considered established in a non-native ecoregion. This excludes a number of stocked non-native species in Asia where it is not clear if they have established a breeding population in the wild, and which are assigned an Unknown establishment class (see Lee and Reusser, 2012). The specific rules for NIS (Table 4-1) are:

Species has a Master NIS classification with a Master Established classification anywhere globally \Rightarrow 2

Species has a Master NIS classification but is Not Established, Unknown Establishment, or only Stocked classification $\Rightarrow 0$

Species does not have a Master NIS classification $\Rightarrow 0$.

We use our previous synthesis of the distribution of NIS in the North Pacific (Lee and Reusser, 2012) to identify species from the Northwest Pacific (NWP) that have invaded the NEP and, conversely, native species from the NEP that have invaded the NWP. For invaders on the U.S. East Coast, Europe, and other areas, we use previous summaries of NIS (e.g., Ruiz et al., 2000; Streftaris et al., 2005). Using these sources, we identified five established NIS brachyuran crabs and one nonindigenous lithodid crab that was purposely introduced by the Russians into the Barents Sea (Jørstad et al., 2002) (Table 4-7). There are no established non-native rockfish and ten established nonindigenous bivalves.

4.3 Baseline/Status Traits – Relative Abundance Patterns

4.3.1 Background on Relative Abundance Metrics

As mentioned, ecoregional abundance patterns provide additional insights into vulnerabilities than those provided by biogeographical distribution patterns alone and we propose six sets of rules based on relative abundance (Table 4-9). Because of the substantially greater percentage of species classified at Leve II relative abundance compared to Level III, we utilize Level II in generating the rules.

Table 4-9. The number of species identified by each of the relative abundance rules.

Values in parentheses are percentage of the species in the taxon. All values are preliminary. NYA = not yet analyzed.

Taxon	# Species	Hyper -rare	Abundant Someplace	Rare Everywhere	Population Decline	S. Ecoregion Rare – N. Ecoregion Abundant	Northern Transient
Brachyuran crabs	365	19 (5.20)	36 (9.86)	57 (15.61)	77 (21.10)	0 (0)	13 (3.56)
Lithodid crabs	21	0 (0)	1 (4.76)	3 (14.28)	3 (14.29)	1 (4.76)	0 (0)
Rockfish	71	0 (0)	21 (29.58)	24 (33.80)	20 (28.17)	3 (14.28)	1 (1.41)
Bivalves	892	5 (0.56)	107 (12.00)	172 (19.28)	NYA	NYA	27 (3.02)

4.3.2 Hyper-Rare Species – Vulnerability Trait

Because of the high percentage of rare species (e.g., Gaston, 1994; Flather and Sieg, 2007), rarity in itself is an insufficient trait to identify vulnerable species. The one exception are Hyper-rare species, which are species that have not been observed in 50 years, assuming at least a minimal sampling effort (see Section 3.3). We interpret this extreme rarity as an indicator of environmental/biotic conditions unfavorable for the species, which in turn indicates a high vulnerability to other stressors. The specific rules are (Table 4-1):

Species is Hyper-rare \Rightarrow -3 Species is not Hyper-rare \Rightarrow 0

No lithodid crabs or rockfish are classified as Hyper-rare and only five bivalves (Table 4-9). In comparison, there are 19 brachyuran crabs classified as Hyper-rare in one or more ecoregions. Part of the reason for the higher number of brachyurans may result from initial poor descriptions of some of the species, especially pinnotherid crabs, reducing the likelihood that recent researchers would report these species. Because of this possibility, researchers should check the taxonomy of Hyper-rare species to help distinguish between true rarity and taxonomic uncertainty.

4.3.3 Abundant Someplace/Rare Everywhere – Vulnerability and Resilience Traits

Species that are abundant someplace possess a suite of traits that allow them to effectively exploit the available resources under the correct conditions, a suite of traits not shared by many species as indicated by the relatively small percentage of abundant species in nearly all assemblages (see Section 3; Gaston, 1994; Flather and Sieg, 2007). The life history attributes promoting abundance are presumably related to those allowing a species to adapt to

environmental changes. Additionally, the occurrence of a large population in one or more regions provides at least a short-term buffer against detrimental environmental changes and a greater opportunity for re-colonization of impacted regions. Accordingly, we predict species that are abundant in at least one ecoregion are more likely to adapt to environmental changes. Species that are rare everywhere are essentially the converse of this, and are predicted to have a higher vulnerability and lesser ability to adapt to climatic changes. Because of the myriad of ecological, historical, and sampling factors that can affect abundance estimates, we assign a low resilience or vulnerability score to these two attributes. The specific rules are (Table 4-1):

Species is Abundant in any ecoregion $\Rightarrow 1$

Species is not Abundant in any ecoregion $\Rightarrow 0$

And for rarity:

Species is Rare or Hyper-Rare in all ecoregions \Rightarrow -1

Species is Present, Moderate, or Abundant in one or more ecoregions $\Rightarrow 0$

Ecoregions outside of the Northeast Pacific and U.S. Arctic are included in both analyses. The criterion for rarity is applied strictly and species are not classified as "rare everywhere" if they are classified as Present in any ecoregion. Thirty-seven crabs are abundant somewhere, including 36 brachyurans and 1 lithodid crab, while 21 rockfish and 107 bivalves are abundant somewhere (Table 4-9). In terms of rarity, 57 brachyuran crabs are rare everywhere compared to 3 lithodid crabs. A total of 24 rockfish and 172 bivalves are rare everywhere.

4.3.4 Population Trends – Vulnerability and Resilience Traits

Population trends are an important criterion in evaluating whether a species is at risk in conservation ecology (Flather and Sieg, 2007) and is a key factor in determining extinction risk in the IUCN's Red List (<u>http://www.iucnredlist.org/</u>; Keller and Bollmann, 2004; Akçakaya et al., 2006). Population trends are also used in evaluating risk to climate change; the evaluation of freshwater fish vulnerability to climate change used four measures of population decline over different time periods (Moyle et al., 2013).

Incorporating population trends into the present risk schema requires three steps, the first of which is generating thresholds or cutpoints for different classes of population increases or declines. To the extent possible, we harmonized our thresholds with the A2-A4 criteria of the IUCN in their Red Book listing (IUCN, 2016) (Table 4-10). This resulted in four classes of population decline with thresholds analogous to the A2-A4 criteria. Additionally, our Unknown is generally equivalent to the IUCN's Data Deficient. However, an important difference is that we assign "No Apparent Trend" in ecoregions with at least minimal background information on the species if there is no indication of a decline instead of "Unknown". Our logic is that even with poorly sampled species, a > 30% decline in a species or a large loss in the species' habitat

will often be noted by natural historians or observed in sampling programs. While this approach has the advantage of moving beyond the refrain of insufficient information, it is not as comprehensive as the procedure used by IUCN. Another difference is that the IUCN rule for population reductions is that population declines should be calculated for the most recent three generations or 10 years, whichever is longer. We attempted to follow this guideline, but in some cases recent information was not available for non-commercial species and we had to rely on older observations. Because of these differences, the population trend assignments in CBRAT can be used to identify species of concern but they are not directly transferable to an IUCN Red List assessment without additional analysis.

The IUCN does not have thresholds for population increases, which are important for capturing climate change "winners". Accordingly, we generated increase trend cutpoints that mirror the declines. The 100% increase is a doubling, which is proportionally equivalent to a 50% decline. In some cases, there may be very large increases and the "Order of Magnitude Increase" class was added to capture population "booms" in recent invaders as well as for the potential of large initial increases in native species migrating into a northern ecoregion.

Population Trend Class	Population Trend (% change in population size)	Closest Equivalent IUCN A2-A4 Criterion
Order-of-Magnitude Increase	<u>></u> 10X	None
Major Increase	<u>></u> 100% to <10X	None
Substantial Increase	50% to 100%	None
Moderate Increase	30% to 49%	None
No Apparent Trend	-29% to 29%	<30% decline
Moderate Decrease	-30% to -49%	Vulnerable (<u>></u> 30% decline)
Substantial Decrease	-50% to -79%	Endangered (>50% decline)
Extreme Decrease	-80% to -99%	Critically Endangered (>80% decline)
Extinct/Extirpated	-100%	Possibly Extinct & Extinct
Unknown	NA	Data Deficient

Table 4-10. Population trend classes based on percent change in population size within an ecoregion. The closest equivalent IUCN A2-A4 criteria (IUCN, 2016) are given. The CBRAT assignments are not directly transferable to an IUCN Red List assessment without additional analysis.

The second step in incorporating population trends is to generate a set of rules relating the population trends classes to risk classes. The logic is that stress due to climate change will exacerbate any current population declines due to habitat loss, overfishing, or other non-climate drivers (e.g., Hewitt et al., 2016). While the exact nature of such interactions are generally unknown, we assume that the greater the current population decline the greater the impact of additional climate-related stress. Thus, we assign high, moderate, and low climate risks to the IUCN's critically endangered, endangered, and vulnerable classes, respectively. This assignment

is similar to that used in the climate risk analysis for freshwater fishes (Moyle et al., 2013), which used >80% and >50% reduction as the two most severe classes of long-term population trends. However, we modify the risk based on population abundance. The default risk for a Substantial Decrease is Moderate, but increased to High when the species is Rare within an ecoregion. This increased risk is based on the premises that a rare population has less of a buffer to respond to an additional stressor and that the existing environmental conditions in the ecoregion are unfavorable to rare species.

Using this logic, the following rule set is applied on an ecoregion-by-ecoregion basis (Table 4-1):

If Population Trend is "Major Increase" OR "Order of Magnitude Increase" \Rightarrow 3

If Population Trend is "Substantial Increase" $\Rightarrow 2$

If Population Trend is "Moderate Increase" $\Rightarrow 1$

If Population Trend is "No Apparent Trend" $\Rightarrow 0$

If Population Trend is "Moderate Decrease" \Rightarrow -1

If Population Trend is "Substantial Decrease" AND abundance is Present, Moderate, or Abundant \Rightarrow -2

If Population Trend is "Substantial Decrease" AND abundance is Rare \Rightarrow -3

If Population Trend is "Extreme Decrease" \Rightarrow -3

If Population Trend is "Unknown" \Rightarrow Null

The third step is to estimate population trends across all the species and ecoregions being evaluated. Ideally, quantitative trend data would be used for each species in each ecoregion, however the reality is that such data are not available for the vast majority of near-coastal species, with the exception of some commercial species. Rather than limit our analysis to commercial species, we take a more liberal approach and use whatever population information is available. The following are used as indicators of Substantial to Extreme declines: 1) closed fishery and 2) species included on regional threatened or endangered lists. Other indicators used to support quantitative population trend data, or used when such data are not available, include: 1) vulnerability to overfishing; 2) vulnerability to by-catch; 3) vulnerability to trawling damage; 4) documented or projected near-term habitat loss; 5) vulnerability to NIS; and 6) vulnerability to pollution.

An example of using expert opinion is that several crabs in the Gulf of California occurring at the depths of shrimp trawlers are considered to be declining due to their susceptibility to trawling damage and as by-catch (R. Brusca, personal communication to Henry Lee, 2015). An example of using habitat loss to identify likely declines is the pinnotherid crab *Scleroplax granulata*,

which is likely declining due to the decline of a major host, *Upogebia pugettensis*, resulting from an invasive parasitic isopod (Griffen, 2009; Dumbauld et al., 2011).

Based on these multiple lines of evidence, we assign a population trend class. If there is sufficient information to assign an abundance class but no evidence of a decline, the "No Apparent Trend" class is assigned. If there is insufficient information to assign an abundance class, "Unknown" is assigned. There is reasonable population trend data for rockfish in many of the ecoregions, and 20 of the 71 bottom-associated rockfish in the Northeast Pacific are classified as experiencing at least moderate declines in one or more ecoregions (Table 4-9). In nearly all cases, these declines are the result of overfishing of these slow growing, long-lived species (e.g., Musick et al., 2000, Drake et al., 2010). While there are less data for the crabs, 77 brachyuran crabs and 3 lithodid crabs are classified as undergoing population declines in one or more ecoregions (Table 4-9).

4.3.5 Southern Ecoregion Rare and Ecoregion to North Abundant – Vulnerability Trait

A few species show a strong gradient in their relative abundance, being Rare in a southern ecoregion and then Abundant in the ecoregion immediately to the north. Our interpretation is that these species are not well adapted to the direct or indirect effects of the higher temperature regime in the south compared to the cooler northern ecoregion. Thus, the population in the southernmost ecoregion is considered to be moderately vulnerable to increased air and/or water temperatures, whether through direct thermal effects or indirectly through altering ecological processes (e.g., trophic dynamics, competitive interactions).

In the case of disjunct distributions, all disjunct ecoregions to the south of the Rare ecoregion abutting the Abundant northern ecoregion are assigned a moderate climate risk if they are all Rare. However, if any of these disjunct southern ecoregions are not classified as Rare, the risk for all the ecoregions is set to 0. The Aleutians are considered north of the Gulf of Alaska because the Aleutian Ecoregion has a lower mean sea surface temperature (Payne et al., 2012a). Similarly, the Puget Trough/Georgia Basin Ecoregion is considered north of the Oregon, Washington, Vancouver Coast and Shelf Ecoregion. With these definitions, the specific rules are (Table 4-1):

If a Rare ecoregion abuts an Abundant ecoregion to the north and there are no Present, Moderate, or Abundant ecoregions to the south of the Rare ecoregion \Rightarrow -2

All ecoregions to the south of the Rare ecoregion abutting the Abundant ecoregion are also Rare \Rightarrow -2

If not one of the above cases $\Rightarrow 0$

This is an uncommon pattern, and no brachyuran crabs and only one lithodid crab, *Lithodes aequispinus*, displays this regional abundance pattern (Table 4-9). The pattern is slightly more common among the rockfish, with three species showing this regional pattern.

4.3.6 Northern Transients – Resilience Trait

We define Transients as species that temporarily inhabit an ecoregion beyond their normal range due to unusual climatic or oceanographic events. By definition, Transients are unable to maintain a long-term viable population in the new ecoregion under present conditions, and thus die out in one or a few generations. Species introduced outside of their natural range via anthropogenic vectors, such as ballast water discharges, are considered NIS and not transients. Our concept of Transient is similar to "vagrant", "visitor", "extralimital", or "ephemeral" species as used by various authors (e.g., Rodrigues and Gaston, 2002). We further distinguish between "northern transients" that occur to the north of the species' northern range limit versus the less frequent "southern transients" that occur to the south of the species' southern range limit.

Transients are often rare in their "invaded" ecoregion, though this is not inherent in its definition. Since abundance alone cannot be used to differentiate between the random sampling of rare, native species versus transients, we utilize the species' association with an event, the presence of only juveniles, higher abundances to the south, and expert opinion as the primary approaches to identifying transients. On the Pacific Coast, the major oceanographic event resulting in northern transient species is the occurrence of El Niño, which results in warmer waters off of Baja, Mexico to Alaska (e.g., Chavez et al., 2002). For example, the 1997-1998 El Niño was exemplified by "an unusually high occurrence of subtropical organisms along the California coast" (Pondella and Allen, 2001; also see Lea and Rosenblatt, 2000; Engle and Richards, 2001).

Occurrence of these southern species in northern ecoregions during these warm-water events demonstrates that they have the characteristics needed to migrate rapidly under favorable conditions. Such migration may be active, which may be the case with swimming portunid crabs. Alternatively, species may possess traits that promote their passive transport northward during larval or adult stages. Occurrence of transients outside their normal range also demonstrates that they can survive at least for short periods in the northern ecoregion(s) under the conditions associated with an El Niño. Our projection is that with the advent of increased water temperatures there is a high likelihood that these species will become established in these northern ecoregions, assuming no other environmental limitation. The specific rules for northern transients in their invaded ecoregion are (Table 4-1):

If a Transient ecoregion occurs to the north of an occupied ecoregion $\Rightarrow 3$

If not a Transient to the north of occupied ecoregion $\Rightarrow 0$

Thirteen brachyuran crabs were associated with El Niño or other oceanographic events and are classified as northern transients in one or more ecoregions (Table 4-9). There are no northern transients among the lithodid crabs, though there is one southern transient, *Hapalogaster cavicauda*, in the Gulf of California. Only one rockfish (*Sebastes alutus*) has a transient population recorded in the Chukchi Sea, most probably carried from the Bering Sea by ocean currents (Mecklenburg et al., 2002). Among the bivalves there are 27 northern transients.

4.4 Baseline/Status Traits – Life History

4.4.1 Introduction

Key life history attributes related to a species' vulnerability include degree of specialization, reproductive strategies, and population growth rates. Addressing specialization first, a host of studies have linked niche specialization with increased species' vulnerability. McKinney (1997) summarized fossil evidence for terrestrial and marine taxa indicating that rare stenotopic (specialist) species were more prone to extinction than rare eurytopic (generalist) species. Studies on extant populations of birds (Jiguet et al., 2007) and butterflies (Warren et al, 2001) found that specialists were more vulnerable than generalists. Specialization has also been used specifically to assess vulnerability to climate change. "Specialized habitat and/or microhabitat requirements" is one of five attributes used by the IUCN in assessing vulnerability to climate change in bird, amphibian, and reef-building corals (Foden et al., 2008) while the "degree of habitat specialization" is used as one of the key components of terrestrial species' sensitivity to climate change (U.S. EPA, 2009).

We distinguish three types of specialization: habitat specialization, trophic specialization and symbiotic relationships. Recognizing that there is a gradient in the biotic relationships between habitat specialization and symbiotic relationships, we differentiate symbiotic relationships as species that live directly on or in its hosts, while habitat specialists live in the general vicinity of a particular biotic habitat, particularly macrophytes. A crab living within a polychaete tube would be classified as a symbiont while a crab living in association with mangroves would be classified as a habitat specialist. We also classify symbionts as habitat specialists, and trophic specialists when appropriate, to highlight the nature of the biotic interactions.

Two other life history traits that we use to predict vulnerabilities are first the presence of a diadromous reproductive strategy, where the species spends part of its life in freshwater and part in saltwater, and second the potential population growth rate of fishes.

4.4.2 Symbiotic Relationships – Vulnerability Trait

Symbiotic interactions are often referred to as commensalism, defined as a biotic relationship in which the commensal (symbiont) benefits and the host is not affected (+/0 relationship), or mutualism where both symbiont and host benefit (+/+ relationship). In many cases, closer

examination of these relationships shows that the symbiont benefits at the expense of its host (+/relationship). In particular, kleptoparasitism, where the symbiont steals food from the host, may be relatively common among marine symbionts (e.g., Telford, 1982; Morissette and Himmelman, 2000; Iyengar, 2005). Classic parasitism, such as a gill parasite, is also a type of +/symbiotic relationship. Regardless of the nature of the interactions, three key aspects of a symbiotic relationship in terms of vulnerability are: 1) strength of the biotic relationship; 2) vulnerability of the host to climate change; and 3) abundance of the symbiont.

In terms of the strength, we define an obligatory relationship as one where at least one life history stage of the symbiont requires a host(s). Obligatory symbionts are nearly always found (\geq 90%) in association with a single host or suite of host taxa. We do not assume a 100% association because symbionts may occasionally be found outside the host(s) because of reproduction (e.g., male *Pinnixa* crabs searching for females) or when migrating to a new host. With these highly dependent species, loss of the host(s) would result in a major population decline, potentially resulting in local or regional extinction. In cases where the symbiont infests multiple hosts, each host would be considered a facultative relationship but the symbiont would be considered obligate if it is nearly always associated with a host. We define a facultative relationship as when the target species occurs with its host(s) 10% to <90% of the time. While less vulnerable, populations of facultative symbionts likely would experience declines with the reduction or loss of their host(s). An "incidental" relationship is defined as one that occurs <10% of the time; loss of such a host(s) would presumably have a minor impact on the symbiont population. Note that while we pose these as quantitative thresholds, in most cases the strength of the association has to be evaluated from qualitative data.

Another factor affecting the risk to a symbiont is the vulnerability of the host(s) to climate change. Ideally, the risk analysis for the symbiont would explicitly incorporate the risk to each host in each ecoregion. This is not currently possible because the climate risks of many of the host taxa (polychaetes, echinoderms, and corals) have not yet been completed. In the interim, we take a conservative approach of assuming that the hosts are vulnerable, which may overestimate symbiont risk in some ecoregions. To at least identify the potential for such interactions, CBRAT has a simple classification whether climate change is likely to impact the primary hosts. While not currently utilized in the rules, users can evaluate our current general assessment of climate impacts on the primary hosts.

The third factor impacting a symbiont's risk is its relative abundance, with abundant symbionts having a greater buffer to environmental changes compared to rare symbionts. A high frequency of occurrence of a symbiont with its host(s) does not in itself indicate that the symbiont is abundant as the host(s) may be uncommon. Rather, the relative abundance of the host(s) needs to

be factored into assessing a symbiont's abundance. After incorporating abundance, the rules for symbionts become (Table 4-1):

If "Strength of Relationship" (Symbiotic) is Incidental $\Rightarrow 0$ If "Strength of Relationship" (Symbiotic) is Facultative $\Rightarrow -2$ If "Strength of Relationship" (Symbiotic) is Obligate AND abundance is Present, Moderate, or Abundant $\Rightarrow -2$ If "Strength of Relationship" (Symbiotic) is Obligate AND abundance is Rare or Hyper-Rare $\Rightarrow -3$ If no symbiotic relationship $\Rightarrow 0$

Symbiotic relationships are relatively common among the brachyuran crabs, with 51 species having an obligate relationship (Table 4-11), the majority of which are pinnotherid crabs. In comparison, no lithodid crabs or rockfish are symbiotic. The analysis for symbiotic relationships for the bivalves has not been completed.

Table 4-11. Number of species with symbiotic relationship, habitat specialization, trophic specialization and anadromous/catadromous reproduction. Numbers are for high levels of specialization. Habitat specialization for the brachyurans does not include the pinnotherid crabs, which are captured under symbiotic relationships. Specialization classifications have not yet been completed for the bivalves. All values are based on a preliminary analysis. NYD = not yet determined. Numbers in parentheses are percent of species

Taxon	# Species	Obligate Symbiotic Relationship	High Habitat Specialization	High Trophic Specialization	Anadromous/ Catadromous
Brachyuran crabs	365	51 (13.97)	8 (2.19)	5 (1.36)	1 (0.27)
Lithodid crabs	21	0 (0)	0 (0)	0 (0)	0 (0)
Rockfish	71	0 (0)	0 (0)	0 (0)	0 (0)
Bivalves	892	NYD	NYD	NYD	0 (0)

4.4.3 Habitat Specialization

Certain species occupy "unique habitats of limited distribution", which we define as spatiallylimited habitats with a physical/chemical structure distinct from other habitats, providing unique environmental conditions. Spatially limited is used in comparison to the area of all the other habitats within the ecoregion. Some unique habitats, such as tide pools, are extremely limited in area. Others, like marshes and mangroves, occupy much larger areas but are still relatively small compared to other habitats averaged over the ecoregion, in particular unvegetated sand/mud (see Appendix C).

A total of 24 habitats or ecosystems are considered unique habitats of limited distribution (Table 4-12). Because not all these habitats are equally vulnerable to climate change, we separate them into "climate vulnerable" and "climate resilient" habitats. This differentiation is used in a comparative sense to separate the unique habitats most susceptible to climate change; it does not mean that the resilient habitats will not be impacted by climate change. Marshes, mangroves, and SAV habitats are included among the climate resilient habitats because independent risks are generated for SLR for each of these habitats (Section 7). For these habitats, the resilient classification is meant to capture non-SLR effects thus avoiding double accounting for SLR risks.

Table 4-12. Unique habitats of limited distribution.

Unique habitats are separated into those most susceptible to climate change, the "climate vulnerable" habitats, and those less susceptible, the "climate resilient" habitats. Each habitat is classified as whether it is unconsolidated, consolidated, pelagic, or a specialized system. Specialized systems are unique and spatially limited ecosystems composed of more than one habitat type. Non-coral reefs include sponge and polychaete reefs. As used here, oyster beds are limited to those on unconsolidated sediments. *Indicates classified as resilient because a separate SLR risk is calculated for each habitat.

Climate V	/ulnerable	Climate R	esilient
Burrowing shrimp	Unconsolidated	Algal mats	Consolidated
Coral reef	Consolidated	Cold seeps	Specialized systems
Kelp	Consolidated	Dune	Unconsolidated
Mussel beds	Consolidated	Emergent Marshes*	Unconsolidated
Non-coral reefs	Consolidated	Hydrothermal vents	Specialized systems
Oyster beds	Unconsolidated	Mangrove*	Unconsolidated
Phyllospadix	Consolidated	Pelagic systems	Pelagic
Rhodoliths / Maerl	Consolidated	Saline lagoons	Specialized systems
Sea ice	Specialized systems	Sea mounts	Specialized systems
Solitary corals	Consolidated	Submerged Aquatic Vegetation*	Unconsolidated
Tide Pools	Consolidated	Whale falls	Specialized systems
Wrack	Unconsolidated	Wood	Consolidated

As with the symbiotic relationships, habitat specializations may be obligate, facultative, or incidental; independently a species utilization of a habitat is classified as observed or preferred. Obligate is used in the sense that loss of the habitat would result in a substantial population decline. All obligate habitat specializations are also classified as preferred habitats. In comparison, all incidental specialized habitat utilizations are classified as observed habitats.

Facultative utilization covers a broader range of reliance on the habitat with its importance classified as an observed or preferred habitat. The specialization classification is keyed to the most sensitive life history stage, and for some species the juvenile stage utilizes the habitat of limited distribution. For example, several rockfish preferentially settle from the planktonic stage into kelp beds (Love et al., 2002). While only dependent upon the habitat for a portion of its life cycle, loss or reduction of nursery habitats could result in a population bottleneck.

Based on these definitions, the following rules were generated (Table 4-1):

If no Specialized Habitats $\Rightarrow 0$ <u>Vulnerable Specialized Habitats</u> Obligate AND Preferred Habitat $\Rightarrow -3$ Facultative AND Preferred Habitat $\Rightarrow -2$ Facultative AND Observed Habitat $\Rightarrow -1$ Incidental AND Observed Habitat $\Rightarrow 0$ <u>Resilient Specialized Habitats</u> Obligate AND Preferred Habitat $\Rightarrow -2$ Facultative AND Preferred Habitat $\Rightarrow -1$ Facultative AND Preferred Habitat $\Rightarrow -1$

Incidental AND Observed Habitat $\Rightarrow 0$

Some degree of utilization of these unique habitats is relatively common among brachyuran crabs, with approximately 118 species utilizing one or more of the unique habitats listed in Table 4-12. However, only eight non-pinnotherid brachyuran crabs are classified as obligate habitat specialists (Table 4-11). None of the lithodid crabs or rockfish are obligate habitat specialists, though as mentioned above, some juvenile rockfish are facultative habitat specialists.

4.4.4 Trophic Specialization

Several lines of evidence indicate that trophic specialists are more vulnerable to environmental changes. The fossil record shows that detritus-feeders (= deposit feeders) have lower background extinction rates than other feeding types, which McKinney (1997) attributed to "a more generalized diet and lack of feeding specialization." Among extant species, trophic specialists have shown greater vulnerability to environmental changes or disturbances in both terrestrial (e.g., Charrette et al., 2006) and marine (e.g., Graham, 2007) species. Thus, there is strong support to assign a high baseline/status vulnerability to species with specialized feeding habits.

Details on the feeding regimes of most marine/estuarine species are not well known, but a limited number of trophic specialists have been documented. Tropical corallivores display varying degrees of specialization (Graham, 2007) while in temperate systems a small number of species that are closely associated with biotic structures have restricted diets. Examples include crabs associated with kelp (e.g., *Pugettia producta*; Hines, 1982; Jensen, 1995, 2014), limpets living in association with kelp (e.g., *Patella argenvillei*; Bustamante et al., 1995), and crabs living in coral (e.g., *Trapezia bidentata*; Abele, 1976). Most marine herbivore gastropods are generalists with the exception of ascoglossan sea slugs, in contrast to terrestrial herbivores where many species are specialists (Trowbridge, 1994; also see Clark, 1994). However, such trophic specialists appear to be the exception among marine/estuarine species.

In the absence of species-specific information, a set of guidelines are used to assign trophic classifications (Figure 4-6). Based on these guidelines, species are automatically assigned a trophic classification in CBRAT for a single feeding mode using the rules below or according to those in Figure 4-6 for multiple feeding modes. These rules are an initial effort at classifying trophic interactions, and the automatic assignment based on these rules can be changed by users via a "Manual Override" in CBRAT.

Species with Symbiotic Algae \Rightarrow Specialist Species with chemoautotrophic bacteria \Rightarrow Moderate Parasites/disease \Rightarrow Unknown Primary producer \Rightarrow Generalist Herbivore \Rightarrow Unknown Herbivore – grazer \Rightarrow Generalist Herbivore – folivore \Rightarrow Depends on number of plants species consumed Specialist if < 5 food items. Moderate if >5 food items and <10 food items Generalist if >10 food items Predator \Rightarrow Depends upon the number of prey items consumed Specialist if ≤ 5 prey items. Moderate if >5 prey items and <10 prey items Generalist if ≥ 10 prey items Scavenger \Rightarrow Generalist Detrivore \Rightarrow Generalist $Decomposer \Rightarrow Generalist$

Suspension Feeder \Rightarrow Moderate

Deposit Feeder \Rightarrow Generalist

 $Osmotrophy \Rightarrow Generalist$

Table 4-13. Guidelines for assigning levels of trophic specialization for single and multiple feeding modes.

	Assigning Levels of Trophic Specialization
•	Assign an Unknown as the default for unusual feeding modes, and then classify each of these species by the specifics of its feeding modes.
•	Parasites/diseases vary greatly in specificity so set to Unknown. Parasites may occasionally have other feeding modes, but not generalizable. Use same guidelines for number of hosts as with predators.
•	Loss of symbiotic algae harms corals, which are suspension feeders. This is the rationale for Specialist with that combination. However, Unknown with other combinations since it depends upon how strongly the species relies on symbiotic algae (e.g., predatory nudibranchs with symbiotic algae).
•	Assume that chemosynthetic bacteria are more robust than symbiotic algae, so assign Moderate if only feeding type. Suspension feeders are Moderate, so combination with chemosynthetic bacteria results in Generalist classification. Osmotrophy is not sufficient to change from Moderate unless shown to be a substantial nutritional source.
•	Primary producers include both photosynthesis and chemosynthesis but classification is limited to macrophytes, not symbiotic algae. Set to Generalist. Macrophytes not commonly combined with other feeding modes (e.g., Venus fly trap). Set combinations to Unknown.
•	Herbivore alone is Unknown.
	 Grazers appear to be Generalists on microalgae, so addition of other feeding type is still a Generalist.
	 Folivores are Unknown and are classified by the number of macrophytes species consumed.
•	. Herbivore with osmotrophy falls under the unusual guideline (Unknown).
•	Specialization of predators depend upon the number of prey consumed. Combination of predation with other active feeding types is Generalist, except parasites which depends upon number of prey/hosts and osmotrophy, which depends upon how important it is, so Unknown.
•	Scavengers, detritivores, and decomposers tend to feed on what they find (= Generalist) and addition of other feeding types would not decrease level of specialization unless they were the dominant feeding type.
•	Suspension feeders appear to be less general in their feeding than deposit feeders, so Moderate. Combined with other feeding type assign a Generalist except for primary producer and parasite/disease which fall under the unusual trophic type guideline of Unknown.
•	While deposit feeders may select particular particle sizes, they are classified as Generalists in sense that their food source is not highly susceptible to climate change. Combined with other feeding type does not reduce Generalist classification except for primary producer and parasite/disease which fall under the unusual trophic type guideline of Unknown.
•	Uptake of DOC as a primary food source is considered a Generalist. However, uptake of DOC appears to be a supplemental trophic mode in many cases. Classification of osmotrophy combined with other feeding modes depends upon the relative importance of osmotrophy compared to other feeding mode.

	Parasite / Disease	Symbiotic Algae	Chemo- autotrophic	Primary Producer	Herbivore	Herbivore - Grazer	Herbivore - Folivore	Predator	Scavenger	Detritivore	Decomposer	Suspension Feeder	Deposit Feeder	Osmo- trophy
Parasite / Disease	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Symbiotic Algae		Specialist	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Specialist	Unknown	Unknown
Chemo-autotrophic			Moderate	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Generalist	Generalist	Moderate
Primary Producer				Generalist	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Herbivore					Unknown	NA	NA	Generalist	Generalist	Generalist	Generalist	Generalist	Generalist	Unknown
Herbivore - Grazer						Generalist	Generalist	Generalist	Generalist	Generalist	Generalist	Generalist	Generalist	Generalist
Herbivore - Folivore							Unknown	Generalist	Generalist	Generalist	Generalist	Generalist	Generalist	Unknown
Predator								Unknown	Generalist	Generalist	Generalist	Generalist	Generalist	Unknown
Scavenger									Generalist	Generalist	Generalist	Generalist	Generalist	Generalist
Detritivore										Generalist	Generalist	Generalist	Generalist	Generalist
Decomposer											Generalist	Generalist	Generalist	Generalist
Suspension Feeder												Moderate	Generalist	Generalist
Deposit Feeder													Generalist	Generalist
Osmotrophy														Generalist

Figure 4-6. Default levels of trophic specialization based on single and two feeding modes.

These are the default levels of specialization generated automatically from the feeding type, but they can be modified by users in CBRAT. Unknown = level of specialization varies depending upon the specific feeding habitats of the species, including the number of different types of prey consumed. Several of the feeding combinations are possible but rare (e.g., predator and herbivore). Guidelines used to assign the levels of tropic specialization are given in Table 4-13. The climate risks are then assigned based on the degree of specialization. With moderate specialization, a reduction in key food items may have some impact on population viability. However, many marine/estuarine species can switch diets (e.g., Graham, 2007; Jumars et al., 2015), including native predators learning to prey on introduced species (e.g., Inger et al., 2010; Dijkstra et al., 2013). Accordingly, moderate trophic specialists are assigned a low risk. In contrast, trophic specialists are assigned a high risk since they have limited options to switch diet. The specific rules (Table 4-1) become:

If Generalist Trophic Specialization $\Rightarrow 0$ If Moderate Trophic Specialization $\Rightarrow -1$ If Specialist Trophic Specialization $\Rightarrow -3$

Not including the pinnotherid crabs, which may be kleptoparasites, five brachyuran crabs display a high degree of trophic specialization (Table 4-11). No lithodid crabs or rockfish display a high degree of trophic specialization.

4.4.5 Anadromous/Catadromous

Diadromous species have specialized reproductive strategies in which they migrate to or from marine waters to reproduce. Anadromous species spend most of their adult life in marine waters and then migrate to freshwater to breed. Archetypical anadromous species are Pacific Northwest salmon, such as ocean-type Chinook (*Oncorhynchus tshawytscha*) and chum salmon (*O. keta*). Catadromous species spend most of their adult life in freshwater and then migrate to the ocean to breed. This life history strategy is less common (Allen et al., 2006), but one example is the American eel, *Anguilla rostrata*, on the East Coast of the United States. These life history strategies are vulnerable to anthropogenic impacts both on their ability to migrate between freshwater and marine environments and to climate impacts on their freshwater, estuarine, and marine habitats (Greene et al., 2009).

We assign a high vulnerability to both life history strategies if the population is rare. Because larger populations provide a buffer to the effects of climate impacts, we assign a moderate risk when the species is moderate or abundant. The specific rules (Table 4-1) are:

- If species is anadromous or catadromous AND Rare \Rightarrow -3
- If species is anadromous or catadromous AND Present, Moderate, or Abundant \Rightarrow -2
- If species is not anadromous or catadromous $\Rightarrow 0$

There are no anadromous crabs, rockfish, or bivalves in the NEP or U.S. Arctic (Table 4-11) but there is one catadromous brachyuran crab. The mitten crab (*Eriocheir sinensis*) was introduced into the San Francisco Estuary, where it spends most of its adult life in the freshwater delta,

migrating down to the estuary to spawn (Rudnick et al., 2005). It was considered a serious pest species in the Bay-Delta region, but its population has been declining such that adults were rarely observed in 2012 (http://nas.er.usgs.gov/queries/FactSheet.aspx?speciesID=182).

4.4.6 Growth and Productivity

Life history parameters related to population productivity, including fecundity, intrinsic rate of increase, age at maturity, and maximum age, have been used to evaluate vulnerability among a diverse group of vertebrates including whales, sharks, and bony fishes (Musick 1999; Musick et al. 2000; Dulvy et al., 2004; Gallagher et al., 2012). Using these traits, Musick et al. (2000) provided thresholds for different risk levels with a primary focus on fishing pressure. In this section, we adapt these thresholds are available for invertebrate taxa.

Threshold values for these productivity metrics to evaluate extinction risk with fish are shown in Table 4-14 When the intrinsic rate of increase (r) is not available, age at maturity is the next most important factor along with maximum age (Musick 1999). These later two metrics are often correlated with the von Bertalanffy coefficient (k) (Musick 1999). High fecundity rates are useful in some cases but may be misleading for Pacific rockfish whose reproductive patterns indicate very low larval survival as well as infrequent recruitment (Musick 1999; Parker, et al., 2000). Additionally, Denney et al. (2002) and Reynolds et al. (2005) found no evidence that high fecundity increases recruit production or reduces likelihood of extinction.

Productivity Parameter	High Productivity	Medium Productivity	Low Productivity	Very Low Productivity		
r (yr. ⁻¹)	> 0.50	0.16 - 0.50	0.05 - 0.15	< 0.05		
von Bertalanffy k (yr. ⁻¹)	> 0.30	0.16 - 0.30	0.05 - 0.15	< 0.05		
Fecundity per year	>104	10 ² - 10 ³	10 ¹ - 10 ²	< 10 ¹		
Age at maturity (Tmat)	<u><</u> 1 yr.	2-4 yr.	5-10 yr.	> 10 yr.		
Maximum age (Tmax)	1-3 yr.	4 -10 yr.	11-30 yr.	> 30 yr.		

Table 4-14. Productivity index parameter thresholds for fishes.

Measures include intrinsic rate of increase (r), von Bertalanffy k, fecundity, age at maturity (Tmat), and maximum age (Tmax). The thresholds are guidelines for the risk of extinction from Musick (1999) and Musick et al. (2000). Lower risk is associated with high productivity and higher risk with very low productivity. These classifications are primarily developed for the effects of fishing pressure.

We generated the productivity climate rules based on maximum age and age at maturity for females (Table 4-2) because they are among the most readily available productivity measures for Pacific rockfish (e.g., Love 2011). These rules are based on the assumption that short-lived species that mature earlier are less vulnerable to climate change impacts than species that take

longer to mature. Such short-lived, rapidly maturing species are also more likely to rebound from short-term climatic events better than slower maturing species. Table 4-15 summarizes the available productivity values for *Sebastes*.

There are a number of differences in how fishing pressure and climate change impact fish populations. For example, while overfishing tends to extirpate the largest/oldest rockfish (Dulvy et al. 2003), climate change and habitat alterations often have a greater impact on larval/juvenile recruitment and survivorship, as observed from the last 20 years of warming oceans (Love and Yoklavich 2006). Another difference is that while long-lived species are at risk due to slower reproduction, their ability to survive over decades has demonstrated an ability to adapt to a range of environmental conditions. The spatial patterns of the stressors are also different, with fishing concentrated where the fish are most abundant, while climate change will impact rare populations as well as abundant ones.

Because of these differences, we suggest that the risk levels developed primarily for fishing pressure (Table 4-14) need to be modified, including incorporating the potential buffering of climate effects when there are abundant populations. Incorporating abundance with the various combinations of maximum life span and age at maturity results in 15 rules (Table 4-2). As detailed in Table 4-15, both required productivity values are available for 46 of the 71 bottom-associated *Sebastes* species, a well-studied taxon. Of these 46 species, 37 are considered somewhat to highly vulnerable to climate change based on the productivity metrics in at least one ecoregion.

Table 4-15. Sebastes productivity parameters.

Productivity parameters are rated high (green), medium (yellow), low (orange), and very low (red) based on Musick (1999) and Musick et al. (2000) (see Table 4-14). Von Bertalanffy k values are for females or sexes combined. Climate vulnerability is based on Tmat and Tmax, with the von Bertalanffy coefficient and fecundity given for comparison. Productivity values are from Love et al. (2002) and Love (2011). Gray indicates species for which none of the productivity parameters are available. The table includes three primarily pelagic species (*S. peduncularis, S. sinensis, S. varispinis*) that are not included in the risk analysis. ND = no data.

Species	Age at Maturity (Female; Tmat) (years)	Max age (Tmax) (years)	von Bertalanffy (k)	Fecundity (# eggs)
Sebastes aleutianus	20	205	0.108	ND
Sebastes alutus	4-10	104	0.175	2,000-505,000
Sebastes atrovirens	3-6	25	0.29	10,000-340,000
Sebastes auriculatus	3-10	34	0.16	55,000-339,000
Sebastes aurora	11-32	118	0.06	ND
Sebastes babcocki	3-19	106	ND	ND

Species	Age at Maturity (Female; Tmat) (years)	Max age (Tmax) (years)	von Bertalanffy (k)	Fecundity (# eggs)
Sebastes baramenuke	ND	ND	ND	ND
Sebastes borealis	21-23	160	0.03	ND
Sebastes brevispinis	9-18	82	0.093	181,000- 1,917,000
Sebastes carnatus	ND	24	0.253	ND
Sebastes caurinus	3-8	50	0.1	16,000-650,000
Sebastes chlorostictus	6-19	51	0.062	14,000-760,000
Sebastes chrysomelas	3-6	30	0.22	25,000-450,000
Sebastes ciliatus	11	67	ND	ND
Sebastes constellatus	6-14	32	0.09	33,000-228,000
Sebastes cortezi	ND	ND	ND	ND
Sebastes crameri	8-9	105	0.16	20,000-610,000
Sebastes dallii	ND	12	0.12	3,900-18,000
Sebastes diploproa	6-10	103	0.1	14,000-255,000
Sebastes elongatus	3333-12	54	0.079	11,000-295,000
Sebastes emphaeus	1-2	22	0.53	3,300-58,000
Sebastes ensifer	3	43	0.14	12,200-38,000
Sebastes entomelas	3-8	60	0.2	95,000- 1,113,000
Sebastes eos	ND	52	ND	ND
Sebastes exsul	ND	24	ND	ND
Sebastes flavidus	<15	64	0.17	56,000- 1,992,700
Sebastes gilli	ND	60	ND	ND
Sebastes glaucus	7-10	19	ND	ND
Sebastes goodei	3-8	39	0.17	18,000-538,000
Sebastes helvomaculatus	ND	87	0.1	ND
Sebastes hopkinsi	3-7	19	0.18	9,000-39,000
Sebastes jordani	2-4	32	0.198	50,000
Sebastes lentiginosus	ND	22	ND	ND
Sebastes levis	ND	55	0.06	181,000- 1,925,000
Sebastes macdonaldi	ND	20	ND	ND
Sebastes maliger	5-22	95	0.07	ND
Sebastes melanops	5-15	56	0.33	283,618- 1,135,457
Sebastes melanosema	ND	ND	ND	ND

Species	Age at Maturity (Female; Tmat) (years)	Max age (Tmax) (years)	von Bertalanffy (k)	Fecundity (# eggs)
Sebastes melanostictus	ND	205	0.108	ND
Sebastes melanostomus	13-26	90	0.04	152,000-769,000
Sebastes miniatus	4-9	60	ND	63,000- 2,600,000
Sebastes moseri	ND	29	ND	ND
Sebastes mystinus	4-11	44	0.149	525,000
Sebastes nebulosus	3-6	79	ND	ND
Sebastes nigrocinctus	ND	116	ND	ND
Sebastes notius	ND	ND	ND	ND
Sebastes ovalis	4-12	37	0.05	61,000-160,000
Sebastes paucispinis	3-6	58	0.163	20,000- 2,298,000
Sebastes peduncularis	ND	ND	ND	ND
Sebastes phillipsi	ND	53	ND	ND
Sebastes pinniger	7-20	84	0.163	260,000- 1,900,000
Sebastes polyspinis	6-13	88	0.178	ND
Sebastes proriger	7 or more	70	0.166	ND
Sebastes rastrelliger	2-5	23	0.11	80,000-760,000
Sebastes reedi	ND	100	0.25	ND
Sebastes rosaceus	ND	14	0.12	12,600-95,000
Sebastes rosenblatti	4-15	58	0.05	30,000-655,000
Sebastes ruberrimus	20	147	0.04	1,200,000- 2,700,000
Sebastes rubrivinctus	ND	38	ND	ND
Sebastes rufinanus	ND	ND	ND	ND
Sebastes rufus	10-20	53	0.04	65,000-608,000
Sebastes saxicola	2-9	38	0.06	15,000-230,000
Sebastes semicinctus	1-6	15	0.37	3,000-31,000
Sebastes serranoides	3-8	30	0.18	30,000-490,000
Sebastes serriceps	3-7	25	0.233	70,000
Sebastes simulator	ND	36	ND	20,880-63,700
Sebastes sinensis	ND	ND	ND	ND
Sebastes spinorbis	ND	45	ND	ND
Sebastes umbrosus	3-8	31	ND	ND
Sebastes variabilis	9	76	0.235	ND

Species	Age at Maturity (Female; Tmat) (years)	Max age (Tmax) (years)	von Bertalanffy (k)	Fecundity (# eggs)
Sebastes variegatus	ND	47	0.11	ND
Sebastes varispinis	ND	ND	ND	ND
Sebastes wilsoni	ND	26	ND	ND
Sebastes zacentrus	6-10	73	0.122	ND

4.5 Climate-Adjusted Baseline/Status Risks - Linking Baseline/Status & Climate Risks

As discussed in Section 4.1, the baseline/status risks are defined as the increased risks under climate stress. If there is no climate risk, these baseline/status risks would not contribute to the overall climate risk score regardless of their value. This is not to state that traits like habitat specialization or endemicity do not represent a vulnerability for these species under current climatic conditions, but that the overall climate risk should not be increased if there is no substantial stress from climate change. Conversely, in cases where a species is impacted by one or more climate drivers, the baseline/status risk potentially contribute to the species' overall climate vulnerability.

The procedure for linking baseline/status risks to the extent of climate change is to first determine the greatest individual climate risk among temperature, ocean acidification, and sea level rise and the greatest individual baseline/status risk. From these two values, the climate-adjusted baseline/status risk is calculated as:

1. If greatest climate risk is Minor (0), the climate-adjusted baseline/status risk is set to Minor (0) regardless of the individual baseline/status risk values.

2. If the greatest climate risk is Low (-1), the climate-adjusted baseline/status risk is the greatest individual baseline/status risk minus one (e.g., from -3 to -2).

3. If the greatest climate risk is Moderate (-2) or High (-3), the climate-adjusted baseline/status risk is equal to the greatest individual baseline/status risk.

4. Resilience baseline/status values (1 to 3) are ignored.

These rules are illustrated in Table 4-16 The climate-adjusted baseline/status risk value is used in calculating the overall climate risk rather than the individual baseline/stature risk values. As shown in Table 4-16, the climate-adjusted baseline/status risk factors increase the overall climate risk only when the baseline/status risk is High (-3) and the greatest climate risk is Low (-1) or

Moderate (-2). The values for the greatest climate risk, the greatest baseline/status risk, and the climate-adjusted baseline/status risk are all output in the Vulnerability Summary (Appendix B).

Table 4-16. Climate-adjusted baseline/status risk values.

Values of the climate-adjusted baseline/status risk are based on the combination of the greatest individual climate risk and the greatest individual baseline/status risk. Multiple risks of the same value do not alter the calculation. The climate-adjusted baseline/status risk is used in determining the overall risk for a species within an ecoregion. Red = climate-adjusted baseline/status risk is greater than the greatest climate risk, increasing overall risk. Blue = Climate-adjusted baseline/status risk same as the greatest climate risk. Black = climate-adjusted baseline/status risk less than the greatest climate risk.

Greatest Climate Risk	Greatest Baseline/Status risk					
	0	-1	-2	-3		
0	0	0	0	0		
-1	0	0	-1	-2		
-2	0	-1	-2	-3		
-3	0	-1	-2	-3		

Section 5. Temperature Predictions

5.1 Introduction

Temperature is the public manifestation of climate change. To date, the bulk of the climate change debate has focused on temperature increases as have policy discussions. As part of the Copenhagen Accord, a general consensus was reached that the increase in global mean surface air temperature should be limited to 2° C. Though there are concerns whether a cap of 2° C is sufficiently protective (see examples in Pörtner et al., 2014), it has become a concrete rallying point for the management of global climate change. A practical issue is the extent of emission reductions required to stay under this cap. A recent summary of Coupled Model Intercomparison Project Phase 5 (CMIP5) results (Table 5-1) indicates that an emission scenario of RCP 6.0 or 4.5 is required to reach this global air temperature goal. RCP 4.5 "is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions" (Wayne, 2013). In comparison, RCP 8.5 is "A high scenario that assumes continued increases in greenhouse gas emissions until the end of the 21st century" (Snover et al., 2013).

Table 5-1. CMIP5 annual mean surface air temperature anomalies (°C) from the 1986–2005 reference period to 2081-2100 for the four RCPs.

Modified from Table 12.2 of Collins et al., 2013. "The multi-model mean ±1 standard deviation ranges across the individual models are listed and the 5 to 95% ranges from the models' distribution (based on a Gaussian assumption and obtained by multiplying the CMIP5 ensemble standard deviation by 1.64) are given in brackets. Only one ensemble member is used from each model and the number of models differs for each RCP"

Region	RCP 2.6	RCP 4.5	RCP 6.0	RCP 8.5
Global	1.0 ± 0.4 (0.3, 1.7)	1.8 ± 0.5 (1.1, 2.6)	2.2 ± 0.5 (1.4, 3.1)	3.7 ± 0.7 (2.6, 4.8)
Land	1.2 ± 0.6 (0.3, 2.2)	2.4 ± 0.6 (1.3, 3.4)	3.0 ± 0.7 (1.8, 4.1)	4.8 ± 0.9 (3.4, 6.2)
`Ocean	0.8 ± 0.4 (0.2, 1.4)	1.5 ± 0.4 (0.9, 2.2)	1.9 ± 0.4 (1.1, 2.6)	3.1 ± 0.6 (2.1, 4.0)
Tropics	0.9 ± 0.3 (0.3, 1.4)	1.6 ± 0.4 (0.9, 2.3)	2.0 ± 0.4 (1.3, 2.7)	3.3 ± 0.6 (2.2, 4.4)
Arctic	2.2 ± 1.7 (-0.5, 5.0)	4.2 ± 1.6 (1.6, 6.9)	5.2 ± 1.9 (2.1, 8.3)	8.3 ± 1.9 (5.2, 11.4)
Antarctic	0.8 ± 0.6 (-0.2, 1.8)	1.5 ± 0.7 (0.3, 2.7)	1.7 ± 0.9 (0.2, 3.2)	3.1 ± 1.2 (1.1, 5.1)

This section describes two approaches to predicting the effects of temperature increases on nearcoastal organisms, which we refer to as the Ecoregional Thermal Window (ETW) approach and the Biogeographic Thermal Limit (BTL) approach. Both approaches generate ecoregion-specific
risks for the NEP and U.S. Arctic, as well as allowing the assessment of different climate scenarios. The two approaches make the basic assumption that biogeographic distributions reflect the ecological thermal limits for a species. While a number of factors potentially affect a species' vulnerability to temperature at a microscale (e.g., Helmuth et al., 2010), the bulk of the evidence supports the contention that temperature is the overriding variable setting the biogeographical range limits of most species as reviewed in Appendix D.

It is important to emphasize that the temperatures limiting species' ranges at an ecoregional scale are not necessarily physiological thermal limits (e.g., CT_{max}). Besides the possibility of direct thermal effects on adults, limitation of species in the warmer ecoregions could result from effects on larval/juvenile stages, sublethal effects, such as reductions in fecundity, or indirect effects such as changes in predator-prey relationships or loss of key ecosystem engineers (e.g., Wernberg et al., 2016; Lord et al., 2017). While analysis of temperature changes at an ecoregional-scale does not identify the specific mechanism(s), it presumably captures the effects on the population regardless of life-history stage or whether the effects are direct or indirect.

The ETW and BTL approaches use different methodologies to assign risk and different sources for baseline temperature data. The ETW evaluates risk based on the range of sea surface temperatures (SSTs) observed via remote sensing in the "warmest occupied ecoregion" (WOE) (Figure 5-1), where "occupied" includes a classification of Present or any Level II or III abundance classes. The BTL compares temperatures in the WOE to those observed in the "next warmest unoccupied ecoregion" (NWUE), which is usually, but not always, the ecoregion directly to the south (Figure 5-1). Use of two different ecological climate models was not undertaken in the blind hope that there would be a complete one-to-one correspondence. Rather, similarities in predictions provide greater confidence in the results while differences help identify values and/or assumptions requiring additional research.

5.2 Future Temperature Predictions

Both approaches use NOAA's Climate Web Portal

(http://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html; Scott et al., 2016) for the default projected changes in temperature. Data served on the Climate Web Portal are based on the Coupled Model Inter-comparison Project Phase 5 (CMIP5; Taylor et al., 2012; Bopp et al., 2013) that informed the temperature predictions in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Collins et al., 2013). Outputs from different models used in the CMIP5 are interpolated to a 1-degree latitude/longitude grid to allow for intermodel comparisons.



Figure 5-1. Distribution of *Chionoecetes bairdi* illustrating WOE, NWUE, COE, and NCUE ecoregions. WOE = warmest occupied ecoregion; NWUE = next warmest unoccupied

ecoregion; COE = coolest occupied ecoregion; NCUE = next coolest unoccupied ecoregion. Purple shading indicates an occupied ecoregion.

The following options were chosen for the default temperature projections for SST, air temperature, 30-m temperature, and 100-m temperature:

- a. Historical period: 1956-2005 (1980/1981 average)
- b. Future period: 2050-2099 (2074/2075 average)
- c. RCP 8.5
- d. Average of all models
- e. Statistic of change: Anomaly
- f. Download entire year, summer (July-Aug.-Sept.), and winter (Jan.-Feb.-March) for SST and air temperature
- g. Download annual values for 30-m and 100-m depths

The number of models incorporated into the average predictions depends upon the parameter, currently ranging from 37 for air temperature to 10 for subsurface water temperatures at 30 and 100 meters. The anomaly is the predicted difference in temperature between the future time

period compared to the historical period. The anomaly is added to the historic baseline value to generate the projected future temperature.

To generate ecoregion-scale temperature values, GIS was used to extract all the grids within each ecoregion, and then the mean value of the climate parameter calculated within each of the ecoregions. Details on the GIS techniques are given in Appendix E.

5.3 Ecoregional Thermal Windows Approach

5.3.1 ETW Approach

The ETW approach is based on comparing the projected SST in the target ecoregion to the historic range of SST values observed in the warmest occupied ecoregion (WOE). Specifically, the risk is determined by comparing the projected temperature in the target ecoregion to the number of standard deviation (SD) units around the historic mean SST in the WOE, which is based on 28 years of remote sensing SST data (Section 5.3.6). The rules to generate risk are:

- a. Projected SST in target ecoregion < Historic mean SST + 1 SD in WOE = Minor risk (temperatures normally experienced).
- b. Projected SST in target ecoregion ≥ Historic mean SST + 1 SD in WOE AND
 < Historic mean SST + 2 SDs in WOE = Low risk (temperatures frequently experienced).
- c. Projected SST in target ecoregion ≥ Historic mean + 2 SDs in WOE AND < Historic mean + 3 SDs in WOE = Moderate risk (temperatures rarely experienced).
- d. Projected SST in target ecoregion \geq Historic mean SST + 3 SDs in WOE = High risk (temperatures very rarely if ever experienced in recent past).

Risks are analyzed for the annual average SSTs as well as for summer (July-August-September) and winter (January-February-March) independently to gain insight into what season is likely to be limiting.

We currently do not have ecoregion temperatures or projections in the tropics other than for the Mexican Tropical Pacific (MTP) ecoregion. Thus, if a species occurs in any tropical ecoregion globally, the temperatures in the MTP are used as the tropical WOE surrogate. A list of tropical ecoregions is given in CBRAT. Examination of global baseline SST maps produced from NOAA's Climate Web Portal indicates that the MTP is as warm as the other ecoregions comprising the Eastern Tropical Pacific and Tropical Atlantic. However, the MTP appears to be about 2°C cooler than much of the Indo-West Pacific and Indian Ocean. Use of temperatures in the MTP for species that occur in these locations underestimates the actual upper thermal window of these species. Consequently, it can overestimate the risk. Not many NEP species occur in the Indo-West Pacific or Indian Ocean, but for those that do, users should evaluate the

risk based on this possibility. A future improvement to CBRAT would be to identify a surrogate ecoregion in the Indo-Pacific and/or Indian Ocean to be used as the default for species occurring in these regions.

Ecoregion	Mean Historical Value	Minor Risk Range	Low Risk Range	Moderate Risk Range	High Risk range
Beaufort Sea - Continental Coast/Shelf	0.03	≤0.46	0.47 – 0.9	0.91 – 1.34	≥1.35
Chukchi Sea	0.55	≤1.23	1.24 – 1.92	1.93 – 2.61	≥2.62
Eastern Bering Sea	3.75	≤4.32	4.33 – 4.9	4.91 – 5.47	≥5.48
Aleutian Islands	5.67	≤6.06	6.07 – 6.47	6.48 – 6.87	≥6.88
Gulf of Alaska	7.42	≤7.89	7.9 – 8.38	8.39 - 8.87	≥8.88
North American Pacific Fjordland	9.47	≤9.92	9.93 – 10.38	10.39 – 10.84	≥10.85
Puget Trough/Georgia Basin	10.44	≤10.93	10.94 – 11.43	11.44 – 11.94	≥11.95
Oregon, WA, Vancouver Coast/Shelf	11.51	≤12.06	12.07 – 12.61	12.62 – 13.17	≥13.18
Northern California	13.55	≤14.16	14.17 – 14.78	14.79 – 15.4	≥15.41
Southern California Bight	17.81	≤18.39	18.4 – 18.99	19.0 – 19.58	≥19.59
Magdalena Transition	22.61	≤23.27	23.28 – 23.94	23.95 – 24.61	≥24.62
Cortezian	24.79	≤25.23	25.24 – 25.68	25.69 – 26.13	≥26.14
Mexican Tropical Pacific	28.87	≤29.22	29.23 – 29.58	29.59 – 29.94	≥29.95

Table 5-2. Temperature ranges (°C) associated with different risk levels for ecoregion mean annual SSTs. Analysis based on 28 years of AVHRR remote sensing data.

Table 5-3. Temperature ranges (°C) associated with different risk levels for ecoregion mean summer SSTs.

Data source same as in Table 5-2.

Ecoregion	Mean Historical Value	Minor Risk Range	Low Risk Range	Moderate Risk Range	High Risk Range
Beaufort Sea - Continental Coast/Shelf	1.77	≤3.07	3.08 – 4.38	4.39 – 5.68	≥5.69
Chukchi Sea	3.35	≤4.81	4.82 - 6.27	6.28 – 7.74	≥7.75

Ecoregion	Mean Historical Value	Minor Risk Range	Low Risk Range	Moderate Risk Range	High Risk Range
Eastern Bering Sea	8.67	≤9.64	9.65 – 10.62	10.63 – 11.6	≥11.61
Aleutian Islands	8.44	≤9.02	9.03 - 9.62	9.63 – 10.21	≥10.22
Gulf of Alaska	11.82	≤12.49	12.5 – 13.17	13.18 – 13.85	≥13.86
North American Pacific Fjordland	13.22	≤13.94	13.95 – 14.66	14.67 – 15.38	≥15.39
Puget Trough/Georgia Basin	13.59	≤14.92	14.93 – 16.26	16.27 – 17.6	≥17.61
Oregon, WA, Vancouver Coast/Shelf	14.12	≤14.98	14.99 – 15.85	15.86 – 16.72	≥16.73
Northern California	15.19	≤15.96	15.97 – 16.74	16.75 – 17.52	≥17.53
Southern California Bight	20.53	≤21.4	21.41 – 22.29	22.3 – 23.17	≥23.18
Magdalena Transition	26.15	≤27.22	27.23 – 28.3	28.31 – 29.38	≥29.39
Cortezian	30.22	≤30.6	30.61 - 30.99	31.0 – 31.38	≥31.39
Mexican Tropical Pacific	30.49	30.91	30.92 - 31.34	31.35 – 31.77	≥31.78

Table 5-4. Temperature ranges associated with different risk levels for ecoregion mean winter SST
(JanFebMarch).
Data source as in Table 5-2.

Ecoregion	Mean Historical Value	Minor Risk Range	Low Risk Range	Moderate Risk Range	High Risk Range
Beaufort Sea - Continental Coast/Shelf	-1.26	≤ -0.76	≤ -0.76 -0.750.25		≥0.27
Chukchi Sea	-1.53	≤ -1.31	-1.3 – -1.07	-1.06 – -0.83	≥-0.82
Eastern Bering Sea	1.0	≤ 1.54	1.55 – 2.08	2.09 – 2.63	≥2.64
Aleutian Islands	3.68	≤ 4.15	4.16 - 4.64	4.65 – 5.13	≥5.14
Gulf of Alaska	4.12	≤ 4.73	4.74 - 5.34	5.35 – 5.95	≥5.96
North American Pacific Fjordland	6.68	≤ 7.28	7.29 – 7.9	7.91 – 8.52	≥8.53
Puget Trough/Georgia Basin	7.51	≤ 7.94	7.95 – 8.38	8.39 - 8.82	≥8.83

Ecoregion	Mean Historical Value	Minor Risk Range	Low Risk Range	Moderate Risk Range	High Risk Range
Oregon, WA, Vancouver Coast/Shelf	9.34	≤ 10.04	10.05 – 10.76	10.77 – 11.47	≥11.48
Northern California	12.64	≤ 13.52	13.53 – 14.41	14.42 – 15.3	≥15.31
Southern California Bight	15.72	≤ 16.56	16.57 – 17.42	17.43 – 18.27	≥18.28
Magdalena Transition	19.96	≤ 20.98	20.99 – 22.02	22.03 - 23.05	≥23.06
Cortezian	19.57	≤ 20.57	20.58 – 21.58	21.59 – 22.59	≥22.6
Mexican Tropical Pacific	27.53	≤ 27.97	27.98 - 28.42	28.43 - 28.87	≥28.88

Table 5-5. Predicted increases in annual, summer, and winter SSTs for 2050-2099 based on the RCP 8.5 scenario (°C).

Predictions are based on an analysis of the CMIP5 climate models downloaded from the NOAA Climate Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html</u>).

Ecoregion	Annual Increase	Summer Increase	Winter Increase
Beaufort Sea - Continental Coast/Shelf	2.29	5.55	0.16
Chukchi Sea	2.6	5.13	0.61
Eastern Bering Sea	3.56	4.03	2.92
Aleutian Islands	3.03	3.63	2.53
Gulf of Alaska	3.1	3.53	2.79
North American Pacific Fjordland	2.8	3.18	2.53
Puget Trough/Georgia Basin	2.15	3.12	1.8
Oregon, WA, Vancouver Coast/Shelf	2.62	2.9	2.41
Northern California	2.54	2.83	2.34
Southern California Bight	2.4	2.38	2.34
Magdalena Transition	2.27	2.33	2.21
Cortezian	2.42	2.52	2.31

5.3.2 Conceptual Framework

The concept behind the ETW approach is that the historic temperatures in the WOE represent the upper temperature range for the species to maintain a viable population. The species has frequently experienced temperatures close to the WOE mean. However, the species has rarely, if ever, experienced temperatures over ecological timeframes two or three standard deviations warmer than the WOE mean. These higher temperatures become increasingly stressful until they reach the mean temperature in the NWUE, a temperature at which the species no longer

maintains a viable population. Thus, the temperature ranges in the WOE provide an ecological thermal "window" on the upper temperature limits. Using the temperatures in the historically warmest ecoregion to predict thermal ranges is analogous to the use of "environmental matching" between a species' native range (donor region) and nonnative range (recipient region) in invasive species risk assessments (e.g., Gollasch, 2006; Committee on Assessing Numeric Limits for Living Organisms in Ballast Water, National Research Council, 2011). Though at a different sampling scale, predicting suitable versus unsuitable temperatures is also analogous to the incorporation of temperature in species' distribution models (SDMs) to predict range changes.

It is possible that populations in more northern, cooler ecoregions consist of genotypes less tolerant of warmer temperatures compared to those in the WOE (see Visser, 2008). To the extent this occurs, using temperature ranges in the WOE may underestimate short-term risk in these cooler ecoregions. However, over decades to a century, we assume that the more warm-adapted genotypes within the northern ecoregion will replace the less tolerant genotypes. Additionally, warm-tolerant genotypes in southern ecoregions may migrate northward. One line of support for the potential for warm-adapted genotypes to migrate in relatively short time periods is the rapid expansion of a whole host of nonindigenous species within decades (e.g., Sorte et al., 2010; Pilgrim et al., 2013). A similar line of support is the rapid northward migration of marine species in response to recent temperature increases (see Appendix D). Finally, many marine species have a rapid rate of dispersal compared to terrestrial species (Kinlan and Gaines, 2003).

5.3.3 Within-Ecoregion Temperature Risks ("Worst-Case Scenario")

By comparing projected temperatures in the northern ecoregions to those in the WOE, the ETW approach inherently assumes that genotypes adapted to the increased temperature either exist in the northern ecoregion or will colonize from southern ecoregions. As mentioned above, there is support that many if not most near-coastal species are able to migrate reasonably rapidly. However, some species may have much slower migration rates either due to inherent properties of the species or due to barriers. For example, species with short pelagic larval durations (PLD) tend to have more genetic isolation-by distance, indicating less connectivity among the populations (Selkoe and Toonen, 2011). Thus, species with short PLDs may colonize northern ecoregions more slowly than those with longer PLDs. In cases with a lag in colonization, the species' population may show an initial decline or other symptoms of stress but then recover as the southern genotypes colonize.

To assess the risk associated with warm-genotypes either not existing or not colonizing in an ecological relevant timeframe, we calculate thermal risks with the ETW approach using the temperature range within the target ecoregion. For a species that ranges from the Gulf of Alaska to Northern California, the projected temperature in the Gulf of Alaska is compared to the historical temperature range in the Gulf of Alaska instead of the WOE (Northern California).

Using the temperature within the ecoregion as the reference represents a "worst-case" scenario for thermal risks. This within-ecoregion temperature risk is calculated using the annual, summer, and winter SSTs, and is referred to as the "Within-Ecoregion Temperature" risk. Depending upon a species' distribution, these risks can be substantially more sensitive, with a moderate risks occurring in many cases with about a 1 °C increase. These annual and seasonal risks are output in the Vulnerability Summary (Appendix B), but are not used in calculating the overall risk, though the user is encouraged to evaluate whether they better capture the risks for a particular species.

5.3.4 Abundance-Normalized Temperature Risks ("Ecosystem Services Risks")

Another method using the ETW approach is to define the thermal risks from the temperature in the northernmost ecoregion at which there is a decrease in abundance. Figure 5-2 shows the biogeographic abundance pattern for *Hemigrapsus nudus*, with the North Pacific Fjordland, Puget Trough/Georgia Basin, and Oregon, Washington, Vancouver Coast and Shelf ecoregions classified as abundant. Using the "abundance-normalized temperature" risks, the projected temperatures in these ecoregions are compared to the historical range in the Northern California Ecoregion, the northernmost ecoregion with a reduced Level II abundance. Similarly, the risk in the Northern California Ecoregion is compared to the Southern California Bight Ecoregion, which has a lower abundance (and is the WOE in this case). The abundance-normalized risks are most informative when the primary interest is in reductions in ecosystem services, such as commercial/recreational species, or with ecological dominants such as keystone species and ecological engineers.

Hemigrapsus nudus is an ideal case for calculating abundance-normalized risks, and in many cases the abundance patterns are "mixed" with a lower abundance near the center of the species' distribution. Because such patterns make automation of the risks complicated and slow the risk algorithm, we do not calculate these risks in CBRAT at this time. However, using the ecoregion historical temperature ranges (Tables 5-2 to 5-5) and the abundance patterns from the Vulnerability Summary or the Basic Export (see Lee et al., 2015), it is feasible for users to calculate this risk by hand for a limited number of key species.



Figure 5-2. Abundance pattern of *Hemigrapsus nudus* as example for calculation of abundance-normalized temperature risks. Projected temperatures in the three ecoregions where *H. nudus* is abundant (Pacific Fjords, Puget, and Oregonian) are compared to the historical temperature range in Northern California, the northernmost ecoregion with a lower Level II abundance. Similarly, the risk for the Northern California is derived by comparing the projected temperature to the historical range in the Southern California Bight Ecoregion, which has a lower abundance. The color key to the ecoregion relative abundance classes is given in Figure 4-1.

5.3.5 Evaluation of ETW Thermal Thresholds

A question in generating risk ranges was how much of a deviation from the mean ecoregion temperature should constitute minor, low, moderate, and high risks? First, it was decided to use ranges based on standard deviations rather than quartiles because standard deviations provide at least an approximation of how frequently various temperature ranges might occur within an ecoregion. Second, a two-tailed evaluation was used in generating the deviations around the means because the same data can be used to evaluate deviations around the lower temperature range to predict the potential for northward migration (Section 5.5).

Because organisms frequently experience temperatures within one SD of the mean, setting the minor and low risks was relatively straight-forward. For the moderate and high risks, the issue was whether the mean plus two SDs and the mean plus three SDs, respectively, were too stringent. In evaluating the actual SSTs across all years and ecoregion (Table 5-6), the mean plus two standard deviations criterion was exceeded 3.9% of the time. Thus, species in these ecoregions only rarely experience temperatures this warm, which fits with our conception of a moderate risk. In comparison, the mean plus three standard deviations was not exceeded in any

of the 304 cases. These upper thresholds represent temperatures never, or very rarely, experienced by the species in an ecological timeframe.

Since the historic temperature in the NWUE is sufficiently warm that the species is unable to maintain a viable population, reaching or exceeding it could result in regional extirpation of the species. Thus, as a check on using the mean plus three SDs as the high threshold, we compared this value to the mean in the NWUE. In 9 of the 12 ecoregions, the mean plus three SDs was less than the temperature in the next warmest ecoregion (Table 5-6), indicating that this threshold identifies a high risk scenario though not necessarily one that would result in regional extirpation. One of the three exceptions was the Beaufort, which may reflect both that the Chukchi-Beaufort are aligned more longitudinally than latitudinally and the paucity of data in these Arctic ecoregions. Another exception is Puget Trough/Georgia Basin, which may reflect properties of inland seas and/or the influence of a terrestrial signal mixed with the ocean signal (see Section 5.3.4). The last exception was the Pacific Fjords when compared to the Puget/Georgia ecoregion. In this case, it might be more appropriate to compare it to the Oregonian rather than to an inland sea, in which case the mean plus 3 SDs was below the next warmest coastal ecoregion. In any case, exceeding the high risk threshold is predicted to have measurable effects on populations in the affected ecoregion, though not necessarily regional extirpation.

5.3.6 Data Source and Analysis

The Ecoregional Thermal Window approach relies on our previous analysis of nearshore SSTs in the North Pacific and U.S. Arctic based on the Advanced Very High Resolution Radiometer (AVHRR) data (Payne et al., 2011, 2012a, 2012b, and unpublished) for the historic mean and standard deviations around the means. Raw data for the North Pacific are available in a USGS Open File Report (Payne et al., 2011; <u>https://pubs.usgs.gov/of/2010/1251/</u>) while the data for the Arctic ecoregions are available in another report (Payne et al., 2012b; <u>http://pubs.usgs.gov/of/2011/1246/</u>).

Detailed GIS and data analysis procedures are given in Payne et al. (2011). Briefly, AVHRR data from January, 1982 through December, 2009 were downloaded, generating 28 years of data. The AVHRR-derived Pathfinder monthly-mean SSTs on 4x4 km grids were analyzed for each of the North Pacific and Arctic ecoregions. Only high quality remote sensing data, according to AVHRR data quality ranks, were used in the analysis. This quality criterion resulted in relatively minor loss of data in the NEP ecoregions, but because of ice, cloud cover and fog, a majority of the points did not meet the quality rank for inclusion in the Arctic ecoregions. This problem was especially acute in the winter months and the analysis was limited to months with at least 10 points. For the NEP ecoregions, the analysis was limited to grids within 20 km of the coastline. Because of the extensive loss of data points, the analysis for the Arctic included the entire ecoregion and not just locations within 20 km of the coastline.

The initial temperature analysis (Payne et al., 2012a) did not include the Puget Trough/Georgia Basin or the Mexican Tropical Pacific ecoregions, both of which were subsequently analyzed using the same procedures. Because of the 4x4 km grid size, it was not possible to remove all grids with any terrestrial influence from the Puget Trough/Georgia Basin analysis.

Predicted annual, summer and winter SST increases for the 8.5 RCP scenario by ecoregion were derived from CMIP5 downloaded from NOAA's Climate Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/</u>) (Appendix E). The predicted increases in each ecoregion were added to the annual or seasonal historic mean SST for the ecoregion to generate the projected ecoregion temperatures.

Table 5-6. Number of exceedances of the moderate and high risk thresholds for annual SST based on the ETW approach.

The first two rows summarize the number of times the moderate and high risk thresholds for SST derived from standard deviation (SD) units were exceeded. The third row summarizes the number of years used in the analysis. The number of years was reduced in the Beaufort and Chukchi because of data loss due to ice, fog and clouds. In the next three rows, the mean + 3 SDs is compared to the temperature in the next warmest ecoregion. In 9 of the 12 comparisons, the mean + 3 SDs is less than the next warmest ecoregion. NA = not applicable.

Years/Mean	Beaufort	Chukchi	Bering	Aleutians	GOA	Pac. Fjords	Puget	Oregonian	N CA	S CA	Magdalena	Cortezian	Sum of Yrs.	% of Yrs.
# years exceeding mean + 3 SDs	0	0	0	0	0	0	0	0	0	0	0	0	0	0%
# years exceeding mean + 2 SDs	1	1	2	1	0	1	0	1	1	2	2	0	12	3.9%
# Years in Analysis	9	17	28	27	28	28	27	28	28	28	28	28	304	NA
Mean SST (°C)	0.03	0.55	3.75	5.67	7.42	9.47	9.94	11.51	13.55	17.81	22.61	24.79	NA	NA
Mean + 3 SD (°C)	1.35	2.62	5.48	6.89	8.88	10.85	11.95	13.18	15.41	19.59	24.62	26.14	NA	NA
Mean SST in Next Warmest Ecoregion (°C)	0.55	3.75	5.67	7.42	9.47	9.94	11.51	13.55	17.81	22.61	24.79	28.87	NA	NA

5.4 Biogeographical Thermal Limit Approach

5.4.1 Introduction

SSTs have frequently been used as indicators of temperature impacts of climate change (e.g., Hiddink et al., 2015; Molinos et al., 2016). However, deeper species experience different temperature means and extremes, and may be exposed to a different relative rate of climate change than shallow species. To evaluate how thermal risks potentially vary with the depth range of the species, we developed the Biogeographical Thermal Limit (BTL) approach. The BTL approach predicts temperature effects by comparing temperatures across ecoregions rather than using observed temperature ranges within the warmest occupied ecoregion as with the ETW approach. Specifically, the BTL thresholds are based on temperature bins between the historic temperatures in the WOE and the NWUE (Figure 5-1) using values from the NOAA Climate Web Portal. Use of bins is necessitated by the absence of multiple year data from the NOAA Climate Web Portal, making the calculation of standard deviations around historic means impossible. The main advantage is that climate risks can be evaluated for a range of species' depth distribution, using temperatures from six different depths:

SST: General thermal stress

Annual Air Temperature: Intertidal thermal stress
Summer Air Temperature: Intertidal thermal stress
Winter Air Temperature: Intertidal thermal stress
30-m Temperature: Thermal stress in shallow subtidal (>0-30 m depth)
100-m Temperature: Thermal stress in deep subtidal (>30-200 m depth)

The primary assumption of the BTL is that the absence of a species in the NWUE is because one or more of the temperature parameters is too warm for the species to maintain a viable population. This assumption that the southern range limits are determined directly or indirectly by temperature appears to be generally applicable, as discussed in Appendix D.

5.4.2 BTL Approach

As with the ETW approach, the ecoregion projected temperature is determined for each of the temperature parameters by adding the predicted ecoregion-specific increase to the historic mean (see Table 5-7 through Table 5-12). The BTL thermal effects thresholds are derived by dividing the temperature difference between the historical WOE and NWUE into four equal bins (Figure 5-3). (Note that these are not quartiles since they are not derived from a distribution.) The BTL effects thresholds are calculated for SSTs, and for air, 30-m, and 100-m temperatures. Then, the

following base rules are used to generate the risk class from these bins:

Projected temperature $<1^{st}$ bin \Rightarrow minor risk Projected temperature $\ge 1^{st}$ bin and $<2^{nd}$ bin \Rightarrow low risk Projected temperature $\ge 2^{nd}$ bin and $<3^{rd}$ bin \Rightarrow moderate risk Projected temperature $\ge 3^{rd}$ bin \Rightarrow high risk



Figure 5-3. Schematic of the derivation of thermal risk values with the BTL approach.

WOE = warmest occupied ecoregion; NWUE = next warmest unoccupied ecoregion. Example given with an historical temperature of 20 °C in the WOE and 24 °C in the NWUE.

Modifiers to these base rules and data are:

- 1) Downgrade the risk for the intertidal, shallow subtidal, or deep subtidal depths by one risk class if the depth within these classes is classified as Observed rather than Preferred.
 - a. As an example, if the risk was calculated as Moderate for the 30-m depth using the base rules, but the organism had an Observed shallow subtidal depth classification, the risk would be downgraded to Low.

- 2) SST is not downgraded by depth preferences since it is an indicator of general thermal stress.
- 3) If a species occurs in any tropical ecoregion, use the MTP as both the WOE and the NWUE, assuming no other ecoregion is warmer than the MTP.
- 4) Ecoregions with an Error/Extinct or Transient classification for a species are not included in the analysis.
- 5) No baseline data are available for the Puget Trough/Georgia Basin ecoregion for the 30-m and 100-m temperatures, though values can be entered into CBRAT as they become available.
 - a. For species whose southern range is the North American Pacific Fjordland Ecoregion, the Oregon, Washington, Vancouver Coast and Shelf Ecoregion is used as the NWUE.

Thermal risks for the population are calculated independently for each of the six depth-season combinations, with the risks modified by the depth preferences of the species. A preferred depth is taken as an indicator that a sizable portion of the total population occurs within that depth range. Conversely, an observed depth class indicates that only a small fraction of the population occurs within that depth range, and thus only a small portion of the total population would be at risk. We account for these differences in population size by downgrading the risk by one class when the depth class is observed versus preferred. The risk for each of these depth classes is applied to the entire population within the ecoregion and it is possible for a species to have high risk at one depth and a low risk at another. In this case, the species would be assigned a high risk. The one exception to modifying the risks by depth are those resulting from the SSTs, which are viewed as an overall predictor of temperature stress (e.g., Molinos et al., 2016).

Table 5-7. Historical and projected mean annual SSTs (°C).

Historical means derived from 1995-2005 baseline. Predicted increases are based on RCP 8.5 and 2050-2099 future timeframe. Ecoregions are ordered by historic mean values. The historic means and predicted increases are derived from the CMIP5 models downloaded from NOAA's Climate Change Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/</u>).

Ecoregion – Annual SSTs	SST Historical Mean	SST Predicted Increase	SST Projected Temperature
Beaufort Sea - Continental Coast/Shelf	-1.07	2.29	1.22
Chukchi Sea	-0.73	2.6	1.87
Eastern Bering Sea	3.02	3.56	6.58
Aleutian Islands	5.95	3.03	8.98
Gulf of Alaska	6.95	3.10	10.05
North American Pacific Fjordland	9.77	2.80	12.57
Puget Trough/Georgia Basin	11.34	2.15	13.49

Ecoregion – Annual SSTs	SST Historical Mean	SST Predicted Increase	SST Projected Temperature
Oregon, WA, Vancouver Coast/Shelf	12.39	2.62	15.01
Northern California	16.37	2.54	18.91
Southern California Bight	20.67	2.40	23.07
Magdalena Transition	24.81	2.27	27.08
Cortezian	25.71	2.42	28.13
Mexican Tropical Pacific	27.64	2.52	30.16

Table 5-8. Historical and projected mean annual air temperatures (°C).

Data sources same as in Table 5-7. *Because of the resolution of the CMIP5 climate model, the air temperatures and projections for the Puget-Georgia Ecoregion are averages of the values in the N Pac Fijord Ecoregion and OR-WA-Vanc Ecoregion.

Ecoregion	Air Annual Historical Mean	Air Annual Predicted Increase	Air Annual Projected Temperature
Beaufort Sea - Continental Coast/Shelf	-11.66	8.34	-3.32
Chukchi Sea	-11.44	8.97	-2.47
Eastern Bering Sea	-0.67	5.56	4.89
Aleutian Islands	4.67	3.52	8.19
Gulf of Alaska	4.84	3.73	8.57
North American Pacific Fjordland	7.70	3.32	11.02
Puget Trough/Georgia Basin*	9.41	3.19	12.60
Oregon, WA, Vancouver Coast/Shelf	11.12	3.05	14.17
Northern California	15.32	2.88	18.2
Southern California Bight	19.38	2.78	22.16
Cortezian	23.22	3.28	26.5
Magdalena Transition	23.32	2.65	25.97
Mexican Tropical Pacific	26.15	2.78	28.93

Table 5-9. Historical and projected mean summer air temperatures (°C).

Data sources same as in Table 5-7. *Because of the resolution of the CMIP5 climate model, the air temperatures and projections for the Puget-Georgia Ecoregion are averages of the values in the N Pac Fijord Ecoregion and OR-WA-Vanc Ecoregion. The historical winter air temperatures based on the average of these two ecoregions were 5.45 °C (RCP 8.5 model) and 5.95 °C (RCP 4.5 model) compared to 6.2 °C based on the average of winter values from six NOAA buoys in the Puget Sound/Georgia Basin.

Ecoregion	Air Summer Historical Mean	Air Summer Predicted Increase	Air Summer Projected Temperature
Chukchi Sea	1.36	5.04	6.40
Beaufort Sea - Continental Coast/Shelf	1.69	5.10	6.79

Ecoregion	Air Summer Historical Mean	Air Summer Predicted Increase	Air Summer Projected Temperature
Eastern Bering Sea	6.87	4.28	11.15
Aleutian Islands	9.24	3.88	13.12
Gulf of Alaska	10.17	3.79	13.96
North American Pacific Fjordland	12.77	3.52	16.29
Puget Trough/Georgia Basin*	14.24	3.49	17.73
Oregon, WA, Vancouver Coast/Shelf	15.7	3.46	19.16
Northern California	19.19	3.15	22.34
Southern California Bight	23.02	2.81	25.83
Magdalena Transition	26.42	2.69	29.11
Cortezian	27.56	3.36	30.92
Mexican Tropical Pacific	27.60	3.02	30.62

Table 5-10. Historical and projected mean winter air temperatures (°C).

Data sources same as in Table 5-7. *Because of the resolution of the CMIP5 climate model, the air temperatures and projections for the Puget-Georgia Ecoregion are averages of the values in the N Pac Fijord Ecoregion and OR-WA-Vanc Ecoregion. The historical winter air temperatures based on the average of these two ecoregions were 5.45 °C (RCP 8.5 model) and 5.95 °C (RCP 4.5 model) compared to 6.2 °C based on the average of winter values from six NOAA buoys in the Puget Sound/Georgia Basin.

Ecoregion	Air Winter Historical Mean	Air Winter Predicted Increase	Air Winter Projected Temperature
Beaufort Sea - Continental Coast/Shelf	-26.14	10.96	-15.18
Chukchi Sea	-25.52	12.56	-12.96
Eastern Bering Sea	-8.56	7.73	-0.83
Gulf of Alaska	0.52	3.89	4.41
Aleutian Islands	1.09	3.33	4.42
North American Pacific Fjordland	3.45	3.33	6.78
Puget Trough/Georgia Basin*	5.45	3.10	8.54
Oregon, WA, Vancouver Coast/Shelf	7.44	2.86	10.30
Northern California	12.12	2.66	14.78
Southern California Bight	16.31	2.71	19.02
Cortezian	19.16	3.10	22.26
Magdalena Transition	20.62	2.58	23.20
Mexican Tropical Pacific	24.47	2.53	27.00

Ecoregion	30-m Historical Mean	30-m Predicted Increase	30-m Projected Temperature
Beaufort Sea - Continental Coast/Shelf	-1.40	0.33	-1.07
Chukchi Sea	-1.09	0.33	-0.76
Eastern Bering Sea	1.75	2.82	4.57
Aleutian Islands	4.59	2.54	7.13
Gulf of Alaska	5.27	3.07	8.34
North American Pacific Fjordland	8.11	2.89	11.00
Oregon, WA, Vancouver Coast/Shelf	10.35	2.74	13.09
Northern California	14.94	2.51	17.45
Southern California Bight	19.55	2.51	22.06
Magdalena Transition	23.79	2.31	26.10
Cortezian	24.92	2.40	27.32
Mexican Tropical Pacific	26.88	2.43	29.31
Puget Trough/Georgia Basin	ND	ND	ND

Table 5-11. Historical and projected mean 30-m temperatures (°C). Data sources same as in Table 5-7. ND = No data.

Table 5-12. Historical and projected mean 100-m temperatures (°C). Data sources same as in Table 5-7. ND = no data.

Ecoregion	100-m Historical Mean	100-m Predicted Increase	100-m Projected Temperature
Beaufort Sea - Continental Coast/Shelf	-1.28	0.82	-0.46
Chukchi Sea	-1.43	0.75	-0.68
Eastern Bering Sea	1.89	3.10	4.99
Aleutian Islands	3.74	2.33	6.07
Gulf of Alaska	4.95	2.77	7.72
North American Pacific Fjordland	7.32	2.36	9.68
Oregon, WA, Vancouver Coast/Shelf	9.23	1.95	11.18
Northern California	11.96	1.54	13.5
Southern California Bight	15.15	1.14	16.29
Mexican Tropical Pacific	17.28	1.44	18.72
Magdalena Transition	17.29	0.89	18.18
Cortezian	17.38	1.89	19.27
Puget Trough/Georgia Basin	ND	ND	ND

5.4.3 Comparison of ETW and BTL

Use of the temperature bins does not have a theoretical statistical underpinning as does the use of standard deviations around the mean. However, bins measure the delta between a suitable temperature (i.e., WOE) and a presumably unsuitable temperature (NWUE) and thus provide a first-order estimate of the risk. To evaluate the efficacy of the thresholds based on quantiles, we compared the BTL predictions against those from the ETW approach for brachyuran crabs (Table 5-13), using the results from the ETW as the standard.

From the Beaufort through Southern California, the BTL and ETW approaches agreed 87% of the time. In 49 of the 50 cases when there was a disagreement, the ETW predicted a high risk versus a moderate risk with the BTL. In only one case was the risk classification two levels apart. The majority of the differences occurred in Southern California, but there was still 70% agreement in this ecoregion. This level of concordance gives us confidence in using the BTL approach to evaluate temperature risks associated with air and in subsurface waters. One possibility to address the potential for the BTL to underestimate risk is to combine the moderate and high risks into a "species at risk" classification.

The BTL did not perform well in the two southern ecoregions. Even though there was a high correspondence between BTL and the ETW in the Magdalena, the BTL overestimated risk by two levels in all the discrepancies. There was very poor correspondence between the two methods in the Cortezian, and all the differences were three risk levels (minor vs. high risk). Because of the high degree of overestimating risk, the BTL approach should not be applied to these two ecoregions.

Table 5-13. Comparison of risk predictions using the ETW versus the BTL approaches. Preliminary analysis of the temperature risks of brachyuran crabs by ecoregion using the ETW and BTL approaches. The ETW results are taken as the standard. BTL risk classes less than the ETW values underestimate risk; classes greater than the ETW values overestimate risk.

Ecoregions	# Predictions	# ETW = BTL	# ETW (high) vs. BTL (moderate)	# ETW (moderate) vs. BTL (minor)	# ETW (minor) vs. BTL (moderate)	# ETW (minor) vs. BTL (high)
Beaufort to Southern California	394	344 (87.3%)	49	1	0	0
Southern California	131	92 (70.2%)	39	0	0	0
Magdalena	138	114 (82.6%	0	0	24	0
Cortezian	295	64 (21.7%)	0	0	0	231

5.5 Northern Colonization

One of the likely effects of warming is the northern colonization of southern species (e.g., Jones et al., 2012; Somero, 2012; Cahill et al., 2013). To evaluate the potential for such colonization, we reversed the logic of the BTL approach to evaluate whether temperatures in unoccupied northern (cooler) ecoregions will be become sufficiently warm to allow colonization. We choose the BTL approach over the ETW to allow assessments for air, 30-m depth and 100-m depth temperatures as well as SSTs, with the assumption that colonization would be unlikely if any occupied temperature range was not suitable.

This analysis requires two new definitions (Figure 5-1):

COE = Coolest occupied ecoregion; usually the northernmost occupied ecoregion.

NCUE = Next coolest unoccupied ecoregion; usually just north of the COE.

The logic to predict the thermal suitability of northern unoccupied ecoregions is analogous to the approach for predicting thermal risks. The projected future temperature in each of the unoccupied northern ecoregions is compared to the bins derived from the historical temperatures in the COE and NCUE, but the rules predict thermal suitability rather than risk:

Projected temperature in target ecoregion $\ge 3^{rd}$ bin of COE and NCUE $\Rightarrow 3$ (high suitability)

Projected temperature in target ecoregion $< 3^{rd}$ bin of COE and NCUE & $\geq 2^{nd}$ bin $\Rightarrow 2$ (moderate suitability)

Projected temperature in target ecoregion $<2^{nd}$ bin of COE and NCUE & $\geq 1^{st}$ bin $\Rightarrow 1$ (low suitability)

Projected temperature in target ecoregion $<1^{st}$ bin $\Rightarrow 0$ (minor suitability)

The suitabilities are modified by depth similar to the risk calculations, with suitabilities downgraded by one level if the species has an observed versus preferred depth class. The Puget Sound/Georgia Basin Ecoregion did not have values for the 30-m and 100-m depth strata. Additionally, because of the resolution of CMIP5 model, we used the average of the air temperatures in the North Pacific Fijord and OR-WA-Vanc ecoregions. The BTL approach should not be used in predicting colonization potential into the Magdalena or Cortezian ecoregions given the issues with this approach in these areas.

High and moderate suitabilities in unoccupied ecoregions indicate that temperature is not likely to be a limiting factor to northern colonization. However, the analysis does not evaluate whether other factors, such as lack of suitable habitat or dispersal limitation, could limit a species' spread. An example is an obligate coral specialist that would be unable to colonize northern ecoregions until corals colonized them. These factors should be evaluated for species with temperatures suitable for colonization of northern ecoregions.

Section 6. Ocean/Coastal Acidification

6.1 Background

It has become increasingly clear over the last decade that ocean acidification is a major threat to the biodiversity of marine/estuarine ecosystems and the associated ecosystem services. (Note we use the term "ocean acidification" for consistency with the literature but the risk framework is focused on "coastal acidification", which can have different dynamics than true oceanic systems; see Waldbusser and Salisbury, 2014.) These threats have been expounded upon in a number of reviews (e.g., Pörtner, 2008; Hendriks et al., 2010; Byrne, 2011; Ross et al., 2011; Whiteley, 2011; Bellard et al., 2012; Wicks and Roberts, 2012; Kroeker et al., 2013; Wittmann and Pörtner 2013; Waldbusser and Salisbury, 2014; Mathis et al., 2015; Ross et al., 2016; Foo and Byrne, 2016). However, even with these recent efforts, ocean acidification is the least understood of the three climate drivers addressed in CBRAT. While it is beyond the scope of this document to provide a detailed review of the uncertainties associated with ocean acidification, the following highlights some of the challenges, from measurement to interpreting exposure studies:

- pH in marine waters has been measured using four different scales, which can differ by more than 0.1 pH unit (see http://pmel.noaa.gov/co2/story/Quality+of+pH+Measurements+in+the+NODC+Data+Ar chives). This affects both the intercomparability of laboratory studies as well as use of historic pH measurements.
- Most high resolution pH measurements have been taken in the ocean or coastal waters, with relatively few within estuaries. Further, current regional projections for pH and aragonite saturation state (Ω a) from the Gulf of California to the Beaufort are at too coarse a scale to model estuaries.
- pH and aragonite saturation state both tend to decrease with depth, though the pattern with depth varies geographically. However, regional projections for pH and aragonite saturation state from the Gulf of California to the Beaufort are only available for surface waters.
- A wide range of physiological, behavioral, and survival end-points, and exposure durations have been used to evaluate impacts on eggs, larvae, juveniles, and adults. This lack of uniformity makes it challenging to compare among studies and taxa.

- Ninety-five percent of the ocean acidification laboratory studies reviewed up to 2014 "had interdependent or non-randomly interspersed treatment replicates, or did not report sufficient methodological details" (Cornwall and Hurd, 2016).
- There is an inadequate understanding of the factors conveying resiliency to certain taxa, such as their evolutionary history of exposure to low pH (e.g., estuarine species).
- In addition to direct effects, ocean acidification may impact food webs and trophic interactions (Haigh et al., 2015).
- Ocean acidification may interact with other stressors, in particular hypoxia and temperature increases (Harvey et al., 2013; Breitburg et al., 2015).

We identify these sources of uncertainty not to be disheartening but to provide a perspective on the state-of-the-science. While recognizing these uncertainties, we believe there is sufficient information to generate a first-order regional-scale risk assessment of ocean acidification. Besides providing an overview of the patterns of risk, the risk assessment provides an ancillary benefit of providing a framework to organize the data and to identify major information gaps. However, the regional-scale risk assessments conducted in CBRAT are not sufficient to manage fisheries within a locality, which are better addressed by higher resolution models (e.g., Mathis et al., 2015; Punt et al., 2016).

The steps in the risk analysis are: 1) generate ecoregion-scale historical baseline values for pH and aragonite saturation state; 2) generate ecoregion-scale projections for future pH and aragonite saturation states; 3) identify high, moderate, and low sensitivity classes of species within a taxon; 4) generate pH and aragonite saturation state thresholds for minor, low, moderate, and high risks for each of the sensitivity classes; 5) identify whether pH, aragonite saturation state, or both are the major stressor for each species; and 6) overlay the appropriate taxon-specific threshold on the projected pH or aragonite saturation value to generate an ecoregion-specific risk for each species. To evaluate the extent of the uncertainties in these values, CBRAT was designed to allow users to change baseline and projected pH and aragonite saturation state values, the sensitivity class of a species, threshold values for pH and aragonite saturation state, and whether reductions in pH or aragonite saturation is the major stressor.

6.2 Background and Projected pH and Aragonite Saturation State (Ωa) Values

6.2.1 pH Values

Both the historic mean sea surface pH values and the predicted sea surface pH values are from the CMIP5 model downloaded from NOAA's Climate Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/</u>). As mentioned, the CMIP5 was used in the Fifth IPCC Report (Collins et al., 2013). Outputs from different models used in the CMIP5 are interpolated

to a 1-degree latitude/longitude grid to allow for intermodel comparisons. The same default settings were used for pH as for temperature:

- a. Historical period: 1956-2005 (1980/1981 average)
- b. Future period: 2050-2099 (2074/2075 average)
- c. RCP 8.5
- d. Average of all models
- e. Statistic of change: Anomaly
- f. Download entire year, summer (July-Aug.-Sept.), and winter (Jan.-Feb.-March)

GIS was used to clip the gridded data to the MEOW ecoregion borders and then the mean pH was calculated within each of the ecoregions. Details on the GIS techniques are given in Appendix E. The CMIP5 models output pH in the total pH scale (log of total hydrogen ion concentration; personal communication from James Scott (NOAA) to Henry Lee, 9/1/2016). The default values for historic and projected pH values are given in Table 6-1 to Table 6-3.

6.2.2 Aragonite Saturation State (Ωa) Values

NOAA's Climate Change Web Portal does not provide aragonite saturation state projections. Therefore, we followed Foden et al. (2013) in their analysis of hermatypic corals and use the aragonite saturation state projections developed by Cao and Caldeira (2008) based on the University of Victoria Earth System Climate Model version 2.8. The aragonite saturation values were provided by Dr. Cao (Long Cao on 7/19/2014 to Henry Lee). Simulation results were provided for the 2010 (baseline), 2050 and 2100 for RCPs 2.6, 4.4, 6.0, and 8.5. We focus on RCP 8.5 and 2100 scenario. The model has a resolution of 1.8 degrees latitude by 3.6 degrees longitude. As with the NOAA temperature data, GIS was used to derive a weighted average for each ecoregion (Appendix E). As pointed out by Cao and Caldeira (2008), the resolution of the model is too coarse to resolve aragonite values in coastal regions though "changes in coastal ocean chemistry should largely track corresponding changes in nearby open ocean waters." The baseline and projected aragonite saturation state values are given in Table 6-4.

Table 6-1. Historical and projected annual pH.

Historical means derived from 1995-2005 baseline. Predicted increases are based on RCP 8.5 and 2050-2099 future timeframe. The historical means and predicted increases are derived from the CMIP5 models downloaded from NOAA's Climate Change Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/</u>). pH reported in total pH scale. ND = no data.

Ecoregion	Historical Annual pH	Predicted Annual pH Decline	Projected Annual pH
Beaufort Sea - continental coast and shelf	8.12	-0.35	7.77
Chukchi Sea	8.11	-0.33	7.78
Eastern Bering Sea	8.11	-0.3	7.81
Aleutian Islands	8.09	-0.28	7.81
Gulf of Alaska	8.11	-0.3	7.81
North American Pacific Fjordland	8.1	-0.3	7.8
Puget Trough/Georgia Basin	ND	ND	ND
Oregon, Washington, Vancouver Coast and Shelf	8.11	-0.3	7.81
Northern California	8.1	-0.27	7.83
Southern California Bight	8.09	-0.27	7.82
Magdalena Transition	8.09	-0.26	7.83
Cortezian	8.11	-0.25	7.86

Table 6-2. Historical and projected summer pH. ` Data sources same as in Table 6-1. ND = no data.

Ecoregion – Summer pH	Historical Summer pH	Predicted Summer pH Decline	Projected Summer pH
Beaufort Sea - continental coast and shelf	8.15	-0.38	7.77
Chukchi Sea	8.15	-0.36	7.79
Eastern Bering Sea	8.1	-0.3	7.8
Aleutian Islands	8.1	-0.28	7.82
Gulf of Alaska	8.09	-0.29	7.8
North American Pacific Fjordland	8.07	-0.28	7.79
Puget Trough/Georgia Basin	ND	ND	ND
Oregon, Washington, Vancouver Coast and Shelf	8.08	-0.28	7.8
Northern California	8.07	-0.27	7.8
Southern California Bight	8.04	-0.26	7.78
Magdalena Transition	8.05	-0.25	7.8
Cortezian	8.07	-0.25	7.82

Ecoregion – Winter pH	Historical Winter pH	Predicted Winter pH Decline	Projected Winter pH
Beaufort Sea - continental coast and shelf	8.1	-0.33	7.77
Chukchi Sea	8.09	-0.31	7.78
Eastern Bering Sea	8.1	-0.3	7.8
Aleutian Islands	8.07	-0.28	7.79
Gulf of Alaska	8.11	-0.3	7.81
North American Pacific Fjordland	8.12	-0.31	7.81
Puget Trough/Georgia Basin	ND	ND	ND
Oregon, Washington, Vancouver Coast and Shelf	8.13	-0.3	7.83
Northern California	8.13	-0.28	7.85
Southern California Bight	8.12	-0.27	7.85
Magdalena Transition	8.13	-0.26	7.87
Cortezian	8.15	-0.25	7.9

Table 6-3. Historical and projected winter pH. Data sources same as in Table 6-1. ND = no data.

Table 6-4. Historical and projected aragonite saturation state values. Historical means derived from 2010. Predicted ecoregion decreases in aragonite saturation based on RCP 8.5 and 2100 future timeframe. Values based on Cao and Caldeira (2008) analysis using the University of Victoria Earth System Climate Model version 2.8.

Ecoregion – Annual aragonite saturation state	Historical Aragonite Saturation State	Predicted Aragonite Saturation State Decline	Projected Aragonite Saturation State
Beaufort Sea - continental coast and shelf	1.49	-0.84	0.65
Chukchi Sea	1.44	-0.77	0.67
Eastern Bering Sea	2.33	-0.88	1.45
Aleutian Islands	1.86	-0.85	1.01
Gulf of Alaska	1.97	-0.87	1.1
North American Pacific Fjordland	2.22	-1.0	1.22
Puget Trough/Georgia Basin	2.44	-1.02	1.42
Oregon, Washington, Vancouver Coast and Shelf	2.4	-1.03	1.37
Northern California	2.48	-1.11	1.37
Southern California Bight	2.63	-1.18	1.45
Magdalena Transition	2.56	-1.25	1.31
Cortezian	2.61	-1.22	1.39

6.3 Toxicology Approach to Establishing pH Effects Thresholds

6.3.1 Introduction

We propose that pH and aragonite saturation state effects thresholds can be generated using approaches derived from toxicology. We provide the specifics for decapods with pH but the approach would be analogous for other taxa and for aragonite saturation state. The initial step is to synthesize the field and experimental exposures for a taxon. Such a summary for the decapod is presented in Table 6-5; the full summary included additional parameters such as the pH scale and life history traits of the test species (available from the authors). At this time, 34 studies covering 25 decapod species have been synthesized, which will be updated as new information becomes available. An examination of Table 6-5 reveals that a wide range of behavioral, calcification, development, genetics, mortality, and physiological endpoints have been evaluated. An initial evaluation of other taxa also indicate a wide range of endpoints were used in these exposure experiments.

Several ocean acidification reviews have highlighted the differences in sensitivity among major taxa, with the crustaceans less sensitive than corals, mollusks, or echinoderms (e.g., Kroeker et al., 2013; Wittmann and Pörtner, 2013). However, examination of Table 6-5 indicates that there also is a wide range of sensitivities among species within a taxon. Zoea of the European lobster, *Homarus gammarus*, had nearly 50% less calcium in the carapace at a pH of 8.1 compared to the control of 8.39 (Arnold et al., 2009), while the commercially important southern Tanner crab, *Chionoecetes bairdi*, had a reduced survival at a pH of 7.8 compared to the control at 8.1 (Swiney et al., 2016). In contrast to these species, the burrowing shrimp, *Upogebia deltaura*, did not experience significant mortality at a pH of 7.35 (Donohue et al., 2012).

Since one of our objectives is to predict differences in risk among species, we focused on developing a framework capable of capturing such within-taxon differences. Because species-specific thresholds are available for only a handful of species, our approach is to develop thresholds for three classes: high, moderate, and low sensitivity species with each sensitivity class having a different set of effects thresholds. While not as precise as species-specific sensitivity levels, the three classes should provide sufficient resolution to identify the major patterns. The challenge with three sensitivity classes is the number of threshold values required. Three threshold values are needed to separate the four risk levels (minor, low, moderate, and high) within each sensitivity class, so a total of nine threshold values are required.

6.3.2 Use of Maximum Acceptable Toxicant Concentrations (MATCs) to Generate Comprehensive Effects Thresholds

Results from the pH exposure experiments are amenable to deriving multiple thresholds using the "maximum acceptable toxicant concentration" (MATC). The MATC (or GMATC) is the geometric mean of the "no observed adverse effects level" (NOAEL), the highest test level for

which effects are not statistically different from the lowest effect concentration, and the "lowest observed adverse effects level" (LOAEL), the lowest level at which the effects were significantly different than the controls or non-significant exposure concentration (U.S. EPA Risk Assessment Forum, 1998). Note that the NOAEL and LOAEL are defined as the "lowest" contaminant concentrations, but for pH they are for the highest no effect pH and highest significant effect pH, respectively. Because of their long-standing use, we continue to use the terms for pH. Also, because pHs are in log₁₀ units, MATCs are calculated using the antilogs of the pHs and then back transformed into a pH by taking the log₁₀.

MATCs are used to estimate the "safe" concentration of a contaminant and have been used in ecological risk assessments (U.S. EPA, 1998), in evaluating soil contamination for Superfund (EPA, 2003), evaluating contaminants under the Toxic Substances Control Act (TSCA) (Nabholz, 1991), and pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) (EPA, 2004; Fairchild et al., 2009). MATCs have been derived in two ways; firstly, in a more restricted sense limited to results from chronic tests and secondly, in a more general sense based on less than chronic tests. Because of the limitations of the pH exposure data, we use MATC in the general sense, and calculate the "comprehensive" threshold using the lowest pH resulting in a significant effect, the LOAEL, for each species regardless of the endpoint or exposure duration. The MATC was then calculated using the control pH or the lowest non-significant pH value, whichever was lower. A single MATC values, ranging from a pH of 7.35 to 7.96 (Table 6-6).

While thresholds based on a range of mortality, physiological, and behavioral endpoints is not ideal, aggregating results from multiple types of endpoints has a long history in toxicology. The "effects range – median" (ERM) is the median sediment concentration resulting in any significant effect based on all available information, ranging from bacterial responses (MicrotoxTM) to laboratory and field studies (Long et al., 1995). ERMs have been used extensively to compare the toxicity among contaminants and to evaluate spatial patterns of sediment toxicity (e.g., Belan, 2003; Hyland et al., 2004; Nelson et al., 2005; Hale and Heltshe, 2008; Dasher et al., 2015). We posit that a similar aggregation of results across different endpoints is the best practical approach to synthesizing pH effects until ocean acidification exposures and endpoints are at least quasi-standardized. However, in Section 6.3.3, we present an approach limited to endpoints directly related to population viability.

After synthesizing the MATC values, the next step is to identify the low, moderate, and high sensitive classes by identifying breaks in the cumulative frequency distribution of the MATCs (Figure 6-1). There is a discrete break between 7.75 and 7.60 pH. Though not as discrete, there was another break between 7.87 and 7.80. These breaks identify three sets of species based on sensitivity. In taxa lacking discrete breaks in the cumulative distribution curve, sensitivity classes

can be identified by dividing the data into thirds or by setting the break points at the upper and lower quantiles (Figure 6-1).

After identifying the three sensitivity groups, three values within each group need to be identified to generate the cutpoints for the four risk classes (minor, low, moderate and high) within each sensitivity group. The threshold for minor risks for each sensitivity group is set equal to or greater than the highest pH within each group. The threshold for high risks is set equal or less than the lowest pH within each of the three groups. The cutpoint between the low and moderate risks is calculated as the median of the values within each of the sensitivity groups. Specifically, the median is set as the upper end of the range for moderate risks. For example, within the high sensitivity group, the highest MATC was 7.96, which was set to the minor risk threshold (Table 6-7). The lowest MATC, 7.87, was used as the high risk threshold. The median of all the values within the high sensitivity groups was 7.90, which was set as the higher value within the moderate risk range. From these cutpoints, it was then possible to define the low risk range as 7.91 to 7.95.

The risks generated in this fashion should be reasonably protective since the MATCs are based on the most sensitive significant response for each species. For example, the juveniles of both the red king crab (*Paralithodes camtschaticus*) and the southern Tanner crab (*Chionoecetes bairdi*) displayed significant mortality at pH 7.8 compared to the control at 8.0 (Long et al., 2013). Both of these commercial crabs are classified as sensitive, and any pH equal to or less than 7.87 is considered a high risk and a pH less than 7.9 is classified as a moderate risk. Exposure of the larvae of the moderately sensitive Dungeness crab (*Metacarcinus magister*) to a pH of 7.5 resulted in reduced survival compared to a pH of 8.0 (Miller et al., 2016). This results in a MATC of 7.75, which is at the threshold for a high risk for a moderate sensitivity species. While the values appear protective, the proposed thresholds are considered preliminary because of the limited number of exposure experiments and the lack of consistency in experimental procedures and endpoints. Table 6-5. Summary of pH exposure experiments with decapods.

Taxa: Anom. = Anomuran; Asta. = Astacidea; Brac. = Brachyura; Cari. = Caridea; Gebi. = Gebiidea; Pena. = Penaeoidea.

Sources: 1 = Swiney et al., 2016; 2 = Long et al., 2016; 3 = Meseck et al., 2016; 4 = Rastrick et al., 2014; 5 = Taylor et al., 2015; 6 = Dodd et al., 2015; 7 = Landes and Zimmer, 2012; 8 = Appelhans et al., 2012; 9 = de la Haye et al., 2011; 10 = Miller et al., 2016; 11 = Donohue et al., 2012; 12 = Long et al., 2013; 13 = Kurihara et al., 2008; 14 = Paganini et al., 2014; 15 = Ceballos-Osuna et al., 2013; 16 = Walther et al., 2009b; 17 = Dissanayake and Ishimatsu, 2011; 18 = Kim et al., 2015; 19 = Agnalt et al., 2013; 20 = Keppel et al., 2012; 21 = Arnold et al., 2009; 22 = Small et al., 2010; 23 = Bechmann et al., 2011; 24 = Christmas et al., 2013; 25 = Fehsenfeld et al., 2011; 26 = Hans et al., 2014; 27 = Spicer et al., 2007; 28 = Metzger et al., 2007; 29 = Ries et al., 2009; 30 = Carter et al., 2013; 31 = Arnberg et al., 2013; 32 = Miller et al., 2014; 33 = Small et al. 2016; 34 = Styf et al., 2013; 35 = Walther et al., 2010; 36 = Schiffer et al., 2014. d = day; w = week; m = month. ND = No data.

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Callinectes sapidus	Brac.	8.03	2.13	409	Control	60 d	24.9	Juvenile	Survival rate	75%	Mortality	Control	29
Callinectes sapidus	Brac.	7.85	1.53	606	Exposed	60 d	25	Juvenile	Survival rate	83%	Mortality	Not sig.	29
Callinectes sapidus	Brac.	7.72	1.13	903	Exposed	60 d	25	Juvenile	Survival rate	75%	Mortality	Not sig.	29
Callinectes sapidus	Brac.	7.31	0.47	2856	Exposed	60 d	25.1	Juvenile	Survival rate	67%	Mortality	Not sig.	29
Callinectes sapidus	Brac.	8.03	2.13	409	Control	60 d	24.9	Juvenile	Calcification rate	434%	Calcification	Control	29
Callinectes sapidus	Brac.	7.85	1.53	606	Exposed	60 d	25	Juvenile	Calcification rate	598%	Calcification	Sig.?	29
Callinectes sapidus	Brac.	7.72	1.13	903	Exposed	60 d	25	Juvenile	Calcification rate	601%	Calcification	Sig.?	29
Callinectes sapidus	Brac.	7.31	0.47	2856	Exposed	60 d	25.1	Juvenile	Calcification rate	724%	Calcification	Sig.?	29

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Cancer pagurus	Brac.	7.90	ND	Ambient	Control	ca. 3 d	10-22	Adult	Temp. dependent max PaO ₂ values in haemolymph (PaO ₂ (kPa))	Control	Physiological	Control	28
Cancer pagurus	Brac.	7.06	ND	1% CO2	Exposed	ca. 3 d	10-22	Adult	Temp. dependent max PaO ₂ values in haemolymph (PaO ₂ (kPa))	Reduced	Physiological	Sig.	28
Cancer pagurus	Brac.	7.90	ND	Ambient	Control	ca. 3 d	10-22	Adult	Heat tolerance	Control	Physiological	Control	28
Cancer pagurus	Brac.	7.06	ND	1% CO2	Exposed	ca. 3 d	10-22	Adult	Heat tolerance	Downward shift (5 °C) of upper thermal limits of aerobic scope	Physiological	Sig.	28
Carcinus maenas	Brac.	8.00	ND	ND	Control	5 m	8-18 (Seasonal change)	Adult	Cuticle thickness, break resistance of claw	Control Temperature and pH	Calcification	Not sig.	7
Carcinus maenas	Brac.	7.70	ND	ND	Exposed (acidification	5 m	8-18 (Seasonal change)	Adult	Cuticle thickness, break resistance of claw	No effect	Calcification	Not sig.	7

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Carcinus maenas	Brac.	8.00	ND	ND	Exposed (warming)	5 m	13-23 (Seasonal change)	Adult	Cuticle thickness, break resistance of claw	Control pH	Calcification	Not sig.	7
Carcinus maenas	Brac.	7.70	ND	ND	Exposed (acid + warm)	5 m	13-23 (Seasonal change)	Adult	Cuticle thickness, break resistance of claw	No effect	Calcification	Not sig.	7
Carcinus maenas	Brac.	8.06	0.96	650	Control	10	12.9	Adult	Feeding rate and behavior	Control	Behavior	Control	8
Carcinus maenas	Brac.	7.84	0.53	1250	Exposed	10 w	12.9	Adult	Feeding rate and behavior	No effect	Behavior	Not sig.	8
Carcinus maenas	Brac.	7.36	0.2	3500	Exposed	10 w	12.9	Adult	Feeding rate and behavior	41% reduction in feeding	Behavior	Sig.	8
Carcinus maenas	Brac.	8.0 - 8.12	0.96	650	Control	3 d to 11 w	13.0	Adult	Gill gene expression (multiple genes)	Control	Genetic	Control	25
Carcinus maenas	Brac.	7.24 - 7.36	0.2	3500	Exposed	3 d to 11 w	13.0	Adult	Gill gene expression (multiple genes)	Acidification does not act as a strong stressor on the cellular level in gill epithelia	Genetic	Sig.	25
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	1 y (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	99%	Mortality	Control	1

Species	Taxon	Hď	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	1 year (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	99%	Mortality	Not sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	1 year (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	99%	Mortality	Not sig.	1
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	2 y (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	87%	Mortality	Control	1
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	2 y (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	68%	Mortality	Not sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	2 y (adult)	5.0 mean (1-9)	Larval	Percent of viable larvae	46%	Mortality	Sig.	1
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic development	Control	Development	Control	1
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic development	No effect either year	Development	Not sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic development	No effect either year	Development	Not sig.	1
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic morphometrics	Control	Development	Control	1
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic morphometrics	Affected both years	Development	Sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	up to 2 y	5.0 mean (1-9)	Embryonic	Embryonic morphometrics	Affected both years	Development	Sig.	1

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	2 у	5.0 mean (1-9)	Adult	Survival rate	63%	Mortality	Control	1
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	2 у	5.0 mean (1-9)	Adult	Survival rate	38%	Mortality	Sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	2 у	5.0 mean (1-9)	Adult	Survival rate	44%	Mortality	Sig.	1
Chionoecetes bairdi	Brac.	8.10	1.42	396	Control	2 у	5.0 mean (1-9)	Adult	% Calcium dry wt.	ca. 15.5%	Calcification	Control	1
Chionoecetes bairdi	Brac.	7.80	0.77	779	Exposed	2 у	5.0 mean (1-9)	Adult	% Calcium dry wt.	ca. 15%	Calcification	Not sig.	1
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposed	2 у	5.0 mean (1-9)	Adult	% Calcium dry wt.	ca. 11%	Calcification	Sig.	1
Chionoecetes bairdi	Brac.	8.10	1.8	269 ± 20	Control	16 d	5.0	Larval	Survival wild- brooded larvae	Control	Mortality	Control	2
Chionoecetes bairdi	Brac.	7.80	0.8	810 ± 23	Exposed	16 d	5.0	Larval	Survival wild- brooded larvae	No effect, mortality curve similar to control	Mortality	Not sig.	2
Chionoecetes bairdi	Brac.	7.50	0.4	1665 ± 162	Exposed	16 d	5.0	Larval	Survival wild- brooded larvae	No effect, mortality curve similar to control	Mortality	Not sig.	2
Chionoecetes bairdi	Brac.	8.10	1.8	269 ± 20	Control	10 d	5.0	Larval	Morphology of wild-brooded larvae	Control	Development	Control	2

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Chionoecetes bairdi	Brac.	7.80	0.8	810 ± 23	Exposed	10 d	5.0	Larval	Morphology of wild-brooded larvae	No effect	Development	Not sig.	2
Chionoecetes bairdi	Brac.	7.50	0.4	1665 ± 162	Exposed	10 d	5.0	Larval	Morphology of wild-brooded larvae	No effect	Development	Not sig.	2
Chionoecetes bairdi	Brac.	8.1 Embryo & 8.1 Larvae	1.76 ± 0.16	326 ± 34	Control	2 y	7.01 ± 0.55	Larval	LT50	12.42	Mortality	Control	2
Chionoecetes bairdi	Brac.	8.1 Embryo & 7.8 Larvae	0.81 ± 0.04	811 ±38	Exposed (larvae)	2 y	7.12 ± 0.59	Larval	LT50	11.36 (1.06 d shorted than control)	Mortality	Sig.?	2
Chionoecetes bairdi	Brac.	8.1 Embryo & 7.5 Larvae	0.43 ± 0.02	1620 ±60	Exposed (larvae)	2 y	7.06 ± 0.54	Larval	LT50	10.44 (1.98 d shorter than control)	Mortality	Sig.?	2
Chionoecetes bairdi	Brac.	7.8 Embryo & 8.1 Larvae	1.76 ± 0.16	326 ± 34	Exposed (embryo)	2 y	7.01 ± 0.55	Larval	LT50	14.54 (2.12 d longer than control)	Mortality	Sig.?	2
Chionoecetes bairdi	Brac.	7.8 Embryo & 7.8 Larvae	0.81 ± 0.04	811 ±38	Exposed (embryo & larvae)	2 y	7.12 ± 0.59	Larval	LT50	14.05 (1.63 d longer than control)	Mortality	Sig.?	2

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Chionoecetes bairdi	Brac.	7.8 Embryo & 7.5 Larvae	0.43 ± 0.02	1620 ±60	Exposed (embryo & larvae)	2 y	7.06 ± 0.54	Larval	LT50	12.06 (0.36 d shorter than control)	Mortality	Not sig.?	2
Chionoecetes bairdi	Brac.	7.5 Embryo & 8.1 Larvae	1.76 ± 0.16	326 ± 34	Exposed (embryo)	2 y	7.01 ± 0.55	Larval	LT50	15.58 (3.16 d longer than control)	Mortality	Sig.?	2
Chionoecetes bairdi	Brac.	7.5 Embryo & 7.8 Larvae	0.81 ± 0.04	811 ±38	Exposed (embryo & larvae)	2 y	7.12 ± 0.59	Larval	LT50	13.28 (0.86 d longer than control)	Mortality	Not sig.?	2
Chionoecetes bairdi	Brac.	7.5 Embryo & 7.5 Larvae	0.43 ± 0.02	1620 ±60	Exposed (embryo & larvae)	2 y	7.06 ± 0.54	Larval	LT50	15.31 (2.89 d longer than control)	Mortality	Sig.?	2
Chionoecetes bairdi	Brac.	8.10	1.44	392	Control	2 у	Mean =5; 1-9	Adult	Survival rate	63%	Mortality	Control	3
Chionoecetes bairdi	Brac.	7.80	0.78	781	Exposure	2 y	Mean =5; 1-9	Adult	Survival rate	38%	Mortality	Not sig.	3
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposure	2 у	Mean =5; 1-9	Adult	Survival rate	44%	Mortality	Not sig.	3
Chionoecetes bairdi	Brac.	8.10	1.44	392	Control	2 у	Mean =5; 1-9	Adult	Total counts of hemocytes	Control	Physiological	Control	3
Chionoecetes bairdi	Brac.	7.80	0.78	781	Exposure	2 у	Mean =5; 1-9	Adult	Total counts of hemocytes	No effect	Physiological	Not sig.	3
Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
------------------------	-------	------	---------------------	---	------------------------	-------------------------	-----------------	------------	-------------------------------------	--	------------------	-----------------------------------	--------
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposure	2 у	Mean =5; 1-9	Adult	Total counts of hemocytes	No effect	Physiological	Not sig.	3
Chionoecetes bairdi	Brac.	8.10	1.44	392	Control	2 y	Mean =5; 1-9	Adult	# dead cells in the hemolymph	Control	Physiological	Control	3
Chionoecetes bairdi	Brac.	7.80	0.78	781	Exposure	2 y	Mean =5; 1-9	Adult	# dead cells in the hemolymph	No Effect	Physiological	Not sig.	3
Chionoecetes bairdi	Brac.	7.50	0.4	1597	Exposure	2 y	Mean =5; 1-9	Adult	# dead cells in the hemolymph	Increase	Physiological	Sig.	3
Chionoecetes bairdi	Brac.	8.00	1.43	438	Control	200 d	4.4-11.9	Juvenile	Mortality rate	0.0010 day-1	Mortality	Control	12
Chionoecetes bairdi	Brac.	7.80	0.87	792	Exposed	200 d	4.4-11.9	Juvenile	Mortality rate	0.0023 day-1	Mortality	Sig.	12
Chionoecetes bairdi	Brac.	7.50	0.44	1638	Exposed	200 d	4.4-11.9	Juvenile	Mortality rate	0.0050 day-1	Mortality	Sig.	12
Chionoecetes bairdi	Brac.	8.00	1.43	438	Control	200 d	4.4-11.9	Juvenile	Growth rate	Control	Development	Control	12
Chionoecetes bairdi	Brac.	7.80	0.87	792	Exposed	200 d	4.4-11.9	Juvenile	Growth rate	Slower than control, faster than 7.5 treatment	Development	Not sig.	12
Chionoecetes bairdi	Brac.	7.50	0.44	1638	Exposed	200 d	4.4-11.9	Juvenile	Growth rate	Slower than control and 7.8 treatment	Development	Sig.	12

Species	Taxon	Hq	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Hemigrapsus oregonensis	Brac.	7.80	ND	506	Control	5 d	15.9	Larval	Mean swimming speed	Decreased from day 1 to day 5	Behavior	Control	24
Hemigrapsus oregonensis	Brac.	7.53	ND	1031	Exposed	5 d	15.9	Larval	Mean swimming speed	No different than control	Behavior	Not sig.	24
Hemigrapsus oregonensis	Brac.	7.80	ND	506	Control	5 d	15.9	Larval	Avg. # prey consumed in 24 h	Increased, control higher than treatment on day 1, lower on day 5	Behavior	Control	24
Hemigrapsus oregonensis	Brac.	7.53	ND	1031	Exposed	5 d	15.9	Larval	Avg. # prey consumed in 24 h	No significant impact on feeding rate	Behavior	Not sig.	24
Homarus americanus	Asta.	8.10	ND	400	Control	12 d	20	Larval	Carapace length	Control	Development	Control	20
Homarus americanus	Asta.	7.70	ND	1200	Exposed	12 d	20	Larval	Carapace length	Shorter carapace in acidified treatment for larval stages 2-4	Development	Sig.	20
Homarus americanus	Asta.	8.10	ND	400	Control	12 d	20	Larval	Days to reach larval stage III	10 d	Development	Control	20
Homarus americanus	Asta.	7.70	ND	1200	Exposed	12 d	20	Larval	Days to reach Iarval stage III	12 d	Development	Sig.	20
Homarus americanus	Asta.	8.03	2.13	409	Control	60 d	24.9	Juvenile	Survival rate	25%	Mortality	Control	29
Homarus americanus	Asta.	7.85	1.53	606	Exposed	60 d	25	Juvenile	Survival rate	25%	Mortality	Not sig.	29

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Homarus americanus	Asta.	7.72	1.13	903	Exposed	60 d	25	Juvenile	Survival rate	42%	Mortality	Not sig.	29
Homarus americanus	Asta.	7.31	0.47	2856	Exposed	60 d	25.1	Juvenile	Survival rate	58%	Mortality	Sig.?	29
Homarus americanus	Asta.	8.03	2.13	409	Control	60 d	24.9	Juvenile	Net Calcification rate	353.0 wt% 60 d ⁻¹	Calcification	Control	29
Homarus americanus	Asta.	7.85	1.53	606	Exposed	60 d	25	Juvenile	Net Calcification rate	349.5 wt% 60 d ⁻¹	Calcification	Not sig.	29
Homarus americanus	Asta.	7.72	1.13	903	Exposed	60 d	25	Juvenile	Net Calcification rate	376.3 wt% 60 d ⁻¹	Calcification	Not sig.?	29
Homarus americanus	Asta.	7.31	0.47	2856	Exposed	60 d	25.1	Juvenile	Net Calcification rate	606.1 wt% 60 d ⁻¹	Calcification	Sig.?	29
Homarus gammarus	Asta.	8.07	1.7	497	Control	5 w	9.5	Juvenile	Survival	ca. 100%	Mortality	Control	33
Homarus gammarus	Asta.	7.74	0.82	1086	Exposed	5 w	9.6	Juvenile	Survival	ca. 85%	Mortality	Sig.	33
Homarus gammarus	Asta.	6.9	0.13	8773	Exposed	5 w	9.6	Juvenile	Survival	ca. 72%	Mortality	Sig.	33
Homarus gammarus	Asta.	8.05	1.86	559	Control	5 w	13.1 (ocean warming)	Juvenile	Survival	ca. 100%	Mortality	Control	33

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Homarus gammarus	Asta.	7.73	0.92	1258	Exposed	5 w	13.1 (ocean warming)	Juvenile	Survival	ca. 92%	Mortality	Not sig.	33
Homarus gammarus	Asta.	6.89	0.14	8827	Exposed	5 w	13.2 (ocean warming)	Juvenile	Survival	ca. 79%	Mortality	Sig.	33
Homarus gammarus	Asta.	8.07	1.7	497	Control	5 w	9.5	Juvenile	Mean growth	ca. 6%	Development	Control	33
Homarus gammarus	Asta.	7.74	0.82	1086	Exposed	5 w	9.6	Juvenile	Mean growth	ca. 7.5%	Development	Not sig.	33
Homarus gammarus	Asta.	6.9	0.13	8773	Exposed	5 w	9.6	Juvenile	Mean growth	-0.35%	Development	Sig.	33
Homarus gammarus	Asta.	8.05	1.86	559	Control	5 w	13.1 (ocean warming)	Juvenile	Mean growth	17.10%	Development	Control	33
Homarus gammarus	Asta.	7.73	0.92	1258	Exposed	5 w	13.1 (ocean warming)	Juvenile	Mean growth	ca. 14%	Development	Not sig.	33
Homarus gammarus	Asta.	6.89	0.14	8827	Exposed	5 w	13.2 (ocean warming)	Juvenile	Mean growth	ca. 2%	Development	Sig.	33
Homarus gammarus	Asta.	8.07	1.7	497	Control	5 w	9.5	Juvenile	Oxygen consumption	ca. 0.18 µmol min ⁻ ¹ g ⁻¹	Physiological	Control	33
Homarus gammarus	Asta.	7.74	0.82	1086	Exposed	5 w	9.6	Juvenile	Oxygen consumption	0.105 µmol min ⁻¹ g ⁻¹	Physiological	Sig.	33

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Homarus gammarus	Asta.	6.9	0.13	8773	Exposed	5 w	9.6	Juvenile	Oxygen consumption	ca. 0.24 µmol min ⁻ ¹ g ⁻¹	Physiological	Not sig.	33
Homarus gammarus	Asta.	8.05	1.86	559	Control	5 w	13.1 (ocean warming)	Juvenile	Oxygen consumption	0.263 µmol min ⁻¹ g ⁻¹	Physiological	Control	33
Homarus gammarus	Asta.	7.73	0.92	1258	Exposed	5 w	13.1 (ocean warming)	Juvenile	Oxygen consumption	ca. 0.15 µmol min ⁻ ¹ g ⁻¹	Physiological	Sig.	33
Homarus gammarus	Asta.	6.89	0.14	8827	Exposed	5 w	13.2 (ocean warming)	Juvenile	Oxygen consumption	ca. 017 µmol min ⁻ ¹ g ⁻¹	Physiological	Sig.	33
Homarus gammarus	Asta.	8.07	1.7	497	Control	5 w	9.5	Juvenile	Ca concentration in carapace	ca. 4.0 µmol mg ⁻¹	Calcification	Control	33
Homarus gammarus	Asta.	7.74	0.82	1086	Exposed	5 w	9.6	Juvenile	Ca concentration in carapace	ca. 4.1 µmol mg ⁻¹	Calcification	Not sig.	33
Homarus gammarus	Asta.	8.05	1.86	559	Control	5	13.1 (ocean warming)	Juvenile	Ca concentration in carapace	4.27 µmol mg ⁻¹	Calcification	Control	33
Homarus gammarus	Asta.	7.73	0.92	1258	Exposed	5 w	13.1 (ocean warming)	Juvenile	Ca concentration in carapace	3.31 µmol mg ⁻¹	Calcification	Sig.	33
Homarus gammarus	Asta.	7.84	1.81	692	Control	5 m	10 or 18	Larval	% deformities	5% or 12%	Development	Control	19
Homarus gammarus	Asta.	7.82	1.75	727	Exposed	5 m	10 or 18	Larval	% deformities	23%	Development	Sig.?	19

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Homarus gammarus	Asta.	7.62	1.02	1198	Exposed	5 m	10 or 18	Larval	% deformities	43%	Development	Sig.?	19
Homarus gammarus	Asta.	7.84	1.81	692	Control	5 m	18	Larval	Survival from stage 4 to 5 months	46%	Mortality	Control	19
Homarus gammarus	Asta.	7.82	1.75	727	Exposed	5 m	18	Larval	Survival from stage 4 to 5 months	17%	Mortality	Not sig.	19
Homarus gammarus	Asta.	7.62	1.02	1198	Exposed	5 m	18	Larval	Survival from stage 4 to 5 months	61%	Mortality	Not sig.	19
Homarus gammarus	Asta.	7.84	1.81	692	Control	1 y	18	Juvenile	% deformities	33%	Development	Control	19
Homarus gammarus	Asta.	7.82	1.02	727	Exposed	1 y	18	Juvenile	% deformities	44%	Development	Not sig.	19
Homarus gammarus	Asta.	7.62	1.02	1198	Exposed	1 y	18	Juvenile	% deformities	21%	Development	Not sig.	19
Homarus gammarus	Asta.	8.39	4.33	315	Control	28 d	17	Larval	Carapace mass	Control	Calcification	Control	21
Homarus gammarus	Asta.	8.10	4.38	1202	Exposed	28 d	17	Larval	Carapace mass	Reduction in mass at Zoea stage 4	Calcification	Sig.	21
Homarus gammarus	Asta.	8.39	4.33	315	Control	28 d	17	Larval	[Ca2+] and [Mg2+] in the carapace	Control	Calcification	Control	21

Species	Taxon	Н	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Homarus gammarus	Asta.	8.10	4.38	1202	Exposed	28 d	17	Larval	[Ca2+] and [Mg2+] in the carapace	Nearly 50% less Ca in carapace at Zoea stage 4	Calcification	Sig.	21
Homarus gammarus	Asta.	8.39	4.33	315	Control	28 d	17	Larval	Survival	Control	Mortality	Control	21
Homarus gammarus	Asta.	8.10	4.38	1202	Exposed	28 d	17	Larval	Survival	No effect	Mortality	Not sig.	21
Hyas araneus	Brac.	8.00	ND	380	Control	several hours	Cooling 10-6	Adult	∆ in blood haemolymph _{ppO2} -kPa	3.75	Physiological	Control	16
Hyas araneus	Brac.	7.80	ND	710	Exposed	several hours	Cooling 10-6	Adult	∆ in blood haemolymph ppO₂ - °C	4.84	Physiological	Not sig.	16
Hyas araneus	Brac.	7.30	ND	3000	Exposed	several hours	Cooling 10-6	Adult	∆ in blood haemolymph ppO₂ - °C	4.6	Physiological	Sig.	16
Hyas araneus	Brac.	8.00	ND	380	Control	several hours	Warming 10-25	Adult	∆ in blood haemolymph ppO₂ - °C	-6	Physiological	Control	16
Hyas araneus	Brac.	7.80	ND	710	Exposed	several hours	Warming 10-25	Adult	∆ in blood haemolymph ppO₂ - °C	-5.5	Physiological	Sig	16
Hyas araneus	Brac.	7.30	ND	3000	Exposed	several hours	Warming 10-25	Adult	Δ in blood haemolymph ppO ₂ - °C	-5.53	Physiological	Sig.	16

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Hyas araneus	Brac.	8.11	ND	354	Control	Length of dev. stage (~10 - 80 d)	3	Zoea II	Duration of larval stage	72 d - Helgoland 59 d - Svalbard	Development	Control	35
Hyas araneus	Brac.	7.81	ND	754	Exposure	Length of dev. stage (~10 - 80 d)	3	Zoea II	Duration of larval stage	74 d - Helgoland 63 d - Svalbard	Development	Sig.	35
Hyas araneus	Brac.	7.33	ND	2378	Exposure	Length of dev. stage (~10 - 80 d)	3	Zoea II	Duration of larval stage	76 d - Helgobard 68 d - Svaldbard	Development	Sig.	35
Hyas araneus	Brac.	8.12	ND	346	Control	Length of dev. stage (~10 - 80 d)	9	Zoea II	Duration of larval stage	18 d - Helgoland 23 d - Svalbard	Development	Control	35
Hyas araneus	Brac.	7.81	ND	786	Exposure	Length of dev. stage (~10 - 80 d)	9	Zoea II	Duration of larval stage	19 d - Helgoland 21 d - Svalbard	Development	Sig.	35
Hyas araneus	Brac.	7.35	ND	2443	Exposure	Length of dev. stage (~10 - 80 d)	9	Zoea II	Duration of larval stage	20 d - Helgoland 22 d - Svalbard	Development	Sig.	35
Hyas araneus	Brac.	8.05	ND	401	Control	Length of dev. stage (~10 - 80 d)	15	Zoea II	Duration of larval stage	11 d – Helgoland 12 d - Svalbard	Development	Control	35
Hyas araneus	Brac.	7.79	ND	846	Exposure	Length of dev. stage (~10 - 80 d)	15	Zoea II	Duration of larval stage	11 d – Helgoland 12 d - Svalbard	Development	Sig.	35
Hyas araneus	Brac.	7.34	ND	2637	Exposure	Length of dev. stage (~10 - 80 d)	15	Zoea II	Duration of larval stage	12 d – Helgoland 13 d - Svalbard	Development	Sig.	35

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Hyas araneus	Brac.	8.13	ND	420	Control	ND	ND	Zoea I	Mortality	15.5%	Mortality	Control	36
Hyas araneus	Brac.	ND	ND	3300	Exposure	ND	ND	Zoea I	Mortality	21.6%	Mortality	Not sig.	36
Hyas araneus	Brac.	ND	ND	420	Control	ND	ND	Zoea II	Mortality	14.7%	Mortality	Control	36
Hyas araneus	Brac.	ND	ND	3300	Exposure	ND	ND	Zoea II	Mortality	32.2%	Mortality	Not sig.	36
Lysmata californica	Cari.	7.99	ND	462	Control	21 d	18.7	Adult	Mean cuticle thickness	27.9 µm	Calcification	Control	5
Lysmata californica	Cari.	7.53	ND	1297	Exposed	21 d	18.7	Adult	Mean cuticle thickness	23.66 µm	Calcification	Not Sig.	5
Lysmata californica	Cari.	7.99	ND	462	Control	21 d	18.7	Adult	Body Transparency Peak Range	630-910nm	Physiological	Control	5
Lysmata californica	Cari.	7.53	ND	1297	Exposed	21 d	18.7	Adult	Body Transparency Peak Range	680-885nm	Physiological	Sig.	5
Metacarcinus magister	Brac.	8.00	1.74	466	Control	45 d	12	Larval	Larval survival	57.90%	Mortality	Control	10
Metacarcinus magister	Brac.	7.50	0.54	1781	Exposed	45 d	12	Larval	Larval survival	13.50%	Mortality	Sig.	10
Metacarcinus magister	Brac.	7.10	0.25	3920	Exposed	45 d	12	Larval	Larval survival	21.10%	Mortality	Sig.	10
Metacarcinus magister	Brac.	8.00	1.74	466	Control	45 d	12	Larval	Percent reaching larval stage 4	68%	Development	Control	10

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Metacarcinus magister	Brac.	7.50	0.54	1781	Exposed	45 d	12	Larval	Percent reaching larval stage 4	25%	Development	Sig.	10
Metacarcinus magister	Brac.	7.10	0.25	3920	Exposed	45 d	12	Larval	Percent reaching larval stage 4	25%	Development	Sig.	10
Metacarcinus magister	Brac.	8.00	1.74	466	Control	34 d	12	Embryonic	Proportion hatched	0.77	Mortality	Control	10
Metacarcinus magister	Brac.	7.50	0.54	1781	Exposed	34 d	12	Embryonic	Proportion hatched	0.59	Mortality	Sig.	10
Metacarcinus magister	Brac.	7.10	0.25	3920	Exposed	34 d	12	Embryonic	Proportion hatched	0.72	Mortality	Not Sig.	10
Metacarcinus magister	Brac.	7.80	ND	506	Control	5 d	15.9	Larval	Mean swimming speed	Decreased from day 1 to day 5	Behavior	Control	24
Metacarcinus magister	Brac.	7.53	ND	1031	Exposed	5 d	15.9	Larval	Mean swimming speed	Increased swimming speed over control	Behavior	Sig.	24
Metacarcinus magister	Brac.	7.80	ND	506	Control	5 d	15.9	Larval	Avg. # prey consumed in 24 h	Increased, control higher than treatment on day 1 and day 5	Behavior	Control	24
Metacarcinus magister	Brac.	7.53	ND	1031	Exposed	5 d	15.9	Larval	Avg. # prey consumed in 24 h	No significant impact on feeding rate	Behavior	Not sig.	24
Metacarcinus magister	Brac.	8.10	ND	49.2 Pa	Control	7-10 d	14	Adult	Hemolymph pH	pH 8.01	Physiological	Control	26

Species	Taxon	Нд	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Metacarcinus magister	Brac.	7.40	ND	327.9 Pa	Exposed	7-10 d	14	Adult	Hemolymph pH	pH 7.93	Physiological	Not sig.	26
Metacarcinus magister	Brac.	8.10	ND	49.2 Pa	Control	7-10 d	14	Adult	Hemolymph pCO ₂	132.9 Pa / 4.91 mM[5]	Physiological	Control	26
Metacarcinus magister	Brac.	8.10	ND	49.2 Pa	Control	7-10 d	14	Adult	Hemolymph [HCO3-]	4.91 mM	Physiological	Control	26
Metacarcinus magister	Brac.	7.40	ND	327.9 Pa	Exposed	7-10 d	14	Adult	Hemolymph pCO ₂	402.2 Pa	Physiological	Sig.	26
Metacarcinus magister	Brac.	7.40	ND	327.9 Pa	Exposed	7-10 d	14	Adult	Hemolymph [HCO3-]	14.89 mM	Physiological	Sig.	26
Metapenaeus joyneri	Pena.	8.14	2.07	0.04 kPa	Control	1-10 d	15	Adult	Metabolic Scope	15.5 Δ AMR- RMR	Physiological	Control	17
Metapenaeus joyneri	Pena.	6.91	0.16	0.92 kPa	Exposed	1-10 d	15	Adult	Metabolic Scope	9.5 Δ AMR- RMR	Physiological	Sig.	17
Metapenaeus joyneri	Pena.	8.16	2.58	0.04 kPa	Control	1-10 d	20	Adult	Metabolic Scope	11.3 Δ AMR- RMR	Physiological	Control	17
Metapenaeus joyneri	Pena.	6.90	0.17	0.92 kPa	Exposed	1-10 d	20	Adult	Metabolic Scope	8.8 Δ AMR- RMR	Physiological	Sig.	17
Metapenaeus joyneri	Pena.	8.14	2.07	0.04 kPa	Control	10 d	15	Adult	Muscle mass (% of body mass)	44.9%	Physiological	Control	17
Metapenaeus joyneri	Pena.	6.91	0.16	0.92 kPa	Exposed	10 d	15	Adult	Muscle mass (% of body mass)	45.5%	Physiological	Not Sig.	17

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Metapenaeus joyneri	Pena.	8.16	2.58	0.04 kPa	Control	10 d	20	Adult	Muscle mass (% of body mass)	45.95%	Physiological	Control	17
Metapenaeus joyneri	Pena.	6.90	0.17	0.92 kPa	Exposed	10 d	20	Adult	Muscle mass (% of body mass)	40.56%	Physiological	Sig.	17
Necora puber	Brac.	7.96	ND	0.08 kPa	Control	16 d	15	Adult	Haemolymph PCO ₂	No change	Physiological	Control	27
Necora puber	Brac.	7.31	ND	0.25 kPa	Exposed	16 d	15	Adult	Haemolymph PCO ₂	No consistent pattern	Physiological	Not sig.	27
Necora puber	Brac.	6.74	ND	1.1 kPa	Exposed	16 d	15	Adult	Haemolymph PCO ₂	Increased	Physiological	Sig.	27
Necora puber	Brac.	6.05	ND	6.04 kPa	Exposed	16 d	15	Adult	Haemolymph PCO ₂	Increased	Physiological	Sig.	27
Necora puber	Brac.	7.96	ND	0.08 kPa	Control	16 d	15	Adult	Haemolymph [HCO ₃ -]	No change	Physiological	Control	27
Necora puber	Brac.	7.31	ND	0.25 kPa	Exposed	16 d	15	Adult	Haemolymph [HCO ₃ -]	Increased	Physiological	Sig	27
Necora puber	Brac.	6.74	ND	1.1 kPa	Exposed	16 d	15	Adult	Haemolymph [HCO ₃ -]	Increased	Physiological	Sig	27
Necora puber	Brac.	6.05	ND	6.04 kPa	Exposed	16 d	15	Adult	Haemolymph [HCO ₃ -]	Increased	Physiological	Sig	27
Necora puber	Brac.	7.96	ND	0.08 kPa	Control	16 d	15	Adult	Mortality	No apparent effect	Mortality	Control	27
Necora puber	Brac.	7.31	ND	0.25 kPa	Exposed	16 d	15	Adult	Mortality	No apparent effect	Mortality	Not sig.	27

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Necora puber	Brac.	6.74	ND	1.1 kPa	Exposed	16 d	15	Adult	Mortality	No apparent effect	Mortality	Not sig.	27
Necora puber	Brac.	6.05	ND	6.04 kPa	Exposed	16 d	15	Adult	Mortality	All died after 5 days	Mortality	Sig.	27
Necora puber	Brac.	7.96	ND	0.08 kPa	Control	16 d	15	Adult	Haemolymph pH	No change (ca. 8.0 pH)	Physiological	Control	27
Necora puber	Brac.	7.31	ND	0.25 kPa	Exposed	16 d	15	Adult	Haemolymph pH	No consistent pattern	Physiological	Not sig.	27
Necora puber	Brac.	6.74	ND	1.1 kPa	Exposed	16 d	15	Adult	Haemolymph pH	No consistent pattern	Physiological	Not sig.	27
Necora puber	Brac.	6.05	ND	6.04 kPa	Exposed	16 d	15	Adult	Haemolymph pH	Declined (ca. 7.4)	Physiological	Sig.	27
Necora puber	Brac.	8.09	1.94	500	Control	14 d	10	Adult	Haemolymph pH	pH 7.84	Physiological	Control	4
Necora puber	Brac.	7.83	1.25	988	Exposed	14 d	10	Adult	Haemolymph pH	pH 7.87	Physiological	Not Sig.	4
Necora puber	Brac.	8.08	2.7	546	Control	14 d	15	Adult	Haemolymph pH	pH 7.89	Physiological	Control	4
Necora puber	Brac.	7.82	1.43	1136	Exposed	14 d	15	Adult	Haemolymph pH	pH 7.95	Physiological	Not Sig.	4
Necora puber	Brac.	8.09	1.94	500	Control	14 d	10	Adult	Haemolymph [HCO3 ⁻]e	6.56 mmol I ⁻¹	Physiological	Control	4
Necora puber	Brac.	7.83	1.25	988	Exposed	14 d	10	Adult	Haemolymph [HCO3 ⁻]e	9.19 mmol I ⁻¹	Physiological	Sig.	4

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Necora puber	Brac.	8.08	2.7	546	Control	14 d	15	Adult	Haemolymph [HCO3 ⁻]e	7.14 mmol l ⁻¹	Physiological	Control	4
Necora puber	Brac.	7.82	1.43	1136	Exposed	14 d	15	Adult	Haemolymph [HCO3 ⁻]e	11.03 mmol l ⁻¹	Physiological	Sig.	4
Necora puber	Brac.	7.85	1.12	734	Control	30 d	17.3	Adult	Oxygen uptake	0.15 µl O₂ mg⁻¹ hr⁻¹	Physiological	Control	22
Necora puber	Brac.	7.26	0.32	3205	Exposed	30 d	17.3	Adult	Oxygen uptake	0.9 µl O ₂ mg ⁻¹ hr ⁻¹	Physiological	Not Sig.	22
Necora puber	Brac.	6.69	0.09	1234	Exposed	30 d	17.3	Adult	Oxygen uptake	0.05 µl O₂ mg⁻¹ hr⁻¹	Physiological	Sig.	22
Necora puber	Brac.	7.85	1.12	734	Control	30 d	17.3	Adult	[Ca2+] and [Mg2+] in the carapace	Control	Calcification	Control	22
Necora puber	Brac.	7.26	0.32	3205	Exposed	30 d	17.3	Adult	[Ca2+] and [Mg2+] in the carapace	No effect	Calcification	Not sig.	22
Necora puber	Brac.	6.69	0.09	1234	Exposed	30 d	17.3	Adult	[Ca2+] and [Mg2+] in the carapace	No effect	Calcification	Not sig.	22
Nephrops norvegicus	Asta.	8	ND	330	Control	4 m	5	Embryonic	Development rate of embryos	Control	Development	Control	34
Nephrops norvegicus	Asta.	7.6	ND	886 - 1787 (higher at higher temperatures)	Exposed (lower pH & various temperatures)	4 m	5-18	Embryonic	Development rate of embryos	No pH effect (temperature has a sig. effect)	Development	Not sig.	34

Species	Taxon	Нд	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Nephrops norvegicus	Asta.	8	ND	330	Control	4 m	5	Embryonic	Oxygen consumption of eggs	Control	Development	Control	34
Nephrops norvegicus	Asta.	7.6	ND	886 - 1787 (higher at higher temperatures)	Exposed (lower pH & various temperatures)	4 m	5-18	Embryonic	Oxygen consumption of eggs	No pH effect (<i>p</i> =0.051; temperature has sig. effect)	Development	Not sig.	34
Nephrops norvegicus	Asta.	8	ND	330	Control	4 m	5	Embryonic	Oxidative stress in eggs	Control	Development	Control	34
Nephrops norvegicus	Asta.	7.6	ND	886 - 1787 (higher at higher temperatures)	Exposed (lower pH & various temperatures)	4 m	5-18	Embryonic	Oxidative stress in eggs	Reduced compared to controls (temperature was not sig.)	Development	Sig.	34
Pagurus bernhardus	Asta.	8.20	2.89	375	Control	5 d	15	Adult	Latency to find shell	10.7% failed to find new shell	Behavior	Control	9
Pagurus bernhardus	Anom.	6.80	0.18	12191	Exposed	5 d	15	Adult	Latency to find shell	45.7% failed to find new shell	Behavior	Sig.	9
Pagurus tannreri (bathyal)	Anom.	7.60	0.83	1379	Control	4 w.	6	Adult	Time for prey detection after 4 wks. exposure	250 seconds	Behavior	Control	18
Pagurus tannreri (bathyal)	Anom.	7.10	0.23	2366	Exposed	4 w	6	Adult	Time for prey detection after 4 wks. exposure	720 seconds	Behavior	Sig.	18

Species	Taxon	Нд	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Pagurus tannreri (bathyal)	Anom.	7.60	0.83	1379	Control	20 w	6	Adult	Antennular flicking	Fairly constant	Behavior	Control	18
Pagurus tannreri (bathyal)	Anom.	7.10	0.23	2366	Exposed	20 w	6	Adult	Antennular flicking	Decreased throughout experiment	Behavior	Sig. > 7 d	18
Pagurus tannreri (bathyal)	Anom.	7.60	0.83	1379	Control	9 w	6	Adult	Respiration rate	Gradual decrease	Physiological	Control	18
Pagurus tannreri (bathyal)	Anom.	7.10	0.23	2366	Exposed	9 w	6	Adult	Respiration rate	Increased 3 weeks, returned to pretreatment by 8 weeks	Physiological	Not sig.	18
Palaemon pacificus	Cari.	8.20	ND	380	Control	30 d	25	Adult	Survival	90%	Mortality	Control	13
Palaemon pacificus	Cari.	7.89	ND	1000	Exposed	30 d	25	Adult	Survival	55%	Mortality	Sig.	13
Palaemon pacificus	Cari.	8.20	ND	380	Control	15 d	25	Adult	Survival	95%	Mortality	Control	13
Palaemon pacificus	Cari.	7.64	ND	1900	Exposed	15 d	25	Adult	Survival	65%	Mortality	Sig.	13
Palaemon pacificus	Cari.	8.20	ND	380	Control	15 & 30 d	25	Adult	% increase in length	Control	Development	Control	13
Palaemon pacificus	Cari.	7.89	ND	1000	Exposed	30 d	25	Adult	% increase in length	No effect	Development	Not sig.	13

Species	Taxon	Hq	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Palaemon pacificus	Cari.	7.64	ND	1900	Exposed	15 d	25	Adult	% increase in length	Slower growth	Development	Sig.	13
Pandalus borealis	Cari.	8.10	ND	ND	Control	35 d	5	Larval	Mean accumulated mortality	37% on day 35	Mortality	Control	23
Pandalus borealis	Cari.	7.60	ND	ND	Exposed	35 d	5	Larval	Mean accumulated mortality	25% on day 35 (lower than control on last day only)	Mortality	Not sig.	23
Pandalus borealis	Cari.	8.10	ND	ND	Control	35 d	5	Larval	Development time (to IV zoea)	Control	Development	Control	23
Pandalus borealis	Cari.	7.60	ND	ND	Exposed	35 d	5	Larval	Development time (to IV zoea)	Lower % than control	Development	Sig.	23
Pandalus borealis	Cari.	8.11	1.3–1.8	337–474	Control	up to 13 d	6.7	Larval	Larval development (Stage II, III, and IV)	Control	Development	Control	31
Pandalus borealis	Cari.	7.65	0.5–0.7	1038 - 1437	Exposed	up to 13 d	6.7	Larval	Larval development (Stage II, III, and IV)	Decreased, greatest decrease in Stage IV	Development	Sig.	31
Pandalus borealis	Cari.	7.60	0.5–0.7	1147 - 1751	Exposed (pH and temperature)	up to 13 d	9.5	Larval	Larval development (Stage II, III, and IV)	Greater values than at lower temp.	Development	Not. sig	31

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Pandalus borealis	Cari.	8.11	1.3–1.8	337–474	Control	up to 13 d	6.7	Embryonic	Hatching success	98.7	Mortality	Control	31
Pandalus borealis	Cari.	7.65	0.5–0.7	1038 - 1437	Exposed	up to 13 d	6.7	Embryonic	Hatching success	ca. 98%	Mortality	Not sig.	31
Pandalus borealis	Cari.	7.60	0.5–0.7	1147 - 1751	Exposed (pH and temperature)	up to 13 d	9.5	Embryonic	Hatching success	96.1 (not dif. than elevated temp. alone)	Mortality	Sig.	31
Pandalus borealis	Cari.	8.11	1.3–1.8	337–474	Control	up to 13 d	6.7	Larval	Feeding rate (Stages II, III and IV)	ca. 2.5 (Stage II)	Behavior	Control	31
Pandalus borealis	Cari.	7.65	0.5–0.7	1038 - 1437	Exposed	up to 13 d	6.7	Larval	Feeding rate (Stages II, III and IV)	ca. 2.5 (Stage II)	Behavior	Not sig.	31
Pandalus borealis	Cari.	7.60	0.5–0.7	1147 - 1751	Exposed (pH and temperature)	up to 13 d	9.5	Larval	Feeding rate (Stages II, III and IV)	ca. 3.3 (Stage II; not different than elevated temp. alone)	Behavior	Sig.	31
Pandalus borealis	Cari.	8.11	1.3–1.8	337–474	Control	up to 13 d	6.7	Larval	Oxygen consumption rate	ca. 50 nmol O ² h ⁻¹ mg ⁻¹ dry mass	Physiological	Control	31
Pandalus borealis	Cari.	7.65	0.5–0.7	1038 - 1437	Exposed	up to 13 d	6.7	Larval	Oxygen consumption rate	ca. 49 nmol O ² h ⁻¹ mg ⁻¹ dry mass	Physiological	Not sig.	31

Species	Taxon	Hq	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Pandalus borealis	Cari.	7.60	0.5–0.7	1147 - 1751	Exposed (pH and temp.)	up to 13 d	9.5	Larval	Oxygen consumption rate	ca. 53 nmol O ² h ⁻¹ mg ⁻¹ dry mass (not different than elevated temp. alone)	Physiological	Sig.	31
Panopeus herbstii	Brac.	8.20	6.7	499	Control	71 d/48hrs	25.97	Adult	Percentage of oysters consumed	67.50%	Behavior	Control	6
Panopeus herbstii	Brac.	8.04	5.1	785	Exposed	71 d/48hrs	25.97	Adult	Percentage of oysters consumed	41%	Behavior	Sig.	6
Panopeus herbstii	Brac.	7.05	0.8	9274	Exposed	71 d/48hrs	25.97	Adult	Percentage of oysters consumed	1%	Behavior	Sig.	6
Panopeus herbstii	Brac.	8.20	6.7	499	Control	72 d/48hrs	25.97	Adult	Time handling prey	40%	Behavior	Control	6
Panopeus herbstii	Brac.	8.04	5.1	785	Exposed	71 d/48hrs	25.97	Adult	Time handling prey	20%	Behavior	Not sig.	6
Panopeus herbstii	Brac.	7.05	0.8	9274	Exposed	71 d/48hrs	25.97	Adult	Time handling prey	5%	Behavior	Sig.	6
Panopeus herbstii	Brac.	8.04	5.1	785	Exposed	71 d/48hrs	25.97	Adult	Calcification rate	No effect	Calcification	Not sig.	6
Panopeus herbstii	Brac.	7.05	0.8	9274	Exposed	71 d/48hrs	25.97	Adult	Calcification rate	No effect	Calcification	Not sig.	6
Paralithodes camtschaticus	Anom.	8.00	1.43	438	Control	200 d	4.4-11.9	Juvenile	Mortality rate	0.0023 day ⁻¹	Mortality	Control	12

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Paralithodes camtschaticus	Anom.	7.80	0.87	792	Exposed	200 d	4.4-11.9	Juvenile	Mortality rate	0.0047 day ⁻¹	Mortality	Sig.	12
Paralithodes camtschaticus	Anom.	7.50	0.44	1638	Exposed	200 d	4.4-11.9	Juvenile	Mortality rate	0.025 day ⁻¹	Mortality	Sig.	12
Paralithodes camtschaticus	Anom.	8.00	1.43	438	Control	200 d	4.4-11.9	Juvenile	Growth rate	61% higher mass than 7.8 treatment	Development	Control	12
Paralithodes camtschaticus	Anom.	7.80	0.87	792	Exposed	200 d	4.4-11.9	Juvenile	Growth rate	Slower than control, faster than 7.5 treatment	Development	Sig.	12
Paralithodes camtschaticus	Anom.	7.50	0.44	1638	Exposed	200 d	4.4-11.9	Juvenile	Growth rate	Slower than control and 7.8 treatment	Development	Sig.	12
Penaeus plebejus	Pena.	8.03	2.13	409	Control	60 d	24.9	Adult	Survival rate	100%	Mortality	Control	29
Penaeus plebejus	Pena.	7.85	1.53	606	Exposed	60 d	25	Adult	Survival rate	100%	Mortality	Not sig.	29
Penaeus plebejus	Pena.	7.72	1.13	903	Exposed	60 d	25	Adult	Survival rate	100%	Mortality	Not sig.	29
Penaeus plebejus	Pena.	7.31	0.47	2856	Exposed	60 d	25.1	Adult	Survival rate	100%	Mortality	Not sig.	29
Penaeus plebejus	Pena.	8.03	2.13	409	Control	60 d	24.9	Adult	Calcification rate	15.3 wt% 60 d ⁻¹	Calcification	Control	29
Penaeus plebejus	Pena.	7.85	1.53	606	Exposed	60 d	25	Adult	Calcification rate	17.3 wt% 60 d ⁻¹	Calcification	Not sig.?	29
Penaeus plebejus	Pena.	7.72	1.13	903	Exposed	60 d	25	Adult	Calcification rate	27.5 wt% 60 d ⁻¹	Calcification	Sig.?	29

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Penaeus plebejus	Pena.	7.31	0.47	2856	Exposed	60 d	25.1	Adult	Calcification rate	37.8 wt% 60 d ⁻¹	Calcification	Sig.?	29
Petrolisthes cinctipes	Anom.	7.93	ND	574	Control	7-10 d	13	Embryonic	Metabolic rate	ca. 1.9 μmol O ₂ h ⁻¹	Physiological	Control	30
Petrolisthes cinctipes	Anom.	7.58	ND	1361	Exposed	7-10 d	13	Embryonic	Metabolic rate	ca. 1.74 µmol O ₂ h ⁻¹	Physiological	Sig.	30
Petrolisthes cinctipes	Anom.	7.93	ND	574	Control	4-10 d	13	Larval	Metabolic rate	ca. 11.75 µmol O ₂ h ⁻¹	Physiological	Control	30
Petrolisthes cinctipes	Anom.	7.58	ND	1361	Exposed	4-10 d	13	Larval	Metabolic rate	ca. 12.25 µmol O₂ h ^{−1}	Physiological	Not sig.	30
Petrolisthes cinctipes	Anom.	7.93	ND	574	Control	3-5 d	13	Juveniles	Metabolic rate	ca. 22.75 µmol O ₂ h ⁻¹	Physiological	Control	30
Petrolisthes cinctipes	Anom.	7.58	ND	1361	Exposed	3-5 d	13	Juveniles	Metabolic rate	ca. 22.8 µmol O ₂ h ⁻¹	Physiological	Not sig.	30
Petrolisthes cinctipes	Anom.	7.93	ND	574	Control	6 d	13	Larval	C/N ratio	ca. 3.38 µmol O ₂ h ⁻¹	Physiological	Control	30
Petrolisthes cinctipes	Anom.	7.58	ND	1361	Exposed	6 d	13	Larval	C/N ratio	ca. 3.58 µmol O ₂ h ⁻¹	Physiological	Sig.	30
Petrolisthes cinctipes	Anom.	8.00	2.033	450	Control	10 d	14	Larval	Oxygen consumption	ca. 0.75 O ₂ larva ⁻¹ hr ⁻¹	Physiological	Control	32
Petrolisthes cinctipes	Anom.	7.71	1.127	949.8	Exposed (CO ₂ only)	10 d	14	Larval	Oxygen consumption	ca. 0.79 O ₂ larva ⁻¹ hr ⁻¹	Physiological	Not sig.	32
Petrolisthes cinctipes	Anom.	7.71	1.127	949.8	Exposed (CO ₂ followed by salinity stress)	10 d	14	Larval	Oxygen consumption	ca. 0.89 O ₂ larva ⁻¹ hr ⁻¹	Physiological	Sig.	32

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Petrolisthes cinctipes	Anom.	8.12	4.6	461	Control	17 d	11	Adult	Respiration rate (_{µmolO2} /min/g)	47	Physiological	Control	14
Petrolisthes cinctipes	Anom.	7.60	1.5	1476	Exposed	17 d	11	Adult	Respiration rate (µmolO₂/min/g)	48	Physiological	Not sig.	14
Petrolisthes cinctipes	Anom.	7.15	0.6	4801	Exposed	17 d	11	Adult	Respiration rate (µmolO₂/min/g)	49	Physiological	Not sig.	14
Petrolisthes cinctipes	Anom.	7.60	1.5	1476	Exposed	17 d	25	Adult	Respiration rate (_{µmolO2} /min/g)	37	Physiological	Not sig. (temp. x pH)	14
Petrolisthes cinctipes	Anom.	7.15	0.6	4801	Exposed	17 d	30	Adult	Respiration rate (µmolO₂/min/g)	35	Physiological	Sig. (temp. x pH)	14
Petrolisthes cinctipes	Anom.	7.90	ND	574	Control (Ambient)	9 d	ambient	Embryonic	Hatching success	Variable	Mortality	Control	15
Petrolisthes cinctipes	Anom.	7.60	ND	1361	Exposed	9 d	ambient	Embryonic	Hatching success	No effect	Mortality	Not sig.	15
Petrolisthes cinctipes	Anom.	7.90	ND	574	Control (Ambient)	9 d	ambient	Embryonic	Embryo development	volume increased 15% before hatching	Development	Control	15
Petrolisthes cinctipes	Anom.	7.60	ND	1361	Exposed	9 d	ambient	Embryonic	Embryo development	No volume increase before hatching	Development	Sig.	15
Petrolisthes cinctipes	Anom.	7.90	ND	574	Control (Ambient)	9 d	ambient	Larval	Larval survival	Control	Mortality	Control	15

Species	Taxon	Hd	Arag. Saturation	pCO ₂ (ppm / µatm / kPa)	Control or Exposure	Duration of Exposure	Temp. °C	Life Stage	End point	Response	Response Type	Significant (Sig./Not sig.)	Source
Petrolisthes cinctipes	Anom.	7.60	ND	1361	Exposed	9 d	ambient	Larval	Larval survival	Routinely lower survival than 7.9 treatment	Mortality	Not Sig.	15
Petrolisthes cinctipes	Anom.	7.90	ND	574	Control (Ambient)	40 d	ambient	Juvenile	Juvenile survival	Control	Mortality	Control	15
Petrolisthes cinctipes	Anom.	7.60	ND	1361	Exposed	40 d	ambient	Juvenile	Juvenile survival	Reduced survival after longer-term exposure (but 95% CI overlap)	Mortality	Sig.	15
Upogebia deltaura	Gebi.	7.99	1.52	607	Control	35 d	14	Adult	Haemolymph pH	Control	Physiological	Control	11
Upogebia deltaura	Gebi.	7.64	0.77	1396	Exposed	35 d	14	Adult	Haemolymph pH	No effect	Physiological	Not sig.	11
Upogebia deltaura	Gebi.	7.35	0.4	2707	Exposed	35 d	14	Adult	Haemolymph pH	Reduced	Physiological	Sig.	11
Upogebia deltaura	Gebi.	7.99	1.52	607	Control	35 d	14	Adult	Mortality	Control	Mortality	Control	11
Upogebia deltaura	Gebi.	7.64	0.77	1396	Exposed	35 d	14	Adult	Mortality	No effect	Mortality	Not sig.	11
Upogebia deltaura	Gebi.	7.35	0.4	2707	Exposed	35 d	14	Adult	Mortality	No effect	Mortality	Not sig.	11
Upogebia deltaura	Gebi.	6.71	0.11	14110	Exposed	35 d	14	Adult	Mortality	100% mortality on day 35	Mortality	Sig.	11

Table 6-6. MATCs for pH for each decapod species based on all endpoints (comprehensive analysis).

NOAEL = no observed adverse effect level; LOAEL = lowest observed adverse effect level; MATC = maximum acceptable toxicant concentration. The NOAEL is the control pH or the lowest non-significant exposure, identified by *. MATC is calculated as the geometric mean of the NOAEL and LOAEL. The MATCs were calculated by first taking the antilog of the pHs and then taking the log10 of the geometric mean. A single MATC is calculated for each species based on the most sensitive sublethal or mortality exposure. Only species with significant effects are included. Data from Table 6-5.

Species	NOAEL	LOAEL	Most Sensitive MATC	Duration of Exposure	Life Stage	End point	Response Type	Citation
Necora puber	8.09	7.83	7.96	14 days	Adult	Haemolymph [HCO3 ⁻] extracellular	Physiological	Rastrick et al., 2014
Chionoecetes bairdi	8.1*	7.8	7.95	up to 2 years (adults)	Embryonic	Embryonic morphometrics (egg size and yolk dimensions)	Development	Swiney et al, 2016
Callinectes sapidus	8.03	7.85	7.94	60 days	Juvenile	Calcification rate	Calcification	Ries et al., 2009
Homarus gammarus	8.07	7.74	7.91	5 weeks	Juvenile	Survival	Mortality	Small et al. 2016
Hyas araneus	8.0	7.8	7.90	several hours	Adult	Change in blood haemolymph oxygen partial pressure °C	Physiological	Walther et al., 2009b
Paralithodes camtschaticus	8.0	7.8	7.90	199days	Juvenile	Mortality rate	Mortality	Long et al., 2013
Homarus americanus	8.1	7.7	7.90	12 days	Larval	Days to reach larval stage III	Development	Keppel et al., 2012
Pandalus borealis	8.11	7.65	7.88	up to 13 days	Larval	Larval development (Stage II, III, and IV)	Development	Arnberg et al., 2013
Penaeus plebejus	8.03	7.72	7.88	60 days	Adult	Calcification rate	Calcification	Ries et al., 2009
Nephrops norvegicus	8.0	7.6	7.80	4 months (adults)	Embryonic	Oxidative stress in eggs	Development	Styf et al., 2013

Species	NOAEL	LOAEL	Most Sensitive MATC	Duration of Exposure	Life Stage	End point	Response Type	Citation
Palaemon pacificus	7.89*	7.64	7.77	15 days	Adult	% increase in length	Development	Kurihara et al., 2008
Lysmata californica	7.99	7.53	7.76	21 days	Adult	Body transparency peak range	Physiological	Taylor et al., 2015
Petrolisthes cinctipes	7.9	7.6	7.75	40 days	Juvenile	Juvenile survival	Mortality	Ceballos-Osuna et al., 2013
Metacarcinus magister	8.0	7.5	7.75	45 days	Larval	Larval survival	Mortality	Miller et al., 2016
Carcinus maenas	7.84*	7.36	7.60	10 weeks	Adult	Feeding rate and behavior	Behavior	Appelhans et al., 2012
Panopeus herbstii	8.04*	7.05	7.55	71 days/48hrs	Adult	Time handling prey	Behavior	Dodd et al., 2015
Metapenaeus joyneri	8.14	6.91	7.53	1 to 10 days	Adult	Metabolic scope	Physiological	Dissanayake & Ishimatsu, 2011
Upogebia deltaura	7.64*	7.35	7.50	35 days	Adult	Haemolymph pH	Physiological	Donohue et al., 2012
Pagurus bernhardus	8.2	6.8	7.50	5 days	Adult	Latency to find shell	Behavior	de la Haye et al., 2011
Cancer pagurus	7.9	7.06	7.48	ca. 3 days	Adult	Heat tolerance	Physiological	Metzger et al., 2007
Pagurus tannreri	7.6	7.1	7.35	4 weeks	Adult	Time for prey detection after 4 weeks' exposure	Behavior	Kim et al., 2015



Figure 6-1. Cumulative distribution of the MATCs for each decapod species based on all endpoints.

Three groups are identified: high sensitivity species (red), moderate sensitivity species (brown) and low sensitivity species (green). The 1st and 3rd quartiles are shown as an example of using percentiles to define the sensitivity classes. Data from Table 6-6.

Table 6-7. Comprehensive pH thresholds for high, moderate, and low sensitivity decapods using most sensitive MATCs.

Thresholds derived from an analysis of the lowest MATC values for each species (Table 6-5 and Table 6-6Table 6-7).

Sensitivity Level	Minor Risk	Low Risk	Moderate Risk	High Risk
High Sensitivity	≥ 7.96	7.91 - 7.95	7.88 - 7.90	≤ 7.87
Moderate Sensitivity	≥ 7.80	7.77 - 7.79	7.76 - 7.76	≤ 7.75
Low Sensitivity	≥ 7.60	7.50 - 7.59	7.36 - 7.49	≤ 7.35

6.3.3 Ocean Acidification Population Viability Effects Thresholds

A limitation of the comprehensive effects thresholds based on all endpoints is that there is a disconnect between the risks for ocean acidification and those for temperature and sea level rise, which are associated with population viability. Inclusion of physiological and behavioral endpoints in the comprehensive analysis may result in more sensitive effects thresholds (higher MATCs) than the population viability associated risks. This general issue has been recognized previously, and in their review of ocean acidification effects on population survival, Busch and McElhany (2016) weighted responses with "a known relationship to population persistence" twice as heavily as "all else". We present here an example of how ocean acidification thresholds

more closely aligned to those for temperature and sea level rise can be generated from MATCs based on endpoints directly linked to population viability: morality, survival, and larval development rate. Larval development rate was included because an extension of the larval phase can reduce recruitment because of the very high larval mortality rates (Rumrill, 1990; Pedersen et al., 2008).

Limiting the analysis to only population viability endpoints reduced the number of studies to 10 (Table 6-8), six of which were used in calculating the comprehensive MATCs (Table 6-6). As with the comprehensive MATCs, the values are plotted as a cumulative frequency distribution and high, moderate, and low sensitivity groups identified (Figure 6-2). The resulting population viability thresholds for the high sensitivity class (Table 6-9) are essentially the same as those based on the comprehensive MATCs (Table 6-7). However, there are only two species identified in the moderate sensitivity class, both of which have the same value (7.75). We use the 7.75 pH as the threshold for high risk, which is the same value as with the comprehensive moderate threshold (Table 6-7). In lieu of any other data, we use the comprehensive thresholds for minor, low, and moderate risks as a first-order approximation. Given the small range in the moderate thresholds with the comprehensive MATCs (7.75-7.80), thresholds based on mortality endpoints should not be substantially different. While there are only two species in the low sensitivity class, there is a spread in the pH values. Taking the mid-point as the threshold for upper end of the moderate risks allows the generation the low sensitivity thresholds (Table 6-9).

While there is considerable uncertainty due to the limited number of studies, users can enter the thresholds in Table 6-9, or other population-based thresholds, to assess how the extent and pattern of ocean acidification risk changes by using thresholds more comparable to the temperature and sea level rise risks.

Table 6-8. MATCs for pH based on the population viability endpoints for each decapod species.

NOAEL = no observed adverse effect level; LOAEL = lowest observed adverse effect level; MATC = maximum acceptable toxicant concentration. The NOAEL is the control pH or the lowest non-significant exposure. MATC is calculated as the geometric mean of the NOAEL and LOAEL, calculated by first taking the antilog of the pHs and then taking the log10 of the geometric mean. A single MATC is calculated for each species based on endpoints directly related to population viability, including mortality, survival, and larval duration. Only species with significant effects are included. Data from Table 6-5. *Indicates species used in calculation of the comprehensive MATCs (Table 6-6).

Species	NOAEL	LOAEL	Most Sensitive Population MATC	Duration of Exposure	Life Stage	End Point	Response Type	Citation
Necora puber	7.74	6.05	6.90	16 days	Adult	Mortality	Mortality	Spicer et al., 2007
Upogebia deltaura	7.99	6.71	7.35	35 days	Adult	Mortality	Mortality	Donohue et al., 2012
Metacarcinus magister *	8	7.5	7.75	45 days	Larvae	Larval survival	Mortality	Miller et al., 2016
Petrolisthes cinctipes *	7.9	7.6	7.75	40 days	Juvenile	Juvenile survival	Mortality	Ceballos-Osuna et al., 2013
Pandalus borealis *	8.1	7.65	7.88	up to 13 days	Larvae	Larval development (Stage II, III, and IV)	Development	Arnberg et al., 2013
Chionoecetes bairdi	8	7.8	7.90	199days	Juvenile	Mortality rate	Mortality	Long et al., 2013
Homarus americanus *	8.1	7.7	7.90	12 days	Larvae	Days to reach larval stage III	Development	Keppel et al., 2013
Paralithodes camtschaticus *	8	7.8	7.90	199days	Juvenile	Mortality rate	Mortality	Long et al., 2013
Homarus gammarus *	8.07	7.74	7.91	5 weeks	Juvenile	Survival	Mortality	Small et al. 2016
Hyas araneus	8.11	7.81	7.96	Length of dev. stage (~10 - 80 d)	Zoea I & II	Duration of larval stage	Development	Walther et al., 2010



Figure 6-2. Cumulative distribution of the MATCs based on population viability endpoints for each decapod species.

Three groups are identified: high sensitivity species (red), moderate sensitivity species (brown) and low sensitivity species (green). Data from Table 6-9.

Table 6-9. Population viability pH thresholds values for high, moderate, and low sensitivity decapods. Thresholds derived from an analysis of MATC values based on mortality, survival, and larval duration for each species (Table 6-8, Figure 6-2). See text for limitations of these values.

Sensitivity	Minor Risk	Low Risk	Moderate Risk	High Risk
High Sensitivity	≥ 7.96	7.91 to 7.95	7.89 to 7.90	≤ 7.88
Moderate Sensitivity	≥ 7.80	7.76 to 7.79	7.76 to 7.76	≤ 7.75
Low Sensitivity	≥ 7.35	7.13 to 7.34	6.91 to 7.12	≤ 6.90

6.4 Biotic Traits Modifying Sensitivity and Temperature-Adjusted Ocean Acidification Risks

Even with the increased interest in ocean acidification, only a handful of species will be experimentally evaluated to determine if they have high, moderate, or low sensitivity to pH

changes. A potential solution to this data deficit is to use biotic traits to identify the species most and least sensitive to ocean acidification. A number of factors have been suggested as affecting sensitivity including: 1) osmoregulatory ability (Whiteley, 2011); 2) species being "pre-adapted" to low pH by their evolutionary history in upwelling regions, areas of hypoxia, and/or estuaries (e.g., Tseng et al., 2013; Pansch et al., 2014; Heinrich et al., 2016); 3) shell structure, especially the difference between the more soluble aragonite versus calcite (Kleypas et al., 2006; Ries, 2011); and 4) pelagic duration by affecting the exposure time of a sensitive life history stage. However, in our evaluation of the literature, none of these patterns were sufficiently clear to generate general rules applying to multiple taxa across subtropical to Arctic environments at this time.

One general pattern that occurs across taxa is a tendency towards increased impacts of reduced pHs at elevated temperatures. In their review, Kroeker et al. (2013) highlighted "a trend towards enhanced sensitivity to acidification when taxa are concurrently exposed to elevated seawater temperature" while Harvey et al. (2013) noted in their meta-analysis that "four of five of the biological responses measured (calcification, photosynthesis, reproduction, and survival, but not growth) interacted synergistically when warming and acidification were combined." Enhanced effects of pH at higher temperatures have been reported from a variety of taxa and habitats, including stony corals (Anlauf et al., 2011, Edmunds et al., 2012), ophiuroids (Wood et al., 2010), decapods (e.g., Paganini et al., 2014), bivalves (Matozzo et al., 2012; Ko et al., 2014), and fish (Munday et al., 2009). While several studies have not demonstrated such an interaction or only a very weak interaction (e.g., Horn et al., 2016; Zhang et al., 2016), enhanced temperature appears to exacerbate the negative effects of reduced pH more frequently than not, especially with greater thermal stress.

To capture this interaction, we calculate the "temperature-adjusted ocean acidification risk" by pairing the greatest individual risk factor for temperature with the greatest risk for pH/aragonite saturation state. The temperature-adjusted ocean acidification risk is considered the overall risk for pH/aragonite saturation state and is used in calculating the overall vulnerability for a species (see Appendix B). The combination of risks is illustrated in Figure 6-2 based on the following rules:

1. Minor ocean acidification risk and any temperature risk \Rightarrow Minor temperature-adjusted ocean acidification risk.

2. Low ocean acidification risk and any temperature risk \Rightarrow Low temperature-adjusted ocean acidification risk.

3. Moderate ocean acidification risk and Minor temperature risk \Rightarrow Moderate temperature-adjusted ocean acidification risk.

4. Moderate ocean acidification risk and Low temperature risk \Rightarrow Moderate temperatureadjusted ocean acidification.

5. Moderate ocean acidification risk and Moderate temperature risk \Rightarrow High temperatureadjusted ocean acidification.

6. Moderate ocean acidification risk and High temperature risk \Rightarrow High temperatureadjusted ocean acidification.

7. High ocean acidification risk and any temperature risk \Rightarrow High temperature-adjusted ocean acidification.

These rules are based on the concept that minor and low temperature risks are not sufficiently detrimental to elevate the ocean acidification risk. For example, the low temperature risk with the ETW approach is defined as a projected temperature less than mean historical temperature and two standard deviations, which occurs frequently (see Section 5.3.1). At the other extreme, temperatures associated with moderate and high temperature risk occur infrequently, and are presumably sufficiently stressful to aggravate effects of ocean acidification.

		Ocean Acidification Risk						
		Minor	Low	Moderate	High			
Temperature Risk	Minor	0	-1	-2	-3			
	Low	0	-1	-2	-3			
	Moderate	0	-1	-3	-3			
	High	0	-1	-3	-3			

Figure 6-3. Temperature-Adjusted Ocean Acidification Risks.

This figure illustrates the value of the "temperature-adjusted ocean acidification risk" based on the interaction between the ocean acidification risk and the greatest temperature risk. Ocean acidification risk is the larger of the risks associated with pH or aragonite saturation state. Moderate ocean acidification risk is elevated to high risk under conditions of moderate or high temperature risk. Color key for the temperature-adjusted ocean acidification risk: minor risk = green, low risk = yellow, moderate risk = orange, high risk = red.

Another apparent pattern is that species with non-feeding larvae or offering some sort of protection to larval/juvenile stages are more resistant to ocean acidification:

 A field study assessed the life history traits of species along a pH gradient created by a shallow vent system in the Mediterranean (Lucey et al., 2015). All 13 polychaetes species occurring at the lowest pH site (6.4-7.8 pH) had some type of brooding and/or direct development. The authors concluded, "long-term survival of marine species in acidic conditions is related to life history strategies where eggs are kept in protected maternal environments (brooders) or where larvae have no free swimming phases (direct developers)."

- 2) The larvae and juveniles of the lecithotrophic sea star *Crossaster papposus* grew faster at the low pH exposure (7.7), and there was no effect on survival or skeletogenesis (Dupont et al., 2010).
- 3) The eggs of the cuttlefish *Sepia officinalis*, which has lecithotrophic development, developed successfully and developed an aragonite shell under low pH conditions within the egg (Gutowska and Melzner, 2009).
- 4) Waldbusser et al. (2016) found that the brooding oyster *Ostrea lurida* was less sensitive to low pH than *Crassostrea gigas*, which has planktotrophic larvae. The actual cause for the enhanced resistance was the slower development of the *O. lurida* embryos rather than brooding per se. Nonetheless, we assume that many if not most brooding bivalves have slower embryo growth than their counterparts with planktotrophic larvae, and should have similar resistance to lower pH.
- 5) *Haliotis rufescens*, the red abalone, has a lecithotrophic larvae. The expression pattern of the two shell formation genes in the early life history stages were not affected at a pH of 7.87 (Zippay and Hofmann, 2010). However, there was an interaction with temperature, and two of the early life history stages had reduced thermal tolerance with higher pH exposure.

Besides the pH exposures, several authors have suggested that species with lecithotrophic development have a lower vulnerability to environmental perturbations than those with strict planktotrophic development. Byrne (2011) suggested that invertebrates "may have evolved a buffered non-feeding larval life history, free of the vagaries of planktonic food supply in response to stressful conditions in the plankton". Supporting evidence included the extinction of several planktotrophic lineages during paleo-climatic events (Valentine and Jablonski 1986, Pechenik 1999, Uthicke et al. 2009). Based on their studies with *Crossaster papposus*, Dupont et al. (2010) postulated that "lecithotrophy may be an advantage in an unpredictable and extreme environment".

Based on these studies, we incorporate breeding and larval type as conditional factors modifying the risk associated with coastal acidification. If the target species has any of the following breeding or developmental strategies, the species is automatically assigned to the low sensitivity class:

Life History
Development
Breeding Strategy
Ovoviviparous
Life History
Development
Breeding Strategy
Oviparous
Eggs brooded in tube

Life History → Development → Juvenile Development → Direct Development Life History → Development → Larval Phase → Planktonic Larvae → Planktonic-lecithotrophy Life History → Development → Larval Phase → Benthic Larvae → Brooded Life History → Development → Larval Phase → Benthic Larvae → Benthic-lecithotrophy

Several invertebrate species (Allen and Pernet, 2007) as well as rockfish (Berkeley et al., 2004) display a mixed reproductive strategy, or facultative planktotrophy, where larvae have oil reserves but actively feed as the larvae mature. Such a mixed strategy is coded in CBRAT by selecting both planktotrophy and lecithotrophy; in terms of the risk calculation this mixed reproductive strategy is treated as lecithotrophic.

As with nearly every generalization about marine species, there may be exceptions to this rule. The gastropod *Crepidula fornicata* broods its embryos within capsules maintained by the females. Based on a set of exposure experiments, it was concluded that encapsulation did not protect them against lower pH (Noisette et al., 2014), though the authors noted "*C. fornicata* larvae seemed less affected than other mollusk species." Another possible exception are small, thin-shelled brooders, such as the bivalve *Carditella marieta*. To accommodate such exceptions, users can change the sensitivity class on a species-by-species basis.

6.5 Risk Type and Risk Algorithm

6.5.1 Risk Type

Taxa vary in whether reductions in pH or aragonite saturation state is the primary stressor. Hermatypic corals are very sensitive to reductions in aragonite saturation state to the point of having their exoskeleton literally dissolve (e.g., Cohen and Holcomb, 2009). Larval and juvenile bivalves are also sensitive to reductions in aragonite saturation state (Waldbusser et al., 2015). As pointed out by (Whiteley, 2011), the calcification process in crustaceans is likely to be less susceptible to ocean acidication than with bivalves because the exoskeletal is mostly composed of calcite rather than aragonite. Based on this, we assign pH rather than aragonite saturation state as the major stressor for crustaceans. However, this conclusion should be experimentally tested since crustacean larvae initially deposit soluble amorphous calcium carbonate and highmagnesium calcite (Ross et al., 2011). pH is also assigned as the main stressor for fish and other taxa lacking carbonate shells (e.g., most polychaetes).

To assign the appropriate stressor in the risk assessments, pH or aragonite saturation state is identified in CBRAT as the primary stressor for major taxa. For example, aragonite saturation state is assigned as the primary stressor for bivalves while pH is assigned as the primary stressor for decapods and fish. The major stressor assigned for polychaetes is pH, though serpulid

polychaetes, as well as some sabellids and cirratulids, create calcium carbonate tubes. To address this type of variation, individual families or species can be assigned a different ocean acidification stressor. Additionally, both pH and aragonite can be identified as major stressors in CBRAT, in which case the ocean acidification vulnerability is based on the greater of the two risks.

6.5.2 Risk Algorithm and Assignment of Sensitivity Classes

The ocean acidification risk algorithm compares the ecoregion-specific projected pH and aragonite saturation state values to the respective thresholds for the target species. For pH, comparisons are conducted for projected annual, summer, and winter values, while only annual values are available for the aragonite saturation state. Only the risk associated with the primary stressor(s) for the assigned sensitivity class is output in the vulnerability summary (see Appendix B), with the temperature-adjusted ocean acidication risk used in calculating the overall risk for a species.

Based on a preliminary risk assessment with decapods, assignment of the high, moderate, or low sensitivity threshold to a species has a major effect on its ocean acidification risk assignment. In even the most optimistic scenario, only a limited number of species within a taxon will be tested experimentally, necessitating assigning sensitivity classes in the absence of direct evidence. One approach is to classify species by their similarity to experimentally tested species, taking into account both taxonomic and ecological similarities. Another approach is to use moderate sensitivity effects thresholds as a "restrained" analysis and the high sensitivity thresholds as a "high risk" analysis. Currently, moderate sensitivity is used as the default in CBRAT, though we suggest users evaluate risk using different sensitivity classes.

Section 7. Sea Level Rise

7.1 Introduction

Sea level rise (SLR) is a threat to near-coastal biotic communities as well as human well-being and infrastructure (e.g., NRC, 2012; Wong et al., 2014; <u>http://www.corpsclimate.us/ccaceslcurves.cfm</u>). Inundation of coastal lands could put upwards of 1.8 to 7.4 million people at risk in the United States and the GDP "could potentially decline by USD 70–289 billion" (Haer et al., 2013). There is also concern regarding the effects of sea level rise on intertidal habitats, such as wetlands and mangroves. Loss of these habitats puts species that depend upon them at risk. Perhaps the most notable example of such an impact is that SLR has resulted in the extirpation of the Australian Bramble Cay melomys, *Melomys rubicola*, from its only known habitat (Gynther et al., 2016), the first documented case of a mammal extinction due to climate change.

In assessing the potential impacts of climate change, it is important to distinguish between global or eustatic SLR and local or relative SLR. Eustatic SLR is the global rise in the ocean level due to changes in the volume of ocean water. There is only one eustatic SLR value for all the oceans. Based on observed contributions to SLR from 1993 to 2010 (Church et al., 2013), the contributors to observed eustatic sea level rise were:

- \sim 34 % thermosteric expansion of sea water from the increased heat content of the ocean
- ~24% Glaciers except in Greenland and Antarctica
- $\sim 15.4\%$ Glaciers and ice sheet in Greenland
- $\sim 8\%$ Antarctic ice sheet
- ~12% Changes in land water storage
- $\sim 13\%$ Other and unexplained

The biggest uncertainties in predicting future eustatic rates are the extent of melting of the large ice sheets of Greenland and Antarctica (Nicholls et al., 2011).

The actual extent of SLR at a location is modified by several local or regional factors, and the net change in sea level at any particular location due to both eustatic SLR and local factors is often

referred to as the relative sea level rise (RSLR). In most cases, the most important of these local factors is isostatic or tectonic effects, which is the subsidence or uplift of the land relative to mean sea level. In some locations, uplift is sufficient to offset the predicted levels of SLR, while in other locations subsidence exacerbates SLR. Other local factors, such as wind, storms, and barometric pressure, can also modify sea level (e.g., NRC, 2012). The effects of these factors are usually temporary, and are not considered here.

In this section, we will first describe our general approach to predicting the relative risk of species to sea level rise on an ecoregional scale. As with other climate drivers, we focus on the regional loss of intertidal habitats and its regional effect on the associated target species. This regional approach does not have the detail of localized models, such as SLAMM (e.g., Glick et al., 2007) but we contend that it has sufficient resolution to identify both the species at greatest risk and how SLR risk varies along the coast. In the remainder of the section, we provide a synthesis of available information used to generate default input values for CBRAT.

7.2 Overview of SLR Approach

The SLR procedure consists of four steps (Figure 7-1). The first is to estimate a relative or net ecoregion sea level rise value (mm) by adding the isostatic rate of a particular ecoregion to the global eustatic SLR rate; that value is then multiplied by the number of years being modeled to generate an estimate of net sea level rise (Sections 7.3–7.5). The second step is to estimate the percentages of each occupied habitat that will be lost to SLR in each ecoregion which are the basis of generating habitat threshold values (classes of the percent of habitat lost with SLR values; Section 7.8). To account for the potential of intertidal habitats to migrate inland, habitat thresholds are developed for both "constrained" and "unconstrained" scenarios (Section 7.6). The third step is to generate risk values for the target species for each occupied habitat from the habitat thresholds and depth preferences of the species (Section 7.9.1). For species occupying multiple habitats, the fourth step is to modify the risk factors generated in step 3 based on its habitat preferences (Section 7.9.2). As with other risks, the SLR risks are classified from "Minor" (0) to "High" (-3). While the approach should be generally applicable in other areas, the habitat thresholds were calibrated for the Northeastern Pacific and would likely need to be adjusted for other regions.


Figure 7-1. Generalized sea level rise approach to calculating relative risk.

Step 1 determines the ecoregion-specific relative sea level rise in mm. Step 2 determines the risk class for each occupied habitat based on the percent of habitat lost by comparing habitat threshold values to the predicted SLR. Different habitat thresholds are used in ecoregions where inland migration of habitats is limited due to barriers (constrained) versus ecoregions where there are few barriers to inland migration ("unconstrained"). Step 3 generates the risk values for the target species based on the species' depth preferences. Step 4 determines the final risk value based on the species' habitat preferences, with the final risk factor based on the greatest risk value across habitats.

7.3 Eustatic Rates

The first input into the SLR risk analysis is the eustatic sea level rise rate (mm/yr). There is considerable uncertainty regarding future levels of sea level rise. As pointed out by Parris et al., 2012, "Scenarios do not predict future changes, but describe future potential conditions in a manner that supports decision-making under conditions of uncertainty." As reasonable default values, we use the rates generated by the NOAA (Parris et al., 2012; Table 7-1) with the modification that the lowest scenario from Parris et al. (2012) was increased from 2 mm/yr to 3.3 mm/yr based on more current estimates of recent SLR (Füssel, 2009; NRC, 2012).

Table 7-1. Eustatic sea-level rise scenarios used as default values for ecoregion SLR risk analysis. Table modified from Parris et al. (2012). Parris et al. used a value 0.2 m SLR by 2100 for the lowest scenario, however we use a value of 0.33 m based on recent sea level data from tide gauges and satellites (Füssel, 2009; NRC, 2012).

Scenarios	SLR by 2100 (m) (mm/yr assuming 100 years)	Source / Applications
Highest	2.0 m (20 mm/yr)	"Our Highest Scenario of global SLR by 2100 is derived from a combination of estimated ocean warming from the IPCC AR4 global SLR projections and a calculation of the maximum possible glacier and ice sheet loss by the end of the century. The Highest Scenario should be considered in situations where there is little tolerance for risk".
Intermediate-High	1.2 m (12 mm/yr)	"based on an average of the high end of semi-empirical, global SLR projections The Intermediate-High Scenario allows experts and decision makers to assess risk from limited ice sheet loss."
Intermediate-Low	0.5 m (5 mm/yr)	"based on the upper end of IPCC Fourth Assessment Report (AR4) global SLR projections resulting from climate models using the B1 emissions scenario The Intermediate Low Scenario allows experts and decision makers to assess risk primarily from ocean warming."
Lowest	0.33 m (3.3 mm/yr)	"based on a linear extrapolation of the historical SLR rate derived from tide gauge records beginning in 1900 (1.7 mm/yr). The Lowest Scenario should be considered where there is a great tolerance for risk." [<i>Note: We suggest a value of 0.33 m versus the 0.2 m in Parris et al., 2012 based on recent observed SLR rates.</i>]

7.4 Regional Isostatic Rates

The eustatic rate of sea level rise is modified locally by a number of factors, the most important of which are isostatic adjustments. To account for isostatic adjustments, we generated average isostatic rates (mm/yr) for each ecoregion. The ecoregion-specific isostatic rate input into CBRAT is multiplied by the duration being modeled, and then this ecoregion-specific adjustment (mm) is added to the eustatic sea level to generate a projected relative sea level rise (mm) for the ecoregion.

For 10 of the 12 ecoregions, the average isostatic value was calculated by first determining the observed historic sea level rise trend at all the sites within the ecoregion. Then, the historic eustatic sea level rise rate was subtracted from each of the observed trends, with the difference assigned as the isostatic rate for that location. These values were averaged for all of the sites within an ecoregion to generate the ecoregion-specific isostatic rate (Table 7-2). For these ten ecoregions, the observed historic sea level trends were downloaded from NOAA's Sea Level Trends site (<u>http://tidesandcurrents.noaa.gov/sltrends/sltrends.html</u>; see Zervas, 2009). For the historic eustatic rate, we use a rate of 1.7 mm/yr, the global average between 1901 and 2010

reported by the IPCC (Church et al., 2013), which has a reported range of 1.5 to 1.9 mm/yr. Because the NOAA Portal does not report sea level trend values for the Magdalena Transition Ecoregion, we took the average of the locations to the north and south, Ensenada and Cabo San Lucas, as an approximation. Sea level rise trends are also not available for the Chukchi Sea from the NOAA Portal. For this ecoregion, we subtracted the eustatic rate (1.7 mm/yr) from the average observed sea level trend for five sites on the Russian side of the Chukchi from Proshutinsky et al. (2004; their Table 3).

Several of the ecoregions had sites with uplift and others with subsidence. Since our objective is to predict habitat loss at the ecoregion level, such within-ecoregion variation should not introduce a substantial error in terms of estimating the overall habitat available. As an example, the Oregonian ecoregion has about a quarter of the sites show uplift and the others showing subsidence. We provide the average isostatic values for these two groups of sites (Table 7-2), which can be used to model the range of possibilities of isostatic adjustment within this ecoregion.

Table 7-2. Derivation of ecoregion-specific isostatic rates.

Except as noted, historical sea level trend values were extracted for each site within an ecoregion from the NOAA Sea Level Trends portal (<u>http://tidesandcurrents.noaa.gov/sltrends/slrmap.htm</u>). The ecoregion-scale isostatic rate was calculated by averaging the historic SLR trends across all the sites within each ecoregion and then subtracting the historic eustatic sea level rise rate (1.7 mm/yr, Church et al., 2013). The value for the Magdalena is the average of the values for the two closest sites, Ensenada and Cabo San Lucas, Mexico. The Chukchi value is the average observed SLR trend from Proshutinsky et al., 2004 ("Observations" in their Table 3) minus the 1.7 mm/yr eustatic rate. Negative isostatic values indicate uplift, while positive values indicate subsidence. For the Oregonian ecoregion, the average isostatic rates are also given separately for sites experiencing uplift versus subsidence (italicized). NA= no data.

ECOREGION	# Sites	Average Historical RSLR (Not Isostatically Corrected) (mm/yr)	Average Ecoregion Isostatic Rate (mm/yr)	# Sites in Ecoregion Showing Historic Uplift (Negative Values)
Beaufort	1	1.20	-0.50	1
Chukchi	5	1.90	0.20	1
Bering	2	2.72	1.02	0
Aleutians	2	-4.11	-5.81	2
Gulf of Alaska	9	-6.41	-8.11	9
Pacific Fjords	5	-6.44	-8.14	5
Puget	7	0.83	-0.87	6
Oregonian	11	0.33	-1.37	8
Oregonian	3	2.87	1.17	0
Oregonian	8	-0.62	-2.32	8
N. California	8	1.20	-0.50	5
S. California	8	1.88	0.18	3
Magdalena	0	2.01	0.31	ND
Cortezian	2	2.89	1.19	1

7.5 Duration

Duration, in years, is input to convert the eustatic and isostatic rates (mm/yr) into a total relative sea level rise value (mm). While it is possible to input any duration, the model was designed and calibrated for 100 years, and we caution about using other durations at this time. Some studies have predicted an initial increase in low wetlands over approximately fifty years but then a decline by 100 years (e.g., Stralberg et al., 2011; Thorne et al., 2015). The default habitat thresholds for emergent marshes are based on the effects over 100 years, and in this case would overestimate the loss of lower wetlands over 50 years. If durations other than 100 years are modeled, it is important to check the applicability of the habitat thresholds.

7.6 Constrained Versus Unconstrained Habitats

The effect of sea level rise on intertidal habitats is alleviated if the habitat can migrate inland as the water level rises. Conversely, habitats surrounded by anthropogenic barriers like rip-rap, dikes, armoring, and seawalls, or natural barriers, like cliffs, are more vulnerable to SLR. The prevention of intertidal habitats to migrate inland with SLR is referred to as "coastal squeeze" (e.g., Short et al., 2016). Coastal squeeze is most important for vegetated and unvegetated soft-sediment habitats while anthropogenic barriers do not appear to be a major factor limiting rocky intertidal assemblages. SLR models vary in how coastal squeeze is parametrized; some studies analyzed just the intertidal land seaward of dikes or other barriers while other studies allowed the model to consider land behind dikes or barriers as potential area for habitat expansion. Because these considerations result in large differences in potential habitat expansion, we analyze the 'unconstrained' and 'constrained' scenarios separately.

Several researchers conducted their analyses using both constrained and unconstrained GIS layers to demonstrate restoration potential if barriers were removed (e.g. Stralberg et al. 2011; Warren Pinnacle Consulting, Inc. 2011). These side-by-side comparisons provide an opportunity to compare projected differences in habitat area loss with and without physical barriers. In Stralberg et al. 2011 the difference between constrained and unconstrained (based on dike removal) ranged from a decrease in 24% of low marsh with the constrained layer to an increase 40% low marsh under the unconstrained data layer.

Besides the effects at a local scale, the concept of constrained versus unconstrained can be applied at a regional scale. The coastal shorelines and estuaries in the Puget, Oregonian, Northern California, and Southern California ecoregions are subject to moderate to extensive shoreline modifications (e.g., Dugan and Hubbard, 2010; Hubbard et al., 2014; Washington State Department of Natural Resources, no date; Myers, 2010). Approximately a third of Puget Sound's shoreline has been anthropogenically modified (Washington State ShoreZone Inventory). In addition to these anthropogenic barriers, natural cliffs are a common shoreline feature in Washington, Oregon and California. Because of the frequency of these barriers, we apply the constrained habitat thresholds for soft-sediment habitats to these ecoregions (Table 7-3). However, with their lower population densities and extents of coastal development, we apply the unconstrained habitat thresholds to the other eight ecoregions. The consequence of using these different habitat thresholds is that the model predicts a greater risk for the same net sea level rise in the four developed ecoregions compared to the less developed ecoregions.

A different type of limitation to migration is that some models are "bounded". That is, they model changes in the relative percent change of different habitat types within a defined, or bounded, area. As such, these model do not incorporate the possibility of landward migration. As discussed below, one such bounded model is that of Thorne et al. (2015).

7.7 High and Low Exposure Habitats

Intertidal habitats that will experience the effects of sea level rise are termed "high exposure" habitats. There is another suite of habitats for which SLR will have no or only a trivial impact, which we refer to as "low exposure" habitats. From the Level I habitats in CBRAT, we identify Terrestrial, Pelagic Ecosystems, and Specialized Systems as low exposure. From the Level II habitats, Unvegetated Subtidal, Kelp, Coral, Subtidal Rocky, Non-coral reefs, Solitary sponge, Bryozoan mats, and Rhodoliths/Maerl are classified as low exposure. A minor risk is assigned to these low exposure habitats by setting the habitat thresholds to the maximum projected sea level rise (80.32 m) resulting from the melting of all the glaciers in the Antarctic, Greenland, and other ice fields (Poore et al., 2000). These habitat thresholds set the extent of habitat loss to zero except with the most extreme SLR projections.

While a few of the low exposure habitats may occasionally occur in the intertidal, such as coralline algal mats, the vast majority of them occur subtidally (e.g., see Chenelot et al., 2008 for subtidal coralline mats in the Aleutians). Thus, functionally assigning them a minor risk by applying the upper bound SLR thresholds should introduce a negligible underestimation of the impacts. The low exposure habitats are based on the NEP and U.S. Arctic and it may be necessary to modify the list for other geographical areas. For example, corals are subtidal in the Gulf of California but may form intertidal assemblages in other regions (Richards et al., 2015).

7.8 Habitat Thresholds

7.8.1 Introduction

A key step to predicting SLR impacts on populations of intertidal species is to approximate the percent habitat loss for each of the habitats the species occupy. We approximate these losses by generating "habitat thresholds" for each of the Level II habitat types in CBRAT (Table 7-3), where habitat thresholds are the net sea level rise, in mm, that result in different ranges of percent losses of specific habitats when averaged across the ecoregion. The concept of the habitat thresholds is that different habitat types vary in their vulnerability to SLR due to factors such as geomorphology and coastal slope, which are similar to the factors Thieler and Hammar-

Klose (2000) used in developing their coastal vulnerability index. As pointed out by these authors, "the relative vulnerability of different coastal environments to sea-level rise may be quantified at a regional to national scale using basic information on coastal geomorphology, rate of sea-level rise, past shoreline evolution, and other factors." The concept of habitat thresholds is also similar in spirit to SLR estimates used by other authors to identify critical levels of SLR rise for different habitats (e.g., Morris et al., 2002; Blankespoor et al., 2012).

Table 7-3. Habitat thresholds associated with different levels of percent habitat loss.

Habitat thresholds are the levels of net SLR (mm) for major habitats that define different percent habitat loss classes. Habitat threshold classes are: minor (\leq 10% loss), low (11% to 29% loss), moderate (30% to 49% loss), and high (\geq 50% loss). Minor is expressed as a loss but under some scenarios habitat area may increase with these levels of SLR. As appropriate, both constrained and unconstrained habitat thresholds are presented. Constrained habitats are impeded from inland migration due to artificial and natural barriers, while unconstrained habitats are not impeded. High exposure systems are intertidal habitats that would be affected by SLR. Low exposure systems are primarily subtidal and pelagic habitats that are essentially immune to all but the most extreme sea level rise. Maximum sea level rise values from Poore et al. (2000) are assigned to the low exposure habitats. Blue values = SLR values equal to or greater than NOAA's Intermediate-High scenario; Red values = SLR values equal to or greater than NOAA's Highest scenario (Table 7-1).

High Exposure Habitat Classes									
	Miı (≤10%	nor loss)	Low Moderate H (11 to 29% loss) (30 to 49% loss) (≥50		Moderate (30 to 49% loss)		Hi (≥50%	gh loss)	
Habitat	Con- strained (mm)	Uncon- strained (mm)	Con- strained (mm)	Uncon- strained (mm)	Con- strained (mm)	Uncon- strained (mm)	Con- strained (mm)	Uncon- strained (mm)	
Oyster Beds	340	390	690	1000	770	2250	>770	>2250	
Tide Flats	340	390	690	1000	770	2250	>770	>2250	
Low Marsh	160	2500	790	2750	1420	3000	>1420	>3000	
Rocky Intertidal	-	400	-	800	-	1400	-	>1400	
Mussel Beds	-	400	-	800	-	1400	-	>1400	
SAV	540	1080	720	1440	900	1800	>900	>1800	
Coastal Beaches	550	650	600	800	800	1000	>800	>1000	
Mangrove	-	750	-	1150	-	1600	-	>1600	
		L	ow Exposi	ure Habitat	Classes				
Low Exposure Habitats	ure 81000 82000 83000 ≥83000							000	

The literature synthesized for the derivation of the habitat thresholds by major habitat type is summarized below (Sections 7.8.2 to 7.8.7). There is considerable uncertainty in several of the thresholds, such as for the unconstrained lower marsh. Such divergent results can be attributed, in part, to the differences in the modeling assumptions, which were influenced by the goals of each analyses. If, for example, the model is allowed to expand into the adjacent grids based on elevation alone, without incorporating real world barriers (e.g., dikes, levees, roads and seawalls), the habitats will increase continuously until elevation limits landward migration. Conversely, if the models use a predefined area (bounded) without any manmade structures, as in Thorne et al. (2015), the future habitat change more likely approaches reality.

Many of the unconstrained modeling efforts that show large increases in habitat do not consider future changes that are likely to exacerbate impacts from sea level rise such as increased armoring and land subsidence due to aquifer depletion with ever increasing coastal populations (California Natural Resources Agency, 2014). We contend that including current and potential future blockages to habitat expansion will provide a more realistic ('pessimistic") scenario of habitat changes with sea level rise. Accordingly, as detailed under emergent marshes (Section 7.8.4) and tide flats (Section 7.8.6), we derive the habitat thresholds based only on the modeling results predicting habitat losses. Further, we note that the purpose of the habitat thresholds is as a metric to help approximate the population loss of the associated species, and not as a habitat model per se. Thus, the uncertainty in the specific value of the thresholds has less of an impact on the risk values, in particular for the high threshold values exceeding likely SLR scenarios (Table 7-1).

Table 7-3 summarizes both constrained and unconstrained habitat thresholds using four classes based on the percent of habitat loss: minor ($\leq 10\%$ loss), low (11% to 29% loss), moderate (30% to 49% loss), and high ($\geq 50\%$ loss). To the extent practical, the percentages defining the habitat threshold classes were harmonized with the percent population changes used in the population trends as shown in Table 7-4.

Table 7-4. Habitat threshold classes based on the percentage of habitat lost to sea level rise. The Minor class captures cases of minor decreases (to 10%), as well as the possibility of habitat increases with SLR. The corresponding population trends classes for individual invertebrate and fish species are shown in the last column (see Section 4.3.4).

Habitat Threshold Class	Percent Loss in Habitat Area	Corresponding Population Trend Classes			
Minor	0% to -10%	Order of Magnitude Increase (>10x increase) to No Apparent Trend (-29% to +29%)			
Low	-11% to -29%	No Apparent Trend (-29% to +29%)			
Moderate	-30% to -49%	Moderate Decrease (-30 to -49%)			
High	<u>></u> -50%	Substantial Decrease (-50 to -79%) and Extreme Decline (-80 to -99%)			

7.8.2 Rocky Intertidal and Mussel Beds

Rocky intertidal habitats will be inundated with a rising ocean, however there is no consensus on the extent of the impact or how to approach the problem. In part, this reflects that less attention has been paid to the effects of SLR on rocky shores compared to marshes and other soft-sediment habitats. In addressing the vulnerability of this habitat, a key question is whether there is suitable hard substrate upward of the existing rocky intertidal assemblage for upward migration with SLR. Based on limited information, it has been suggested that in areas where the seashore is mostly uniform, the risk to coastal squeeze is low (Kendall et al., 2004) but greater in rocky seashores that have steep inclines and/or are backed by hard cliffs (Jackson and McIlvenny, 2011).

We found only a handful of studies assessing the role of SLR on rocky intertidal habitats on the Pacific Coast. In their development of a "coastal vulnerability index" for the Pacific Coast, Thieler and Hammar-Klose (2000) listed "rocky, cliffed coasts" as very low vulnerability, "medium cliffs" as low vulnerability, and "low cliffs" as moderate vulnerability. In comparison, estuaries, mud flats, salt marshes, mangroves, and other soft-sediment habitats were assigned "high" or "very high" vulnerabilities. Glick et al. (2007) used SLAMM 5.0 to predict SLR effects on multiple habitat types in Puget Sound and along the coast of SW Washington and NW Oregon. For the rocky intertidal, they predicted an average 13% loss with a SLR of 0.28m, a 34% loss with a 0.69 m SLR, and a 70% loss with a 1.5 m SLR (Table 7-5). However, our evaluation of SLAMM Ver. 5 indicated that it does not incorporate the area of the hard substrate above the existing rocky intertidal assemblage (see Clough, 2008). Thus, these are losses with no upward migration potential (bounded predictions) and thereby represent upper estimates of rocky intertidal habitat loss. A Pacific Northwest study that did account for upward migration was an

analysis of the loss of rocky intertidal foraging habitat for the black oystercatcher (*Haematopus bachmani*) at Rabbit Rock, Oregon (Hollenbeck et al., 2014). Using terrestrial laser scanning (TLS), the authors predicted that 10.9% of the rocky intertidal will disappear with a 1 m SLR and 57.3% will disappear with a 2 m SLR (Hollenbeck et al., 2014).

Because of the paucity of information for the Pacific Coast, we developed a GIS-based approach using LIDAR derived digital elevation models (DEMs) to estimate the potential area of the hard substrate upward of the existing intertidal assemblage (Clinton and Lee, 2016). The required data were available for the Southern California Bight, Northern California, Oregonian, and Puget Trough/Georgia Basin ecoregions. In this initial analysis, we include the rocky intertidal mussel beds with the general rocky intertidal habitat thresholds. The GIS methodology and the metadata for this analysis are available in Appendix C-4.

Using this model, the percent of rocky intertidal habitat loss is estimated independently for each of the four ecoregions (Table 7-5). However, until this approach is further evaluated, we believe that it is more appropriate to use the average of the four ecoregions rather than ecoregion-specific values. Based on the averages, the rocky intertidal habitat thresholds are: minor <0.4 m, $low \ge 0.4$ m, moderate ≥ 0.8 m, and high ≥ 1.4 m (Table 7-3). Though we advocate using the averages, the ranges across the four ecoregions can be used as an estimate of uncertainty in evaluating different scenarios. Because the required GIS data are not available in other locations, we use the averages of these four ecoregions as first-order estimates for the other eight ecoregions.

To compare our results from the LIDAR analysis, we evaluated rocky intertidal studies in Scotland and Australia. Jackson and McIlvenny (2011), using a modeling study, stated that with a 0.3 m SLR 10-27% of the rocky intertidal habitat in Scotland would be lost and at 1.9 m SLR, 26-50% would disappear. Thorner et al. (2014) combined LIDAR with high-resolution digital imagery in a study of five rock reefs in Australia. It is difficult to directly compare our regionalscale results with this localized study, in part, because they evaluated vulnerability in seven categories of rocky shore habitats (Table 7-5). Nonetheless, it appears that some of the Australian habitats are more sensitive to SLR than our analysis suggests. In particular, their "deep pools" habitat disappear at four of the five sites at 1 m SLR, a SLR that our LIDAR analysis would classify as moderate (30% to 49% habitat loss). Others of their habitats, such as the upper boulder field and lower platform, have generally similar responses to those predicted by our analysis.

Given the general agreement of previous studies with our analysis, we consider our habitat thresholds based on LIDAR analysis sufficient for a first-order analysis of rocky intertidal habitats on a regional scale. Our approach does not assess risk to specific types of rocky intertidal habitats, such as tide pools, which are likely to be more vulnerable (Thorner et al., 2014). Both tide pools and supralittoral splash pools are identified as specialized habitats in CBRAT, and we recommend that the habitat preferences of rocky intertidal species be evaluated for utilization of these habitats to identify which species may have a greater risk than predicted.

Table 7-5. Studies predicting percentage loss of rocky intertidal habitat due to sea level rise. For Glick et al., 2007, we present both the individual values and the combined values for different SLR scenarios for the five sites. The combined values are those reported by Glick et al., 2007. For Thorner et al., 2014, the predicted percent lost was estimated from their Figure 2 that depicted the percentage of area covered for seven habitat types at five different study sites. Their graphs were divided into quartiles and the results were summarized by counting the number of sites that fell within each quartile. These results are displayed as the number of habitats in each quartile with the highest percent habitat loss on top and the lowest percent habitat loss on the bottom. The habitat threshold classes are Minor: 0-10%, Low: 11-29%, Moderate: 30-49%, and High: >50% habitat loss. The average values for the EPA LIDAR analysis and Glick et al. combined results are highlighted. NI=No Information. TLS = terrestrial laser scanning. Sources: 1 = EPA LIDAR Analysis, 2 = Glick et al., 2007, 3 = Hollenbeck et al., 2014, 4 = Jackson and Mcllvenny, 2011, 5 = Thorner et al., 2014.

Source	Location	Ecoregion	Habitat	SLR in 2100 (mm)	Percent Habitat Loss	Type of Study
1	Puget	Puget Trough/ Georgia Basin	Rocky Intertidal	200	12.8	Modeling (LIDAR)
1	Oregonian	Oregonian	Rocky Intertidal	900	13.4	Modeling (LIDAR)
1	N. CA	Northern California	Rocky Intertidal	400	13.7	Modeling (LIDAR)
1	S. CA	S. California Bight	Rocky Intertidal	200	17.6	Modeling (LIDAR)
1	Average Low Habitat Loss EPA LIDAR	Puget Trough thru S. California	Rocky Intertidal	425	14.4	Modeling (LIDAR)
1	Puget	Puget Trough/ Georgia Basin	Rocky Intertidal	500	29.7	Modeling (LIDAR)
1	Oregonian	Oregonian	Rocky Intertidal	1400	32.6	Modeling (LIDAR)
1	N. CA	Northern California	Rocky Intertidal	800	31.2	Modeling (LIDAR)
1	S. CA	S. California Bight	Rocky Intertidal	400	34.2	Modeling (LIDAR)
1	Average Moderate Habitat Loss EPA LIDAR	Puget Trough thru Southern California	Rocky Intertidal	775	31.9	Modeling (LIDAR)
1	Puget	Puget Trough/ Georgia Basin	Rocky Intertidal	NI	NI	Modeling (LIDAR)

Source	Location	Ecoregion	Habitat	SLR in 2100 (mm)	Percent Habitat Loss	Type of Study
1	Oregonian	Oregonian	Rocky Intertidal	2000	50.1	Modeling (LIDAR)
1	N. CA	Northern California	Rocky Intertidal	1500	50.9	Modeling (LIDAR)
1	S. CA	Southern California Bight	Rocky Intertidal	800	50.7	Modeling (LIDAR)
1	Average High Habitat Loss EPA LIDAR	Oregonian thru Southern California	Rocky Intertidal	1433	50.6	Modeling (LIDAR)
2	Site 1: Nooksack Delta, Lummi Bay, & Bellingham Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	280	13	SLAMM
2	Site 2: Padilla Bay, Skagit Bay, & Port Susan Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	280	4	SLAMM
2	Site 6: Dyes Inlet, Sinclair Inlet, & Bainbridge Island	Puget Trough/ Georgia Basin	Rocky Intertidal	280	4	SLAMM
2	Site 7: Elliott Bay to the Duwamish Estuary	Puget Trough/ Georgia Basin	Rocky Intertidal	280	28	SLAMM
2	Site 11: Willapa Bay, Columbia River Estuary, & Tillamook Bay	Oregonian	Rocky Intertidal	280	22	SLAMM
2	Combined 280 mm SLR	Puget and Oregonian	Rocky Intertidal	280	13	SLAMM
2	Site 1: Nooksack Delta, Lummi Bay, & Bellingham Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	690	41	SLAMM
2	Site 2: Padilla Bay, Skagit Bay, & Port Susan Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	690	12	SLAMM
2	Site 6: Dyes Inlet, Sinclair Inlet, & Bainbridge Island	Puget Trough/ Georgia Basin	Rocky Intertidal	690	6	SLAMM
2	Site 7: Elliott Bay to the Duwamish Estuary	Puget Trough/ Georgia Basin	Rocky Intertidal	690	37	SLAMM
2	Site 11: Willapa Bay, Columbia River Estuary, & Tillamook Bay	Oregonian	Rocky Intertidal	690	62	SLAMM
2	Combined 690 mm SLR	Puget and Oregonian	Rocky Intertidal	690	34	SLAMM

Source	Location	Ecoregion	Habitat	SLR in 2100 (mm)	Percent Habitat Loss	Type of Study
2	Site 1: Nooksack Delta, Lummi Bay, & Bellingham Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	1500	81	SLAMM
2	Site 2: Padilla Bay, Skagit Bay, & Port Susan Bay	Puget Trough/ Georgia Basin	Rocky Intertidal	1500	27	SLAMM
2	Site 6: Dyes Inlet, Sinclair Inlet, & Bainbridge Island	Puget Trough/ Georgia Basin	Rocky Intertidal	1500	53	SLAMM
2	Site 7: Elliott Bay to the Duwamish Estuary	Puget Trough/ Georgia Basin	Rocky Intertidal	1500	44	SLAMM
2	Site 11: Willapa Bay, Columbia River Estuary, & Tillamook Bay	Oregonian	Rocky Intertidal	1500	93	SLAMM
2	Combined 1500 mm SLR	Puget and Oregonian	Rocky Intertidal	1500	70	SLAMM
3	Rabbit Rock, OR	Oregonian	Rocky Intertidal	1000	10.9	Modeling (TLS data)
3	Rabbit Rock, OR	Oregonian	Rocky Intertidal	2000	57.3	Modeling (TLS data)
4	Scotland	North Sea	Rocky Intertidal	300	10-27	Modeling (EDINA DIGIMAP)
4	Scotland	North Sea	Rocky Intertidal	1900	26-50	Modeling (EDINA DIGIMAP)
5	Australia	Tweed-Moreton	Upper Boulder Field	300	2 sites >25 2 sites <25 1 site = 0	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Boulder Field	300	4 sites≥50 1 site >25	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Platform	300	2 sites >25 3 sites <25	Modeling (LIDAR & digital imagery)

Source	Location	Ecoregion	Habitat	SLR in 2100 (mm)	Percent Habitat Loss	Type of Study
5	Australia	Tweed-Moreton	Lower Platform	300	1 site >25 2 sites <25 2 sites increased	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Shallow Pool	300	1 site >75 3 sites = 50 1 site >25	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Shallow Pool	300	2 sites > 50 1 site <25 2 sites increased	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Deep Pool	300	2 sites ≥50 2 sites ≤25 1 sites = 0	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Boulder Field	500	1 site >50 3 sites >25 1 site = 0	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Boulder Field	500	1 site = 100 3 sites ≥75 1 site >50	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Platform	500	2 sites >50 2 sites >25 1 site <25	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Platform	500	1 site = 50 1 site >25 1 site <25 2 sites increased	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Shallow Pool	500	3 sites ≥75 2 sites ≥50	Modeling (LIDAR & digital imagery)

Source	Location	Ecoregion	Habitat	SLR in 2100 (mm)	Percent Habitat Loss	Type of Study
5	Australia	Tweed-Moreton	Lower Shallow Pool	500	1 site >75 2 sites >50 2 sites increased	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Deep Pool	500	3 sites = 100 1 site >75 1 site = 0	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Boulder Field	1000	1 site = 100 1 site >75 2 sites ≥50 1 site >25	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Boulder Field	1000	4 sites >75 1 site >50	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Platform	1000	4 sites ≥75 1 site >25	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Platform	1000	1 site = 75 1 site >50 2 sites ≤25 1 site increased	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Upper Shallow Pool	1000	2 sites = 100 2 sites > 75 1 site >50	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Lower Shallow Pool	1000	4 sites >75 1 sites >50	Modeling (LIDAR & digital imagery)
5	Australia	Tweed-Moreton	Deep Pool	1000	4 sites = 100 1 site = 0	Modeling (LIDAR & digital imagery)

7.8.3 Open Coastal Beaches, Backshore Beach Zones and Algal Beach Wrack Open coast beaches and high intertidal backshore zones surrounding estuaries are often characterized by algal wrack deposited along the driftline. Since these habitats are found at approximately the same elevation, we combine them for the purpose of estimating SLR risk. These habitats are vulnerable due to a number of natural factors and anthropogenic disturbances. Coastal headlands are common along the U.S. West Coast and create littoral cells which contribute to spatial isolation of invertebrate species living in these habitats, making these species particularly vulnerable to habitat loss and fragmentation (Hubbard et al. 2014). This vulnerability is exacerbated by coastal development and human activities (armoring, regular beach grooming and sand nourishment). Southern California has disproportionately degraded beach zones, which has had a substantial impact on the invertebrate community structure, including local extirpations and regional declines of endemic isopods (Hubbard et al. 2014).

Coastal beaches also face threats from SLR and shoreline erosion. As the ocean rises, the narrow bluff-backed beaches where many species of upper beach invertebrate populations persist will have little potential to expand into adjacent habitats. The natural supply of fluvial sediment has been greatly reduced due to upriver dams retaining sediment that historically resupplied eroding beaches and provided some vertical resistance to SLR. In their Coastal Vulnerability Index (CVI), Thieler and Hammar-Klose (2000) classify outer coast sand beaches under the most vulnerable category citing high erosion, low coastal slope and a high rate of SLR as the contributing factors. Hubbard et al. (2014) predicts that only a small fraction (<10%) of the 450 km of Southern California coast will have the potential to provide suitable upper beach habitat under a scenario of 1400 mm of sea level rise by 2100 based on the predictions by Revell et al. (2011) and NOAA (2012). Similarly, Glick et al. (2007) reports an average loss of 98% of Pacific Northwest coastal beaches by 2100 under a 1500 mm SLR scenario.

Both Hubbard et al. (2014) and Glick et al. (2007) predict >90% habitat loss with a SLR of 1400-1500 mm. Because our high habitat threshold is based on a \geq 50% habitat loss, we reduced the SLR values to >800 mm under a constrained scenario and >1000 mm under an unconstrained scenario (Table 7-3). For the low habitat threshold, Glick et al. (2007) predicted a 6% habitat loss of coastal beaches for the Pacific Northwest with a SLR of 690 mm by 2100. From these results, and considering the natural vulnerability of these habitats, we set the constrained and unconstrained SLR minor habitat thresholds at 550 and 650 mm, respectively. We then interpolated between the minor and high habitat thresholds to generate the low and moderate habitat thresholds.

7.8.4 Emergent Marsh

For the purposes of establishing SLR risk, we limited our analysis to the "low" marsh habitat where species such as land crabs, high intertidal amphipods, etc. are commonly found. Other marsh vegetation zones (mid, high or transitional marsh) are not currently considered. Thorne et

al. (2015) defined low marsh as, "the range of elevations from the lowest extent of vegetation at a site to the elevation reached by at least one daily high tide on average". Low marsh in the NEP is characterized by salt tolerant plants including *Sarcocornia perennis* (previously referred to as *Salicornia virginica* in the NEP), *Distichlis spicata, Jaumea carnosa, Agrostis stolonifera, Carex lyngbyei*, and *Triglochin maritima* (e.g., Janousek and Folger, 2012).

In the six papers reviewed (Table 7-6), five of the studies have a similar approach in that they considered land seaward of dikes (constrained) or land seaward of dikes as well as land behind dikes (unconstrained) and let elevation determine the extent of potential intertidal habitat area under different SLR scenarios. One modeling effort, Thorne et al. (2015), created defined marsh areas (ranging from 5 to 97 hectares) and allowed the model to predict habitat expansion or constriction according to site-specific DEMs within each predetermined area. With such a bounded model, a habitat type can expand only if another habitat type is reduced. Thorne et al. (2015) reported their model projections in percent habitat type (total of habitat types =100 %). To compare results across studies, we transformed the percent habitat type into percent habitat change using Equation 2 (dates specific to scenario):

Eq. 2: Percent change in marsh area = ((% of low marsh habitat in 2110 - % low marsh habitat in 2010)/% low marsh habitat in 2010) X 100

Expansion and contractions of marsh vegetation zones are highly variable depending on specific marsh geomorphology, gradient, degree of human development, freshwater flow and other physical parameters. Even with these local effects, most models predict that low marshes will experience a net gain in area by 2100 with low to moderate levels of SLR. In comparison, high marsh habitat will likely experience net losses especially under high rates of SLR. Adding to the complexity, changes in marsh habitat may not vary consistently with the rate of SLR. For low marsh habitat (results averaged across nine estuaries), Thorne et al. (2015) projects a decrease in area under the National Research Council (NCR) low SLR rate (1.2 mm/yr), a very large increase under the mid (6.3 mm/yr) rate, and a more substantial loss of low marsh under the high SLR rate (14.2 mm/yr). Under the NRC high SLR rate, sediment accretion rates will not be able to keep pace resulting in a rapid decline in the low marsh habitat. Eventually, most lower elevation marsh habitat will convert to intertidal mudflats as low marshes are no longer able to sustain themselves through natural feedbacks (e.g., sediment accretion, vegetation growth and organic matter accumulation).

Other analyses, such as Warren Pinnacle Consulting, Inc. (2011) predicted large expansions of low marsh at low, mid and high rates of sea level rise for both their constrained and unconstrained analyses. The unconstrained scenario, in particular, resulted in very large increases in low marsh habitat and consequently large losses in adjacent high marsh and upland habitats.

Table 7-6. Summary of low marsh percent habitat change under different SLR rates. Compiled from six studies and 21 estuaries. Thorne et al. (2015) modeled changes in habitats within a bounded area. Stralberg et al. (2011) evaluated removal of diked areas as did Warren Pinnacle Consulting, Inc. (2011) and Ducks Unlimited (no date) evaluated the effects of SLR maintaining dikes (constrained) and with the removal of dikes (unconstrained). Sources: 1 - Warren Pinnacle Consulting, Inc. 2011; 2 - Ducks Unlimited, no date; 3 - Galbraith et al., 2002; 4 - Glick et al., 2007; 5 - Stralberg et al., 2011; 6 - Thorne et al. 2015.

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Alsea River, OR	390	2100	29.0	expansion	SLAMM 6	Constrained
1	Alsea River, OR	690	2100	35.0	expansion	SLAMM 6	Constrained
1	Alsea River, OR	1000	2100	56.0	expansion	SLAMM 6	Constrained
1	Alsea River, OR	1500	2100	150.0	expansion	SLAMM 6	Constrained
1	Alsea River, OR	2000	2100	145.0	expansion	SLAMM 6	Constrained
1	Alsea River, OR	390	2100	61.0	expansion	SLAMM 6	Unconstrained
1	Alsea River, OR	690	2100	80.0	expansion	SLAMM 6	Unconstrained
1	Alsea River, OR	1000	2100	114.0	expansion	SLAMM 6	Unconstrained
1	Alsea River, OR	1500	2100	201.0	expansion	SLAMM 6	Unconstrained
1	Alsea River, OR	2000	2100	180.0	expansion	SLAMM 6	Unconstrained
1	Chetco River, OR	390	2100	363.0	expansion	SLAMM 6	Constrained
1	Chetco River, OR	690	2100	426.0	expansion	SLAMM 6	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Chetco River, OR	1000	2100	684.0	expansion	SLAMM 6	Constrained
1	Chetco River, OR	1500	2100	1592.0	expansion	SLAMM 6	Constrained
1	Chetco River, OR	2000	2100	3287.0	expansion	SLAMM 6	Constrained
1	Chetco River, OR	390	2100	363.0	expansion	SLAMM 6	Unconstrained
1	Chetco River, OR	690	2100	427.0	expansion	SLAMM 6	Unconstrained
1	Chetco River, OR	1000	2100	685.0	expansion	SLAMM 6	Unconstrained
1	Chetco River, OR	1500	2100	1595.0	expansion	SLAMM 6	Unconstrained
1	Chetco River, OR	2000	2100	3294.0	expansion	SLAMM 6	Unconstrained
1	Coos Bay, OR	390	2100	64.0	expansion	SLAMM 6	Constrained
1	Coos Bay, OR	690	2100	92.0	expansion	SLAMM 6	Constrained
1	Coos Bay, OR	1000	2100	112.0	expansion	SLAMM 6	Constrained
1	Coos Bay, OR	1500	2100	175.0	expansion	SLAMM 6	Constrained
1	Coos Bay, OR	2000	2100	193.0	expansion	SLAMM 6	Constrained
1	Coos Bay, OR	390	2100	270.0	expansion	SLAMM 6	Unconstrained
1	Coos Bay, OR	690	2100	242.0	expansion	SLAMM 6	Unconstrained
1	Coos Bay, OR	1000	2100	205.0	expansion	SLAMM 6	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Coos Bay, OR	1500	2100	219.0	expansion	SLAMM 6	Unconstrained
1	Coos Bay, OR	2000	2100	231.0	expansion	SLAMM 6	Unconstrained
1	Nehalem Bay, OR	390	2100	20.0	expansion	SLAMM 6	Constrained
1	Nehalem Bay, OR	690	2100	28.0	expansion	SLAMM 6	Constrained
1	Nehalem Bay, OR	1000	2100	50.0	expansion	SLAMM 6	Constrained
1	Nehalem Bay, OR	1500	2100	140.0	expansion	SLAMM 6	Constrained
1	Nehalem Bay, OR	2000	2100	187.0	expansion	SLAMM 6	Constrained
1	Nehalem Bay, OR	390	2100	123.0	expansion	SLAMM 6	Unconstrained
1	Nehalem Bay, OR	690	2100	181.0	expansion	SLAMM 6	Unconstrained
1	Nehalem Bay, OR	1000	2100	249.0	expansion	SLAMM 6	Unconstrained
1	Nehalem Bay, OR	1500	2100	354.0	expansion	SLAMM 6	Unconstrained
1	Nehalem Bay, OR	2000	2100	370.0	expansion	SLAMM 6	Unconstrained
1	Nestucca Bay, OR	390	2100	25.0	expansion	SLAMM 6	Constrained
1	Nestucca Bay, OR	690	2100	32.0	expansion	SLAMM 6	Constrained
1	Nestucca Bay, OR	1000	2100	54.0	expansion	SLAMM 6	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Nestucca Bay, OR	1500	2100	151.0	expansion	SLAMM 6	Constrained
1	Nestucca Bay, OR	2000	2100	124.0	expansion	SLAMM 6	Constrained
1	Nestucca Bay, OR	390	2100	132.0	expansion SLAMM 6		Unconstrained
1	Nestucca Bay, OR	690	2100	163.0	expansion	SLAMM 6	Unconstrained
1	Nestucca Bay, OR	1000	2100	177.0	expansion	SLAMM 6	Unconstrained
1	Nestucca Bay, OR	1500	2100	240.0	expansion	SLAMM 6	Unconstrained
1	Nestucca Bay, OR	2000	2100	180.0	expansion	SLAMM 6	Unconstrained
1	Rogue River, OR	390	2100	1721.0	expansion	SLAMM 6	Constrained
1	Rogue River, OR	690	2100	2082.0	expansion	SLAMM 6	Constrained
1	Rogue River, OR	1000	2100	2883.0	expansion	SLAMM 6	Constrained
1	Rogue River, OR	1500	2100	6225.0	expansion	SLAMM 6	Constrained
1	Rogue River, OR	2000	2100	11795.0	expansion	SLAMM 6	Constrained
1	Rogue River, OR	390	2100	1723.0	expansion	SLAMM 6	Unconstrained
1	Rogue River, OR	690	2100	2085.0	expansion	SLAMM 6	Unconstrained
1	Rogue River, OR	1000	2100	2890.0	expansion	SLAMM 6	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Rogue River, OR	1500	2100	6244.0	expansion	SLAMM 6	Unconstrained
1	Rogue River, OR	2000	2100	11835.0	expansion	SLAMM 6	Unconstrained
1	Siuslaw R., OR	390	2100	54.0	expansion SLAMM 6		Constrained
1	Siuslaw R., OR	690	2100	73.0	expansion	SLAMM 6	Constrained
1	Siuslaw R., OR	1000	2100	113.0	expansion	SLAMM 6	Constrained
1	Siuslaw R., OR	1500	2100	128.0	expansion	SLAMM 6	Constrained
1	Siuslaw R., OR	2000	2100	118.0	expansion	SLAMM 6	Constrained
1	Siuslaw R., OR	390	2100	143.0	expansion	SLAMM 6	Unconstrained
1	Siuslaw R., OR	690	2100	127.0	expansion	SLAMM 6	Unconstrained
1	Siuslaw R., OR	1000	2100	137.0	expansion	SLAMM 6	Unconstrained
1	Siuslaw R., OR	1500	2100	149.0	expansion	SLAMM 6	Unconstrained
1	Siuslaw R., OR	2000	2100	134.0	expansion	SLAMM 6	Unconstrained
1	Umpqua R., OR	390	2100	62.0	expansion	SLAMM 6	Constrained
1	Umpqua R., OR	690	2100	92.0	expansion	SLAMM 6	Constrained
1	Umpqua R., OR	1000	2100	145.0	expansion	SLAMM 6	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Umpqua R., OR	1500	2100	232.0	expansion	SLAMM 6	Constrained
1	Umpqua R., OR	2000	2100	217.0	expansion	SLAMM 6	Constrained
1	Umpqua R., OR	390	2100	304.0	expansion	SLAMM 6	Unconstrained
1	Umpqua R., OR	690	2100	355.0	expansion	SLAMM 6	Unconstrained
1	Umpqua R., OR	1000	2100	365.0	expansion	SLAMM 6	Unconstrained
1	Umpqua R., OR	1500	2100	349.0	expansion	SLAMM 6	Unconstrained
1	Umpqua R., OR	2000	2100	286.0	expansion	SLAMM 6	Unconstrained
2	Grays Harbor, OR	690	2100	35.0	expansion	SLAMM 6	Constrained
2	Lower Columbia	690	2100	-18.9	loss	SLAMM 6	Constrained
2	Lower Columbia	690	2100	134.1	expansion	SLAMM 6	Unconstrained
2	North Puget Sound	690	2100	2.2	expansion	SLAMM 6	Constrained
2	Willapa Bay, WA	690	2100	-6.4	loss	SLAMM 6	Constrained
3	Humboldt Bay, CA	200	2100	72.6	expansion	SLAMM 4	Constrained
3	Humboldt Bay, CA	340	2100	175.6	expansion	SLAMM 4	Constrained
3	Humboldt Bay, CA	770	2100	1886.0	expansion	SLAMM 4	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
3	Northern San Francisco Bay	200	2100	0.0	no change	SLAMM 4	Constrained
3	Northern San Francisco Bay	340	2100	0.0	0.0 no change		Constrained
3	Northern San Francisco Bay	770	2100	-18.1	-18.1 loss		Constrained
3	Southern San Francisco Bay	200	2100	-50.7	loss	SLAMM 4	Constrained
3	Southern San Francisco Bay	340	2100	-63.2	loss	SLAMM 4	Constrained
3	Southern San Francisco Bay	770	2100	-82.9	loss	SLAMM 4	Constrained
3	Willapa Bay, WA	200	2100	12.8	expansion	SLAMM 4	Constrained
3	Willapa Bay, WA	340	2100	10.5	expansion	SLAMM 4	Constrained
3	Willapa Bay, WA	770	2100	12.8	expansion	SLAMM 4	Constrained
4	Annas Bay and Skokomish estuary	690	2100	49.0	expansion	SLAMM 5	Constrained
4	Annas Bay and Skokomish estuary	1500	2100	48.9	expansion	SLAMM 5	Constrained
4	Dyes & Sinclair Inlet and Bainbridge Is.	690	2100	4388.0	expansion	SLAMM 5	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
4	Dyes & Sinclair Inlet and Bainbridge Is.	1500	2100	5250.0	expansion	SLAMM 5	Constrained
4	Nooksack, Lummi & Bellingham Bays	690	2100	469.0	expansion	SLAMM 5	Constrained
4	Nooksack, Lummi & Bellingham Bays	1500	2100	1786.8	expansion	SLAMM 5	Constrained
4	Nooksack, Lummi & Bellingham Bays	690	2100	3927.0	expansion	SLAMM 5	Unconstrained
4	Olympia, Budd Inlet & Nisqually Delta	690	2100	422.0	expansion	SLAMM 5	Constrained
4	Olympia, Budd Inlet & Nisqually Delta	1500	2100	501.9	expansion	SLAMM 5	Constrained
4	Olympia, Budd Inlet & Nisqually Delta	690	2100	1059.0	expansion	SLAMM 5	Unconstrained
4	Padilla, Skagit & Port Susan Bays	690	2100	96.0	expansion	SLAMM 5	Constrained
4	Padilla, Skagit & Port Susan Bays	1500	2100	41.2	expansion	SLAMM 5	Constrained
4	Padilla, Skagit & Port Susan Bays	690	2100	1115.0	expansion	SLAMM 5	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
4	Port Angeles, Dungeness Spit & Sequim Bay	690	2100	65.0	expansion	SLAMM 5	Constrained
4	Port Angeles, Dungeness Spit & Sequim Bay	1500	2100	190.5	expansion	SLAMM 5	Constrained
4	Snohomish estuary & Everett	690	2100	1522.0	expansion	SLAMM 5	Constrained
4	Snohomish estuary & Everett	1500	2100	1431.0	expansion	SLAMM 5	Constrained
4	Snohomish estuary & Everett	690	2100	7548.0	expansion	SLAMM 5	Unconstrained
4	Whidbey Is., Port Townsend, Admiralty Inlet	690	2100	814.0	expansion	SLAMM 5	Constrained
4	Whidbey Is., Port Townsend, Admiralty Inlet	1500	2100	496.5	expansion	SLAMM 5	Constrained
4	Willapa, Columbia & Tillamook Bay	690	2100	6.0	expansion	SLAMM 5	Constrained
4	Willapa, Columbia & Tillamook Bay	1500	2100	29.9	expansion	SLAMM 5	Constrained
5	San Francisco Bay (Tidal + diked lands)	520	2110	40.0	expansion	Marsh98	Constrained (with dike removal)

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
5	San Francisco Bay (Tidal + diked lands)	1650	2110	108.0	expansion	Marsh98	Constrained (with dike removal)
5	San Francisco Bay (Tidal only)	520	2110	-24.0	-24.0 loss		Constrained
5	San Francisco Bay (Tidal only)	1650	2110	53.3	expansion	Marsh98	Constrained
6	Bandon Marsh, OR	120	2110	2.0	expansion	WARMER	Constrained
6	Bandon Marsh, OR	630	2110	59.1	expansion	WARMER	Constrained
6	Bandon Marsh, OR	Bando n Marsh, OR	2110	-100.0	loss	WARMER	Constrained
6	Coos Bay, OR	120	2110	-100.0	loss	WARMER	Constrained
6	Coos Bay, OR	630	2110	-100.0	loss	WARMER	Constrained
6	Coos Bay, OR	1420	2110	-100.0	loss	WARMER	Constrained
6	Grays Harbor, WA	120	2110	-100.0	loss	WARMER	Constrained

As is apparent from Table 7-6, the predicted responses of lower marshes to SLR are complex. To extract SLR thresholds from these "messy" data, we made two simplifying assumptions. Firstly, at this stage, we ignore non-linear responses (i.e., greater habitat loss at a lower SLR). This assumption may underestimate habitat loss at the minor and low habitat thresholds. Secondly, we derive the habitat thresholds only from the sites with habitat losses. Evaluating sites only with losses is a "pessimistic" scenario resulting from reduced potential for landward migration as a result of increased construction of barriers, such as rip rap, to protect against sea level rise and/or land subsidence. In these cases, sites that were predicted to increase may not be able to migrate

landward as they would have done historically, resulting in a habitat decline with SLR. Such a scenario is certainly not out of the realm of possibilities as social and financial pressures mount to protect infrastructure and shoreline development, especially with increased population densities in coastal areas (King et al., 2011; California Natural Resource Agency, 2014).

At the highest SLR values, it is also possible that the sediment load would be insufficient for sediment accumulation to keep pace with SLR (Stralberg et al. 2011). Much of the West Coast is predicted to experience longer periods of summer drought further reducing the supply of sediment from upriver sources. Further uncertainty stems from the possibility of increased winter storms generating wave erosion at the lower end of marshes and additional erosion from seawalls at the upper end of marshes (Stralberg et al. 2011; CA Natural Resource Agency, 2014). Thus, use of the pessimistic scenario may better capture future impacts. However, in the absence of increased barriers and/or insufficient sediment load, deriving the thresholds from the sites with losses ignores the increases in other marshes, overestimating the extent of habitat loss at an ecoregion scale.

In evaluating the constrained lower marshes (Figure 7-2), some sites showed some minor loss ($\leq 10\%$) of marsh at 120 mm SLR but then a quarter of the sites experienced high (>50%) habitat loss at 200 mm SLR. This indicates that the minor habitat threshold occurs between these two values. Taking the average, we set the cut point between minor and low thresholds at 160 mm. Based on the spike of almost 78% of the sites with high habitat loss at a SLR value of 1420 mm, we use this value as the cut point between moderate and high habitat thresholds. The cut point between the low and moderate thresholds is then generated by taking the average of these values, resulting in a value of 790 mm.

Model results for the unconstrained lower marshes all predict that low marsh habitat will expand continuously with SLR based on the assumption that there are adequate adjacent lands of similar elevation to expand into. Because the modelling results do not identify the cutpoints, we tentatively suggest setting the minor threshold at 2500 mm based on the potential for limited sediment accretion. For the other thresholds, we tentatively added cumulative increments of 250 mm to estimate the higher cutpoints. With all the models predicting increases up to the maximum tested of 2000 mm, it is reasonable to assume that associated species would be at 'minor' or 'low' risk at most likely levels of sea level rise in unconstrained lower marshes (see Table 7-1). Therefore, the exact cut points are not as critical in this habitat compared to a habitat that is expected to decrease.



Figure 7-2. Low marsh habitat – Constrained.

This values represent the percentage of sites in the six papers analyzed that fell within each of the habitat threshold categories (Minor, Low, Moderate, High). Only sites with predicted habitat losses are included in the analysis.

7.8.5 Submerged Aquatic Vegetation

Submerged aquatic vegetation (SAV) is a term used to describe a suite of rooted, vascular plants that grow completely underwater except for periods of exposure at low tides. Species of SAV are often referred to as seagrasses. Eight species of seagrasses occur on the Pacific Coast (Wyllie-Echeverria and Ackerman, 2003), including the nonindigenous *Zostera japonica* (Kaldy, 2006), however we focus on the native *Z. marina*. *Z. marina* is the most abundant seagrass in estuaries in the NEP (Lee and Brown, 2009) and ranges from the Bering Sea into the Gulf of California (Wyllie-Echeverria and Ackerman, 2003; Shaughnessy et al., 2012). Though SLR has been considered a threat to seagrasses for almost two decades (Short and Neckles, 1999), there are relative few studies compared to marshes. Here we synthesize two published models on SLR and the research conducted by EPA. The reason for fewer studies on seagrasses appears to be a result, at least in part, that earlier versions of the often used SLAMM model did not predict effects on SAV. We addressed this limitation by creating a module to SLAMM Ver. 6 that allows users to predict SLR effects on *Zostera* (Lee et al., 2014). Unfortunately, we have not had the resources to use this tool in a regional study of sea level rise effects.

Shaughnessy et al. (2012) modeled SLR effects on seagrass area for a period of 100 years for seven estuaries located from Alaska to Mexico. Modeling combinations of low and high bottom

change (estuarine specific sediment and tectonic rates) with three levels of SLR produced six scenarios at each location. The low SLR rate scenario (2.8 mm/yr) was from the current estimated SLR rate for the Pacific Ocean basin based on satellite altimetry, the moderate SLR rate scenario (6.3 mm/yr) was derived from the mean rate estimated for the period 2090-2099 for IPCC AR4 scenario AI FI (Meehl et al., 2007), and the high SLR rate scenario (12.7 mm/yr) was based on a study linking global sea level rise to projections of global mean surface temperature (Rahmstorf, 2007).

Shaughnessy et al. (2012) predicted that seagrass habitat would increase or only show minor change with SLR at most locations (Table 7-7). Five estuaries that were not topographically constrained and had sufficient available upslope area for migration, experienced a greater increase in seagrass area under moderate and high SLR than with low SLR. However, seagrass declined at the topographically constrained Morro Bay under moderate and high SLR. In north Humboldt Bay, SAV showed declines at "high bottom change" with both low and moderate SRL and with "low bottom change" with low SLR. When averaged across all locations and scenarios, these models predicted a 15.2% increase in SAV with SLR. However, the authors pointed out that barriers to landward migration of SAV had not been encountered in the 100 year simulations in several of the estuaries. Once the water level rises to the point of encountering these barriers, *Z. marina* would likely decline in the subtidal portion of the population due to light extinction. Thus, habitat loss may increase in the longer term.

In a detailed modeling study by Kairis and Rybczyk (2010) of Padilla Bay, WA, seagrass area increased (7.9 to 43.7%) with increasing SLR until leveling off (37.4%) at the highest SLR rate. The authors modeled eight different SLR rates, ranging from 1.714 to 18.182 mm/yr over a 100-year period. In this shallow bay, *Z. marina* was predicted to migrate from the center of the bay shoreward, colonizing the extensive mudflats. We note that while this model appears to be constrained, by colonizing the existing mudflats the expansion of *Z. marina* was not limited by dikes or other barriers.

The EPA constructed a SLR model for SAV based on geomorphological features that was applied to the Yaquina, Tillamook, and Alsea estuaries in Oregon (Clinton et al., 2012). Based on the topobathy, these models allowed landward migration of intertidal habitats. However, since the model did not incorporate sediment accumulation, we consider the results as more closely approximating a constrained condition. The model predicted an increase in *Z. marina* in the Alsea with SLR, but it should be noted that there currently is very little *Zostera* in the Alsea. In comparison, seagrass is an important habitat in both the Yaquina and Tillamook estuaries (Lee and Brown, 2009), and *Z. marina* is predicted to decline by 31% and 68% with a 1 m SLR in these estuaries, respectively.

Using the EPA results as a guide for constrained seagrass, a >50% loss was observed in Tillamook at SLR of 750 and 1000 mm but not in Yaquina. This range suggests, that on the

average, a \geq 50% loss would occur at about a meter increase in depth, and we tentatively set a high constrained threshold at >900 mm. The moderate constrained threshold thus becomes \leq 900 mm. At 500 mm, Yaquina and Tillamook showed a 21% and 40% loss, though Alsea showed a 35% increase. The average of these three sites is an 8.6% loss. From these rates, we set the minor constrained threshold at 540 mm. The low constrained threshold was then set as the average of the minor and moderate thresholds, or 720 mm.

Generating the unconstrained values are even more challenging since the current models predict that they will increase in most cases. Thus, there is likely to be a mosaic of effects, with some areas within an ecoregion increasing and other declining due to factors such as sediment accretion not keeping up with sea level rise. Additionally, there may be some bias in these studies toward areas with few barriers to inland migration, such a Padilla Bay versus other portions of Puget Sound which show extensive armoring (Washington State Department of Natural Resources, no date; Myers, 2010). Given these uncertainties, as a tentative first step, we double the constrained threshold values, resulting in unconstrained thresholds for SAV of 1080 mm for minor, 1440 mm for low, 1800 mm for moderate, and >1800 mm for high.

Table 7-7. <u>Submerged Aquatic Vegetation (*Zostera marina*), s</u>ummary of seagrass percent habitat change under different SLR values.

1

Compiled from three studies and eleven estuaries. The percent area of SAV in Clinton et al. (2012) were converted to percent SAV loss. Sources: 1 = Kairis and Rybczyk, 2010; 2 = Clinton et al., 2012; 3 = Shaughnessy et al., 2012.

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
1	Padilla Bay, WA	170	2102	8	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	330	2102	22	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	560	2102	34	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	560	2102	34	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	640	2102	37	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	860	2102	41	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	1270	2102	44	expansion	Spatial Relative Elev. Model	Constrained
1	Padilla Bay, WA	1820	2102	-37	loss	Spatial Relative Elev. Model	Constrained
2	Alsea, OR	250	2100	9.6	expansion	Geomorphological topobathy model	Constrained
2	Alsea, OR	500	2100	35.4	expansion	Geomorphological topobathy model	Constrained
2	Alsea, OR	750	2100	41.7	expansion	Geomorphological topobathy model	Constrained
2	Alsea, OR	1000	2100	39.6	expansion	Geomorphological topobathy model	Constrained
2	Tillamook, OR	250	2100	-18	loss	Geomorphological topobathy model	Constrained
2	Tillamook, OR	500	2100	-40	loss	Geomorphological topobathy model	Constrained
2	Tillamook, OR	750	2100	-59	loss	Geomorphological topobathy model	Constrained
2	Tillamook, OR	1000	2100	-68	loss	Geomorphological topobathy model	Constrained
2	Yaquina, OR	250	2100	-14	loss	Geomorphological topobathy model	Constrained
2	Yaquina, OR	500	2100	-21	loss	Geomorphological topobathy model	Constrained
2	Yaquina, OR	750	2100	-28	loss	Geomorphological topobathy model	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
2	Yaquina, OR	1000	2100	-31	loss	Geomorphological topobathy model	Constrained
3	Bahia San Quintin, Mexico	280	2112	1	no change	Low accretion, low SLR	Unconstrained
3	Bahia San Quintin, Mexico	630	2112	5	no change	Low accretion, moderate SLR	Unconstrained
3	Bahia San Quintin, Mexico	1270	2112	25	expansion	Low accretion, high SLR	Unconstrained
3	Bahia San Quintin, Mexico	280	2112	11	expansion	High accretion, low SLR	Unconstrained
3	Bahia San Quintin, Mexico	630	2112	0	no change	High accretion, moderate SLR	Unconstrained
3	Bahia San Quintin, Mexico	1270	2112	15	expansion	High accretion, high SLR	Unconstrained
3	lzembek Lagoon, AK	280	2112	8	no change	Low accretion, low SLR	Unconstrained
3	lzembek Lagoon, AK	630	2112	19	expansion	Low accretion, moderate SLR	Unconstrained
3	lzembek Lagoon, AK	1270	2112	16	expansion	Low accretion, high SLR	Unconstrained
3	lzembek Lagoon, AK	280	2112	1	no change	High accretion, low SLR	Unconstrained
3	lzembek Lagoon, AK	630	2112	14	expansion	High accretion, moderate SLR	Unconstrained
3	lzembek Lagoon, AK	1270	2112	21	expansion	High accretion, high SLR	Unconstrained
3	Morro Bay, CA	280	2112	-1	loss	Low accretion, low SLR	Unconstrained
3	Morro Bay, CA	630	2112	22	expansion	Low accretion, moderate SLR	Unconstrained
3	Morro Bay, CA	1270	2112	-45	loss	Low accretion, high SLR	Unconstrained
3	Morro Bay, CA	280	2112	-64	loss	High accretion, low SLR	Unconstrained
3	Morro Bay, CA	630	2112	2	no change	High accretion, moderate SLR	Unconstrained
3	Morro Bay, CA	1270	2112	-6	no change	High accretion, high SLR	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
3	North Humboldt Bay, CA	280	2112	-30	loss	Low accretion, low SLR	Unconstrained
3	North Humboldt Bay, CA	630	2112	18	expansion	Low accretion, moderate SLR	Unconstrained
3	North Humboldt Bay, CA	1270	2112	87	expansion	Low accretion, high SLR	Unconstrained
3	North Humboldt Bay, CA	280	2112	-63	loss	High accretion, low SLR	Unconstrained
3	North Humboldt Bay, CA	630	2112	-5	no change	High accretion, moderate SLR	Unconstrained
3	North Humboldt Bay, CA	1270	2112	64	expansion	High accretion, high SLR	Unconstrained
3	Padilla Bay complex, WA	280	2112	10	no change	Low accretion, low SLR	Unconstrained
3	Padilla Bay complex, WA	630	2112	16	expansion	Low accretion, moderate SLR	Unconstrained
3	Padilla Bay complex, WA	1270	2112	15	expansion	Low accretion, high SLR	Unconstrained
3	Padilla Bay complex, WA	280	2112	4	no change	High accretion, low SLR	Unconstrained
3	Padilla Bay complex, WA	630	2112	11	expansion	High accretion, moderate SLR	Unconstrained
3	Padilla Bay complex, WA	1270	2112	17	expansion	High accretion, high SLR	Unconstrained
3	South Humboldt Bay, CA	280	2112	6	no change	Low accretion, low SLR	Unconstrained
3	South Humboldt Bay, CA	630	2112	27	expansion	Low accretion, moderate SLR	Unconstrained
3	South Humboldt Bay, CA	1270	2112	68	expansion	Low accretion, high SLR	Unconstrained
3	South Humboldt Bay, CA	280	2112	-6	no change	High accretion, low SLR	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion / Loss	Model Type	Upper habitat constrained in model?
3	South Humboldt Bay, CA	630	2112	14	expansion	High accretion, moderate SLR	Unconstrained
3	South Humboldt Bay, CA	1270	2112	64	expansion	High accretion, high SLR	Unconstrained
3	Willapa Bay, WA	280	2112	12	expansion	Low accretion, low SLR	Unconstrained
3	Willapa Bay, WA	630	2112	46	expansion	Low accretion, moderate SLR	Unconstrained
3	Willapa Bay, WA	1270	2112	106	expansion	Low accretion, high SLR	Unconstrained
3	Willapa Bay, WA	280	2112	-6	loss	High accretion, low SLR	Unconstrained
3	Willapa Bay, WA	630	2112	27	expansion	High accretion, moderate SLR	Unconstrained
3	Willapa Bay, WA	1270	2112	94	expansion	High accretion, high SLR	Unconstrained

7.8.6 Tide Flats - Unvegetated Sand/Mud & Oyster Beds & Macroalgal Mats

The beaches and tidal flats of the Pacific Northwest are vulnerable to the rising sea-level over the next century based on the four studies we reviewed (Table 7-8). Under a 693 mm global average sea-level rise scenario, about 65 percent of estuarine beaches and 44 percent of tidal flats are predicted to be lost across all eleven study sites by 2100 according to the 2007 analysis by Glick et al. This degree of loss will likely cause significant changes in the coastal landscape. For example, Dungeness Spit, WA is predicted to be subject to inundation, erosion, and overwash due to storm events, leading to major losses of beach and tidal flat habitats (Glick et al. 2007). A reduction in intertidal habitat corresponds to reduced yields of commercial oyster production as well as recreationally harvested bivalve species. Such declines in shellfish harvesting may have significant impacts on small coastal economies in Oregon and Washington (Norman et al., 2007).

Galbraith et al. 2002, using a constrained dike data layer, predicts major intertidal habitat loss at all four of their West Coast study sites. Willapa Bay, Humboldt Bay, and northern and southern San Francisco Bay are predicted to lose between 20% and 70% of their current intertidal habitat. They predict the most severe losses are likely to occur in the areas where the coastline is unable to move inland because of steep topography or seawalls. In sharp contrast to Galbraith et al. (2002), Thorne et al. (2015), whose study was also considered constrained, predicts that more than one-half of their study sites under a high SLR scenario resulted in very large (near 100%)

increases in mudflat habitat as a result of low tidal marsh transitioning into mudflat; suggesting that rates of net accretion cannot keep pace with rising sea levels.

Table 7-8. Summary of tide flat percent habitat change under different SLR rates. Compiled from four studies and 23 estuaries. Ducks Unlimited (no date) evaluated the effects of dike removal in the lower Columbia. Warren Pinnacle Consulting, Inc. (2011) evaluated the effects of SLR with dikes (constrained) and with dike removal (unconstrained). Sources: 1 - Ducks Unlimited, no date; 2 -Galbraith et al., 2002; 3 - Glick et al., 2007; 4 - Thorne et al., 2015; 5 - Warren Pinnacle Consulting, Inc. 2011. NA's indicate that the original habitat area was zero thus making the Equation 2 undefined.

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
1	Grays Harbor, WA	690	2100	35	expansion	SLAMM 6	Constrained
1	Willapa Bay, WA	690	2100	-6	loss	SLAMM 6	Constrained
1	Lower Columbia	690	2100	-19	loss	SLAMM 6	Constrained
1	North Puget Sound	690	2100	2	expansion	SLAMM 6	Constrained
1	Lower Columbia	690	2100	134	expansion	SLAMM 6	Unconstrained
2	Willapa Bay, WA	historic	2100	-1	loss	SLAMM 4	Constrained
2	Humboldt Bay	historic	2100	0	loss	SLAMM 4	Constrained
2	Northern San Francisco Bay, CA	historic	2100	-4	loss	SLAMM 4	Constrained
2	Southern San Francisco Bay, CA	historic	2100	-54	loss	SLAMM 4	Constrained
2	Humboldt Bay	340	2100	-29	loss	SLAMM 4	Constrained
2	Northern San Francisco Bay, CA	340	2100	-39	loss	SLAMM 4	Constrained
2	Southern San Francisco Bay, CA	340	2100	-70	loss	SLAMM 4	Constrained
2	Willapa Bay, WA	340	2100	-18	loss	SLAMM 4	Constrained
2	Humboldt Bay, CA	770	2100	-91	loss	SLAMM 4	Constrained
2	Northern San Francisco Bay, CA	770	2100	-81	loss	SLAMM 4	Constrained
2	Southern San Francisco Bay, CA	770	2100	-83	loss	SLAMM 4	Constrained
2	Willapa Bay, WA	770	2100	-62	loss	SLAMM 4	Constrained
3	Nooksack, Lummi & Bellingham Bays	690	2100	22	expansion	SLAMM 5	Constrained
Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
--------	--	-------------	--------------------	------------------------	--------------------	---------------	---
3	Padilla, Skagit & Po. Susan Bays	690	2100	613	expansion	SLAMM 5	Constrained
3	Whidbey Is., Po. Townsend, Admiralty Inlet	690	2100	1425	expansion	SLAMM 5	Constrained
3	Snohomish estuary & Everett	690	2100	411	expansion	SLAMM 5	Constrained
3	Port Angeles, Dungeness Spit & Sequim Bay	690	2100	-81	expansion	SLAMM 5	Constrained
3	Dyes & Sinclair Inlet and Bainbridge Is.	690	2100	1916	expansion	SLAMM 5	Constrained
3	Elliot Bay & the Duwamish estuary	690	2100	319	expansion	SLAMM 5	Constrained
3	Annas Bay and Skokomish estuary	690	2100	67.3	expansion	SLAMM 5	Constrained
3	Commencement Bay, Tacoma & Gig Harbor	690	2100	12.5	expansion	SLAMM 5	Constrained
3	Olympia, Budd Inlet & Nisqually Delta	690	2100	50.7	expansion	SLAMM 5	Constrained
3	Willapa, Columbia & Tillamook Bay	690	2100	-63	loss	SLAMM 5	Constrained
3	Nooksack, Lummi & Bellingham Bays	690	2100	75	expansion	SLAMM 5	Unconstrained
3	Padilla, Skagit & Port Susan Bays	690	2100	1559	expansion	SLAMM 5	Unconstrained
3	Snohomish estuary & Everett	690	2100	2422	expansion	SLAMM 5	Unconstrained
3	Olympia, Budd Inlet & Nisqually Delta	690	2100	NA	expansion	SLAMM 5	Unconstrained
3	Nooksack, Lummi & Bellingham Bays	1500	2100	95	expansion	SLAMM 5	Constrained
3	Padilla, Skagit & Po. Susan Bays	1500	2100	869	expansion	SLAMM 5	Constrained
3	Whidbey Is., Port Townsend & Admiralty Inlet	1500	2100	1565	expansion	SLAMM 5	Constrained
3	Snohomish estuary & Everett	1500	2100	706	expansion	SLAMM 5	Constrained
3	Port Angeles, Dungeness Spit & Sequim Bay	1500	2100	-82	loss	SLAMM 5	Constrained
3	Dyes & Sinclair Inlet and Bainbridge Is.	1500	2100	1411	expansion	SLAMM 5	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
3	Elliot Bay & the Duwamish estuary	1500	2100	611	expansion	SLAMM 5	Constrained
3	Annas Bay and Skokomish estuary	1500	2100	58.2	expansion	SLAMM 5	Constrained
3	Commencement Bay, Tacoma & Gig Harbor	1500	2100	22.7	expansion	SLAMM 5	Constrained
3	Olympia, Budd Inlet & Nisqually Delta	1500	2100	64.6	expansion	SLAMM 5	Constrained
3	Willapa, Columbia & Tillamook Bay	1500	2100	-63	loss	SLAMM 5	Constrained
4	Bandon Marsh, OR	120	2110	0	no change	WARMER	Constrained
4	Coos Bay, OR	120	2110	0	no change	WARMER	Constrained
4	Grays Harbor, WA	120	2110	0	no change	WARMER	Constrained
4	Nisqually National	120	2110	0	no change	WARMER	Constrained
4	Padilla Marsh, WA	120	2110	0	no change	WARMER	Constrained
4	Port Susan Bay, WA	120	2110	0	loss	WARMER	Constrained
4	Siletz Bay, OR	120	2110	0	no change	WARMER	Constrained
4	Skokomish Estuary, WA	120	2110	0	no change	WARMER	Constrained
4	Willapa Bay, WA	120	2110	0	no change	WARMER	Constrained
4	Bandon Marsh, OR	630	2110	100	expansion	WARMER	Constrained
4	Coos Bay, OR	630	2110	100	expansion	WARMER	Constrained
4	Grays Harbor, WA	630	2110	0	no change	WARMER	Constrained
4	Nisqually National, WA	630	2110	0	no change	WARMER	Constrained
4	Padilla Marsh, WA	630	2110	0	no change	WARMER	Constrained
4	Port Susan Bay, WA	630	2110	-50	loss	WARMER	Constrained
4	Siletz Bay, OR	630	2110	0	no change	WARMER	Constrained
4	Skokomish Estuary, WA	630	2110	67	expansion	WARMER	Constrained
4	Willapa Bay, WA	630	2110	0	no change	WARMER	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
4	Bandon Marsh, OR	1420	2110	100	expansion	WARMER	Constrained
4	Coos Bay, OR	1420	2110	100	expansion	WARMER	Constrained
4	Grays Harbor, WA	1420	2110	0	no change	WARMER	Constrained
4	Nisqually National, WA	1420	2110	100	expansion	WARMER	Constrained
4	Padilla Marsh, WA	1420	2110	100	expansion	WARMER	Constrained
4	Port Susan Bay, WA	1420	2110	96	expansion	WARMER	Constrained
4	Siletz Bay, OR	1420	2110	100	expansion	WARMER	Constrained
4	Skokomish Estuary, WA	1420	2110	99	expansion	WARMER	Constrained
4	Willapa, OR	1420	2110	100	expansion	WARMER	Constrained
5	Alsea River, OR	390	2100	-3	loss	SLAMM 6	Constrained
5	Alsea River, OR	690	2100	-4	loss	SLAMM 6	Constrained
5	Alsea River, OR	1000	2100	-9	loss	SLAMM 6	Constrained
5	Alsea River, OR	1500	2100	-41	loss	SLAMM 6	Constrained
5	Alsea River, OR	2000	2100	-53	loss	SLAMM 6	Constrained
5	Alsea River, OR	390	2100	-3	loss	SLAMM 6	Unconstrained
5	Alsea River, OR	690	2100	-3	loss	SLAMM 6	Unconstrained
5	Alsea River, OR	1000	2100	-9	loss	SLAMM 6	Unconstrained
5	Alsea River, OR	1500	2100	-39	loss	SLAMM 6	Unconstrained
5	Alsea River, OR	2000	2100	-48	loss	SLAMM 6	Unconstrained
5	Chetco River, OR	390	2100	-21	loss	SLAMM 6	Constrained
5	Chetco River, OR	690	2100	-26	loss	SLAMM 6	Constrained
5	Chetco River, OR	1000	2100	-32	loss	SLAMM 6	Constrained
5	Chetco River, OR	1500	2100	-40	loss	SLAMM 6	Constrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
5	Chetco River, OR	2000	2100	-46	loss	SLAMM 6	Constrained
5	Chetco River, OR	390	2100	-21	loss	SLAMM 6	Unconstrained
5	Chetco River, OR	690	2100	-26	loss	SLAMM 6	Unconstrained
5	Chetco River, OR	1000	2100	-32	loss	SLAMM 6	Unconstrained
5	Chetco River, OR	1500	2100	-40	loss	SLAMM 6	Unconstrained
5	Chetco River, OR	2000	2100	-46	loss	SLAMM 6	Unconstrained
5	Coos Bay, OR	390	2100	-9	loss	SLAMM 6	Constrained
5	Coos Bay, OR	690	2100	-14	loss	SLAMM 6	Constrained
5	Coos Bay, OR	1000	2100	-14	loss	SLAMM 6	Constrained
5	Coos Bay, OR	1500	2100	-14	loss	SLAMM 6	Constrained
5	Coos Bay, OR	2000	2100	-11	loss	SLAMM 6	Constrained
5	Coos Bay, OR	390	2100	-1	loss	SLAMM 6	Unconstrained
5	Coos Bay, OR	690	2100	11	expansion	SLAMM 6	Unconstrained
5	Coos Bay, OR	1000	2100	14	expansion	SLAMM 6	Unconstrained
5	Coos Bay, OR	1500	2100	2	expansion	SLAMM 6	Unconstrained
5	Coos Bay, OR	2000	2100	-1	loss	SLAMM 6	Unconstrained
5	Nehalem Bay, OR	390	2100	-7	loss	SLAMM 6	Constrained
5	Nehalem Bay, OR	690	2100	-9	loss	SLAMM 6	Constrained
5	Nehalem Bay, OR	1000	2100	-13	loss	SLAMM 6	Constrained
5	Nehalem Bay, OR	1500	2100	-20	loss	SLAMM 6	Constrained
5	Nehalem Bay, OR	2000	2100	-19	loss	SLAMM 6	Constrained
5	Nehalem Bay, OR	390	2100	-4	loss	SLAMM 6	Unconstrained
5	Nehalem Bay, OR	690	2100	-4	loss	SLAMM 6	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
5	Nehalem Bay, OR	1000	2100	-5	loss	SLAMM 6	Unconstrained
5	Nehalem Bay, OR	1500	2100	-2	loss	SLAMM 6	Unconstrained
5	Nehalem Bay, OR	2000	2100	13	expansion	SLAMM 6	Unconstrained
5	Nestucca River, OR	390	2100	-6	loss	SLAMM 6	Constrained
5	Nestucca River, OR	690	2100	-4	loss	SLAMM 6	Constrained
5	Nestucca River, OR	1000	2100	-4	loss	SLAMM 6	Constrained
5	Nestucca River, OR	1500	2100	-1	loss	SLAMM 6	Constrained
5	Nestucca River, OR	2000	2100	19	expansion	SLAMM 6	Constrained
5	Nestucca River, OR	390	2100	-5	loss	SLAMM 6	Unconstrained
5	Nestucca River, OR	690	2100	-3	loss	SLAMM 6	Unconstrained
5	Nestucca River, OR	1000	2100	4	expansion	SLAMM 6	Unconstrained
5	Nestucca River, OR	1500	2100	20	expansion	SLAMM 6	Unconstrained
5	Nestucca River, OR	2000	2100	47	expansion	SLAMM 6	Unconstrained
5	Rogue River, OR	390	2100	-18	loss	SLAMM 6	Constrained
5	Rogue River, OR	690	2100	-18	loss	SLAMM 6	Constrained
5	Rogue River, OR	1000	2100	-20	loss	SLAMM 6	Constrained
5	Rogue River, OR	1500	2100	-24	loss	SLAMM 6	Constrained
5	Rogue River, OR	2000	2100	-30	loss	SLAMM 6	Constrained
5	Rogue River, OR	390	2100	-18	loss	SLAMM 6	Unconstrained
5	Rogue River, OR	690	2100	-18	loss	SLAMM 6	Unconstrained
5	Rogue River, OR	1000	2100	-20	loss	SLAMM 6	Unconstrained
5	Rogue River, OR	1500	2100	-24	loss	SLAMM 6	Unconstrained
5	Rogue River, OR	2000	2100	-30	loss	SLAMM 6	Unconstrained

Source	Location	SLR (mm)	Projection Year	% Habitat Change	Expansion /Loss	Model Type	Upper habitat constrained in model?
5	Siuslaw River, OR	390	2100	-6	loss	SLAMM 6	Constrained
5	Siuslaw River, OR	690	2100	-10	loss	SLAMM 6	Constrained
5	Siuslaw River, OR	1000	2100	-15	loss	SLAMM 6	Constrained
5	Siuslaw River, OR	1500	2100	-9	loss	SLAMM 6	Constrained
5	Siuslaw River, OR	2000	2100	-5	loss	SLAMM 6	Constrained
5	Siuslaw River, OR	390	2100	2	expansion	SLAMM 6	Unconstrained
5	Siuslaw River, OR	690	2100	6	expansion	SLAMM 6	Unconstrained
5	Siuslaw River, OR	1000	2100	7	expansion	SLAMM 6	Unconstrained
5	Siuslaw River, OR	1500	2100	8	expansion	SLAMM 6	Unconstrained
5	Siuslaw River, OR	2000	2100	4	expansion	SLAMM 6	Unconstrained
5	Umpqua River, OR	390	2100	0	expansion	SLAMM 6	Constrained
5	Umpqua River, OR	690	2100	3	expansion	SLAMM 6	Constrained
5	Umpqua River, OR	1000	2100	-5	loss	SLAMM 6	Constrained
5	Umpqua River, OR	1500	2100	-24	loss	SLAMM 6	Constrained
5	Umpqua River, OR	2000	2100	-8	loss	SLAMM 6	Constrained
5	Umpqua River, OR	390	2100	7	expansion	SLAMM 6	Unconstrained
5	Umpqua River, OR	690	2100	17	expansion	SLAMM 6	Unconstrained
5	Umpqua River, OR	1000	2100	29	expansion	SLAMM 6	Unconstrained
5	Umpqua River, OR	1500	2100	43	expansion	SLAMM 6	Unconstrained
5	Umpqua River, OR	2000	2100	50	expansion	SLAMM 6	Unconstrained

The tide flats were similar to the marshes in that the models predicted increases at a number of sites. To address this, we treat the tide flats, and associated oyster beds, like the low marshes and focus on the sites with predicted losses (Figure 7-3 and Figure 7-4). At a SLR of 390 mm with the unconstrained tide flats, 50% of the sites had predicted declines of <10% (minor habitat threshold) and 25% of the sites had losses between 11% and 29% (low habitat threshold). No

sites had moderate habitat losses (\geq 30%). Given the number of sites predicted to have a less than a 10% loss, we use 390 mm as the minor habitat threshold. At 1000 mm, both the minor and low percent losses each equaled 25% of the sites but moderate losses now constitute 12.5% of the sites. The onset of sites with losses >30% suggests that a SLR value of 1000 mm is a justifiable threshold between the low and moderate habitat threshold classes. The proportion of sites with moderate habitat losses increases up to a SLR of 2000 mm, but no sites have predicted losses >50%, indicating the high habitat threshold is greater than this value. To approximate the break between moderate and high thresholds, we increase the 2000 mm value to 2250 mm to capture substantial effects on tide flats, though this value should be evaluated in SLAMM or other models.



Figure 7-3. Tide flats - Unconstrained.

The values represent the percentage of sites that fall within each habitat threshold categories (Minor, Low, Moderate, High) under various SLR amounts. Only sites with predicted habitat losses are included in the analysis.



Figure 7-4. Tide flats - Constrained.

The values represent the percentage of sites that fall within each habitat threshold categories (Minor, Low, Moderate, High) under various SLR amounts. Only sites with predicted habitat losses are included in the analysis.

7.8.7 Mangroves

Mangrove forests are critical intertidal ecosystems occurring throughout the subtropics and tropics (FAO, 2007; Spalding et al., 2010). Within the NEP, mangroves are abundant in both the Gulf of California and the Magdalena ecoregions. The northern limit of mangroves in the Eastern Pacific is *Rhizophora mangle* found just north of Laguna San Ignacio at the northern tip of the Magdalena Transition Ecoregion, while *Laguncularia racemosa* is first found just to the south (Spalding et al., 2010). Compared to the Indo-West Pacific (see Polidoro et al., 2010), the diversity of mangrove species is low in the NEP, with only four species: *Avicennia germinans, Rhizophora mangle* (referred to as *Rhizophora samoensis* by Polidoro et al., 2010), *Laguncularia racemosa*, and *Conocarpus erectus*. While recognizing that the relative abundances of these four species will vary among individual mangrove forests, we evaluate mangroves in toto without reference to the individual species.

The mangroves in the Gulf of California are already under stress, decreasing at an annual rate of about 2% because of sedimentation, eutrophication and deforestation (Aburto-Oropeza et al., 2008, Lopez-Medellin et al., 2011). Over an 8-year period between 1973 and 1981 there was a

23% decline in the mangroves in La Paz due to development (Aburto-Oropeza et al., 2008). Sea level rise is now added as an additional stressor. As with other intertidal vegetated habitats, the sediment accretion rate is a key factor determining the long-term effects of SLR (Gilman et al., 2008). Accordingly, the two most vulnerable mangrove forests are low-relief carbonate islands with low rates of sedimentation and little available upland space and arid, semi-arid, and dry sub-humid regions which also have limited sediment inputs (Webber et al., 2016). Examples of vulnerable mangrove forests are those found on low lying keys composed of carbonate sediments. The least vulnerable are those occurring along macrotidal coastlines with significant riverine inputs and high accretion rates (Webber et al., 2016). Under these conditions, mangroves can keep pace with SLR. McIvor et al. (2013) listed locations of mangroves around the world along with the rates of SLR, ranging between 0.85 mm/yr to 10 mm/yr, in which each mangrove forest was able to "keep pace with" SLR via accretion. Though semi-arid, the mangroves in Baja and the Gulf of California appear to tend more towards the less vulnerable category based on the reports of inland migration.

Mangroves have shown an ability to migrate inland with rising water levels. In Magdalena Bay, the landward margins of mangroves have shown a significant increase with SLR (Lopez-Medellin et al., 2011). There has been more than a 20% increase in the canopy cover in Magdalena Bay, with mangrove saplings now growing in the landward mudflats (Lopez-Medellin et al., 2011). A consequence of this inland migration is the loss of marshes, salt flats, and mudflats. In another study, a SLAMM model predicted reductions in salt marsh and oligohaline marsh areas with increased mangrove areas in Tampa Bay, Florida (Meyer, 2013). However, these increases are for mangroves as a group and individual species respond differently. Specifically, the species on the seaward side may be more vulnerable (Lopez-Medellin et al. (2011).

Table 7-9 summarizes 16 papers on how mangroves respond to SLR. One set of these studies evaluated the historical response to sea level rise during the Holocene while the other studies modeled future changes in response to SLR. The Holocene studies relate changes to rates of SLR (mm/yr) and do not report the total SLR (mm), which are the basis of the habitat thresholds. Additionally, some of the initial Holocene studies were alarming. Based on a reconstruction of mangrove responses to SLR during the Holocene, Ellison and Stoddart (1991) concluded that mangroves in low islands would not persist with a SLR rise of 12 cm per 100 years (1.2 mm/yr). However, it has been pointed out that mangroves survived in Key West, Florida at a rate of 19 cm per 100 years (McIovr et al., 2013) and recent reviews (e.g., Alongi, 2015; Godoy and de Lacerda, 2015; Woodroffe et al., 2016) indicated that many, if not most, mangrove systems are relatively robust to sea level rise.

To set habitat threshold values, we focused on the modeling studies and used the Holocene studies with approximately similar environments to Baja and the Gulf of Mexico as a check.

Only two of the studies pushed their models to determine the SLR associated with a \geq 50% decline in mangroves. Geselbracht et al. (2015) had a 59% reduction in mangrove forest at 2000 mm SLR while Warren Pinnacle Consulting, Inc. (2014) predicted a 50%, 62%, and 64% reduction in mangrove cover at 1200 mm, 1500 mm, and 2000 mm SLR, respectively. To generate the high habitat threshold, we averaged the 2000 mm from Geselbracht et al. (2015) with the 1200 mm result from Warren Pinnacle Consulting, Inc. (2014), for a value of >1600 mm. This then sets the moderate threshold at 1600 mm (Table 7-3). The minor habitat threshold is the net SLR that results in \leq 10% loss, and possible gains, which we generated from the lower end of the modeling results. Three studies showed declines of 5 to 13% at SLR of 290 mm to 880 mm. Another two showed increases of 35% at SLR of 640 mm and 700 mm. Based on this range, we set the minor habitat threshold at 750 mm, a value that should not result in substantial effects on mangroves not starved of sediment. To estimate the low habitat threshold, we interpolated between the minor and moderate thresholds to generate a value of 1150 mm.

Table 7-9. Summary of mangroves percent habitat change under different SLR values and rates. Compiled from 16 studies. Modeling studies reported results in sea level rise (mm) while the Holocene studies reported sea level rise rates (mm/yr). ND = no data. Sources: 1 - Geselbracht et al., 2015; 2 -Warren Pinnacle Consulting, Inc. 2014; 3 - Traill et al., 2011; 4 - Di Nitto et al, 2014; 5 - Seddon et al., 2011; 6 - McKee et al., 2007; 7 - Ellison, 2000; 8 - Fujimoto et al., 1996; 9 - Woodroffe and Mulrennan, 1993; 10 - Woodroffe, 1990; 11 - Woodroffe, 1990 (in Woodroffe, 1995); 12 - Maul and Martin, 1993 (in Snedaker et al., 1994); 13 - Parkinson, 1989 (in Snedaker et al., 1994); 14 - Woodroffe, 1995 (in McIvor et al., 2013); 15 - Woodroffe, 1990 (in McIvor et al., 2013); 16 - Ellison and Stoddart, 1991.

Source	Location	Year Projected to / Time Period	SLR (mm)	SLR Rates (mm/yr)	% Habitat Change	Expansion / Loss	Model / Scenario
1	Estuaries in Florida's Gulf Coast	2100	700	ND	+35	expansion	SLAMM
1	Estuaries in Florida's Gulf Coast	2100	1000	ND	+40	expansion	SLAMM
1	Estuaries in Florida's Gulf Coast	2100	2000	ND	- 59	loss	SLAMM
2	US Coastline of Gulf of Mexico	2100	500	ND	- 10	loss	SLAMM
2	US Coastline of Gulf of Mexico	2100	1000	ND	- 39	loss	SLAMM

Source	Location	Year Projected to / Time Period	SLR (mm)	SLR Rates (mm/yr)	% Habitat Change	Expansion / Loss	Model / Scenario
2	US Coastline of Gulf of Mexico	2100	1200	ND	- 50	loss	SLAMM
2	US Coastline of Gulf of Mexico	2100	1500	ND	- 62	loss	SLAMM
2	US Coastline of Gulf of Mexico	2100	2000	ND	- 64	loss	SLAMM
3	Southeast Queensland, Australia	2100	290	ND	- 5	loss	SLAMM
3	Southeast Queensland, Australia	2100	640	ND	+ 35	expansion	SLAMM
3	Southeast Queensland, Australia	2100	1790	ND	- 19	loss	SLAMM
4	Gazi Bay, Kenya, East Africa	2100	90	ND	+ (0-?)	expansion	Computer Modeling
4	Gazi Bay, Kenya, East Africa	2100	200	ND	+ (0-?)	expansion	Computer Modeling
4	Gazi Bay, Kenya, East Africa	2100	480	ND	+ (0-?)	expansion	Computer Modeling
4	Gazi Bay, Kenya, East Africa	2100	880	ND	- 13	loss	Computer Modeling
5	Diablas lagoon, Isabela Island, Galapagos	Since 2700 years BP	ND	5.7	- 10	loss	Holocene Analysis
6	Twin Cays, Caribbean	Since 8000 years BP	ND	3.5	+ (0-?)	expansion	Holocene Analysis

Source	Location	Year Projected to / Time Period	SLR (mm)	SLR Rates (mm/yr)	% Habitat Change	Expansion / Loss	Model / Scenario
6	Twin Cays, Caribbean	Since 7600 years BP	ND	5	- 100	loss	Holocene Analysis
7	Low islands	Holocene	ND	1.2	- (0–10)	loss	Holocene analysis
7	High Islands	Holocene	ND	4.5	- (0–10)	loss	Holocene analysis
8	Kosrae Island, Micronesia	Since 5000 years BP	ND	< 2	- (0–10)	loss	Holocene Analysis
8	Kosrae Island, Micronesia	Since 5000 years BP	ND	2–10	- (10–50)	loss	Holocene Analysis
8	Kosrae Island, Micronesia	Since 5000 years BP	ND	> 10	- (50–100)	loss	Holocene Analysis
9	Australia	Since 6790 years BP	ND	10	- (0–10)	loss	Holocene analysis
10	Multiple studies	Since 6500 years BP	ND	5–8	- (0–10)	loss	Holocene analysis
10	Multiple studies	Since 6500 years BP	ND	8–10	- (10–50)	loss	Holocene analysis
10	Multiple studies	Since 6500 years BP	ND	10–15	- (50–100)	loss	Holocene analysis
11	Northern Australian Estuaries	Not Specified	ND	5-8	- (0–10)	loss	Holocene analysis
12	Key West, Florida	1925-1992	ND	2.3	- (0–10)	loss	1846-1992 data analysis (in Literature Review)
13	Ten Thousand Island region of Florida	Not Specified	ND	2.7	- (0–10)	loss	Holocene analysis (in Literature Review)
14	Northern Australian estuaries	Not Specified	ND	8-10	- (0–10)	loss	Holocene analysis

Source	Location	Year Projected to / Time Period	SLR (mm)	SLR Rates (mm/yr)	% Habitat Change	Expansion / Loss	Model / Scenario
15	South Alligator tidal river	Not Specified	ND	0.2–6	- (0–10)	loss	Holocene analysis
16	Worldwide, low islands?	Not Specified	ND	0.8–0.9	- (0–10)	loss	Holocene analysis
16	Worldwide, low islands?	Not Specified	ND	0.9–1.2	- (10–50)	loss	Holocene analysis
16	Worldwide, low islands?	Not Specified	ND	>1.2	- (0–50)	loss	Holocene analysis
16	South Florida	last 4000- 5000 years	ND	0.46	- (0–10)	loss	Holocene analysis
16	South Florida	last 4000- 5000 years	ND	0.98	- (0–10)	loss	Holocene analysis

7.9 Sea Level Rise Risks for Invertebrate and Fish Species

The habitat thresholds predict the percent loss of major habitat types with SLR. The next step is to translate these habitat losses into impacts on the populations of the invertebrate and fish species associated with the various habitats. As a first-order assumption, we assume that the population decline in the target species is proportional to the loss in its habitat area. This is easiest to visualize with sedentary species, such as barnacles, where the species attaches to the habitat. But even with mobile species, over sufficient time periods, we assume the population equilibrates to the available area, especially at regional scales. This is not a necessary assumption and it would be possible to incorporate "habitat loss for specific habitat types. However, we are unware of information indicating that such non-linear responses to habitat loss are an important general phenomenon with near-coastal species.

Two biotic traits used to assess the relative importance of a habitat to a species are the species' depth preferences and habitat preferences (Figure 7-1). Combined with the concept of high and low exposure habitats (Section 7.7), we produced a SLR risk matrix (Table 7-10). The values in Table 7-10 are global and apply to all ecoregions, but users have the option to modify these values in CBRAT on an ecoregion-by-ecoregion basis.

Table 7-10. Risk values assigned to each combination of depth, habitat and exposure classes for each habitat threshold.

or nabitat, i	ici. – picic	neu uepin e	n nabitat.					
Habitat Threshold	Pref. High Exposure & No Low Exposure Depth	Pref. High Exposure & Obs. Low Exposure Depth	Pref. High Exposure & Pref. Low Exposure Depth	Obs. High Exposure & No Low Exposure Depth	Obs. High Exposure & Obs. Low Exposure Depth	Obs. High Exposure & Pref. Low Exposure Depth	No High Exposure & Obs. Low Exposure Depth	No High Exposure & Pref. Low Exposure Depth
Minor	0	0	0	0	0	0	0	0
Low	-1	-1	-1	-1	-1	-1	0	0
Moderate	-2	-1	-1	-1	-1	-1	0	0
High	-3	-2	-2	-1	-1	-1	0	0

Risks in this table are global values meaning that the same risks are applied to all ecoregions. Risk classifications are: minor risk = 0; low risk = -1; moderate risk = -2; high risk = -3. Obs. = observed depth or habitat.

7.9.1 Depth Preferences

Depth preferences of the target species are used to approximate what proportion of species' population occurs intertidally, and thus is potentially vulnerable to sea level rise. CBRAT uses a three-level classification system for depth classification (Lee et al., 2015). For the current SLR risk algorithm, it is only necessary to use the Level II classifications (e.g., intertidal and neritic) for benthic species and the Level I classification for pelagic species. However, classifying these depth classes as observed versus preferred (see Section 4.1.1) has a major influence on the assigned risk since it is assumed that only a relatively small proportion of the population occurs at depths classified as observed versus the majority of the population occurring in depth(s) classified as preferred.

Depth is divided into high exposure and low exposure depth classes (Section 7.7), with the high exposure classes directly affected by SLR and the low exposure classes minimally affected. Because most species occur in multiple depth classes, a set of rules is used to approximate the extent of the population captured by different combinations of observed and preferred depth classes (Table 7-10). An example is a species with preferred high exposure class(es) and no low exposure class(es). These are exclusively intertidal species, the highest SLR risk scenario. At the other end of the spectrum are species with preferred low exposure classes and no high exposure classes. These are subtidal or pelagic species, and they are assigned a minor (0) risk across all habitat thresholds. One intermediate scenario is a species with preferred high exposure depth classes and an observed low exposure depth classes. Since the majority of the population is predicted to be in an exposed depth, we do not downgrade the risk compared to exclusively

intertidal species. The other intermediate scenario is a species with a preferred low exposure class and just an observed high exposure class. In this case, the assumption is that only a small portion of the population would be vulnerable to SLR, and thus the risk would be downgraded to low (-1).

7.9.2 Habitat Preferences

As with depth preferences, habitat preferences are used to predict where the majority of the population occurs. In this iteration of the SLR model, organisms are keyed to the Level I or Level II Ecosystem/Habitat classes in CBRAT (see Lee et al., 2015). For example, under Unconsolidated Ecosystems (Level I), an organism can be linked to SAV or to mangroves (Level II), but the SLR analysis does not consider the Level III habitats, such as the specific species of SAV or mangrove.

7.9.3 Final SLR Risk

If a species only occurred in one habitat, the risk would be determined from depth and the habitat threshold. However, many, if not most, coastal species occupy more than one habitat type. For example, of the 366 brachyuran crabs, 310 occurred in at least two distinct 2nd level habitat classifications. To address occupancy of multiple habitat types, the risk based on habitat thresholds and depth preferences are modified by the combination of observed and preferred habitat classifications of the target species (Table 7-10). The rules are based on the assumption that the majority of the population occurs in the preferred habitat(s). In cases with occupation of multiple habitats, risk is calculated for each habitat independently with the final SLR risk assigned as the greatest risk among the preferred habitats.

Assessing risk in poorly studied species for which it is not possible to identify preferred habitats or depths is more complicated. Of the four cases (Table 7-10):

In the case of "Observed High Exposure & No Low Exposure Depth", the species has only been reported only from intertidal habitat(s) but it is not known whether this is a preferred habitat or what the preferred depths are. Because of the uncertainty, the risk is downgraded by one class compared to the "Preferred High Exposure & No Low Exposure Depth" (exclusively intertidal) scenario. This results in a moderate risk (-2) with high habitat thresholds and low risk (-1) at moderate to low habitat thresholds.

In the case of "Observed High Exposure & Observed Low Exposure Depth", it is again known that the species occurs in an intertidal habitat, but it is also known that the species extends into the subtidal (or pelagic). Based on the available information, it is assumed that a smaller portion of the population occurs in the intertidal and is thus less vulnerable to sea level rise. For these poorly known intertidal and subtidal species, we assign a low risk (-1) for low to high habitat thresholds. The "Observed High Exposure & Preferred Low Exposure Depth" captures species that are primarily subtidal but also occur in the intertidal. Because the available information indicates that the majority of the population would not be vulnerable to SLR, the risks are set to low (-1) for low to high habitat thresholds.

The last case, "No High Exposure & Observed Low Exposure Depth" captures species that are only known from the subtidal, though it is not known if this is the preferred depth range. Given the uncertainty, these species are assigned a minor (0) risk.

While these cases with only observed habitats are necessary for completeness, only 34 of the 366 brachyuran crabs currently do not have a preferred habit

Section 8. Uncertainty Analysis and Quality Assurance/Quality Control

8.1 Uncertainty Analysis - Overview

Uncertainty analysis is a key component of risk assessments. In this section, we address the strategy for conducting an uncertainty analysis for our climate framework. The full uncertainty analysis will be conducted as part of the climate risk analysis for crabs, bivalves, and rockfish (Lee et al., in progress). Our approach to uncertainty draws from several sources, including the IPCC (Mastrandrea et al., 2010), Integrated Environmental Health Impact Assessment System (http://www.integrated-assessment.eu/eu/index.html, Salway and Shaddick, no date), and Planque et al. (2011). Though the specifics differ slightly among these sources, the key steps for a qualitative uncertainty analysis based on Salway and Shaddick are:

- 1. Identification of uncertainty sources
- 2. Qualitative characterization of uncertainty in terms of:
 - a. direction and magnitude of uncertainty on the results
 - b. knowledge about the uncertainty source
- 3. Reporting of qualitative uncertainties in a non-technical summary

We address identification and characterization of uncertainties in Section 8.2 and the reporting of uncertainties in Section 8.3. Section 8.4 provides the documentation required under the Western Ecology Division's Quality Management Plan.

8.2 Sources and Levels of Uncertainty

Table 8-1 lists the major sources of uncertainty related to the biotic traits and an estimate of their level of uncertainty. We also list examples of major uncertainties related to the numerical climate values and the risk assessment model, specifically the climate thresholds and model assumptions. A full analysis of thresholds and assumptions will be provided with the risk assessment.

Table 8-1. Preliminary analysis of the major sources of uncertainty in the climate risk framework.

Uncertainty levels for biotic traits are derived from estimated percentages of misclassifications. Uncertainty levels for climate projections, thresholds, and major assumptions are preliminary qualitative estimates; quantitative evaluations from sensitivity studies will replace these as part of the formal risk assessment. The "Directionality of Uncertainty" are estimates of whether errors in the parameter are more likely to overestimate risk, underestimate risk, or are random. Sections indicates the primary sections in this document where the parameter is discussed in terms of generating risks.

Parameter	Level of Uncertainty	Directionality of Uncertainty	Sections	Comments
		Biotic	Fraits	
Global distributions	Low	Overestimates risks	4.2	Errors most likely underestimate global distributions, especially in tropics.
Abundance classifications	Low	Random	3.3	Only need to identify abundant or rare species, depending upon the rule.
Depth preferences	Low	Random	5.4, 7.9.1	-
Habitat preferences			7.8	-
Breeding type	Low	Random	6.4	-
Nonindigenous species	Moderate	Underestimates risk	4.2.8	Biggest source of uncertainty is whether an NIS is established in Asia.
Population trends	Moderate	Underestimates risks	4.3.4	In absence of evidence, defaulted to "no apparent trend", which likely underestimated the number of species with population declines.
Transients	Low	Random	4.3.6	Uncertainty in distinguishing rare species vs. a non-established vagrant.
Habitat specialization	Low	Random	4.4.3	-
Trophic specialization	Low	Random	4.4.4	-
Symbiotic relationship	Moderate	Overestimates risks	4.4.2	The major source of uncertainty is the unknown response of the hosts to climate change; assume that hosts impacted.
Anadromous / Catadromous	Low	Random	4.4.5	-

Parameter	Level of Uncertainty	Directionality of Uncertainty	Sections	Comments
Productivity parameters	Low	Random	4.4.6	Fish only.
	Histo	ues and Proje	ections	
Historical SSTs – AVHRR (Cortezian to Eastern Bering)	Low (Estuaries Moderate)	Random	5.3	Values in Puget Trough/Georgia Basin Ecoregion may not be as accurate. SST values for offshore, not in estuaries though at regional scales there should be general correspondence.
Historical SSTs – AVHRR (Chukchi and Beaufort)	Moderate	Underestimates risks?	5.3	Substantial loss of winter data results in higher annual mean. Small differences in mean temperatures between Chukchi and Beaufort are susceptible to small errors.
Historical SST – CMIP5	Low? (Estuaries Moderate)	Random	5.4	CMIP5 is at too coarse a resolution for estuaries.
Historical 30-m and 100-m depth temperatures – CMIP5	Low? (Estuaries Moderate to High?)	Random?	5.4	Subsurface temperatures only very generally applicable to estuaries.
Projected SST and subsurface temperature increases	Moderate (Estuaries Moderate to High)	Random?	5.4	Will evaluate min and max models in risk assessment. Subsurface temperatures only very generally applicable to estuaries.
Historical temperatures - Air	Low	Random	5.4	Moderate to High for the Puget Trough/Georgia Basin because of averaging temperatues to the north and south.
				Will evaluate min and max models in risk assessment.
Projected temperature - Air	Moderate	Random?	5.4	Moderate to High for the Puget Trough/Georgia Basin because of averaging projections to the north and south.
Historical aragonite saturation state values	Low? (Estuaries Moderate to High?)	Random?	6.2.2	-
Projected aragonite saturation values	Moderate (Estuaries Moderate to High)	Random?	6.2.2	-
Historical pH values	Low? (Estuaries Moderate?)	Random	6.2.1	CMIP5 is at too coarse a resolution for estuaries.

Parameter	Level of Uncertainty	Directionality of Uncertainty	Sections	Comments
Projected pH values	Moderate (Estuaries Moderate to High?)	Random	6.2.1	-
Projected sea level rise	Moderate?	Underestimates risks?	7.3	Several models projected greater sea level rise. Limited isostatic rates in several ecoregions.
		Climate Th	resholds	
ETW thresholds based on SDs around mean in WOE	Low?	Random	5.3.3	-
BTL thresholds based on bins between WOE and NWUE	Moderate? (High for Magdalena and Cortezian)	Underestimates risks	5.4.2	From S. California north, the BTL underestimated risk compared to the ETW in about 13% of the cases. Overestimated risk in Magdalena and Cortezian.
pH & aragonite saturation state	High	Random?	6.3	Relatively small changes in the MATC values can have large impacts on risk. Changes in classification of species as high, moderate, or low sensitivity can have large impacts on risk.
SLR habitat thresholds	Moderate?	Overestimates risk	7.8	In many localities, in absence of barriers, SAV, lower marsh, and mangrove can stay up with SLR by migrating inland.
		Major Assumption	ons (Example	s)
Warm edge limits are determined by direct and indirect effects of temperature.	Low	Overestimates risks	Appendix D	When temperature is not the direct/indirect cause for the absence of a species in a warmer ecoregion, assigning temperature as the cause overestimates the temperature risk.
Warm genotypes from southern ecoregions will colonize northern ecoregions as they warm.	Moderate	Underestimates risks	5.3.2	Violation results in greater thermal risk in northern ecoregions.
Ocean projections for pH and aragonite saturation are indicative of estuarine risk.	High	Unknown	6.1	Current regional-scale models are at too coarse a resolution to generate estuarine projections.

The IPCC provides guidance for quantitatively calibrated levels of confidence (Mastrandrea et al., 2010) that we adapted to evaluate levels of uncertainty (Table 8-2). For abundance and biotic trait classifications, we can estimate the confidence levels based on the likely number of misclassifications for the corresponding classes. For example, there are 704 crab species X ecoregion combinations that have an abundance classification. Based on our interactions with experts at several workshops, we estimate the error rate for abundance classifications is less than 20% (\leq 140 misclassifications) and potentially less than 10% (\leq 70 misclassifications). Thus, we assign a low uncertainty to this parameter, especially considering it is only necessary to identify the rare or abundant species, depending upon the rule. There may be greater uncertainty in the assignment of depth range as observed versus preferred, but we estimate that this parameter has less than a 20% error rate, and is also assigned a low level of uncertainty. A more detailed analysis, as will be conducted with the risk assessments, would evaluate whether different confidence levels should be applied to abundant species versus rare species, which are less well known.

Adapted from Mastrandrea et al. (2010). We derived the "Uncertainty Levels in Current Analysis" based on the IPCC guidance.											
Level of	Degree of Confidence	Uncertainty Level in									
Confidence	in Being Correct	Current Analysis									

Low

Low

Moderate

High

High

At least 9 out of 10 chance

About 8 out of 10

About 5 out of 10

About 2 out of 10

Less than 1 out of 10

Table 8-2. Level of confidence adapted from the IPCC.

Very high

High

Medium

Low

Very low

The translation of the criteria in Table 8-2 to numerical parameters and model structure is less clear than for the biotic traits. Rather, we use the criteria listed in Salway and Shaddick for qualitative risk assessments:

"The magnitude of uncertainty is rated low when it is judged that large changes within the source of uncertainty would have only a small effect on the assessment results and when the values of the data sets needed for the assessment are known. A designation of medium implies that a change within the source of uncertainty is likely to have a moderate effect on the results and the values of the data sets needed for the assessment are unknown (completely or partially). A characterization of high implies that a small change in the source would have a large effect on results and the values of the data sets needed for the assessment are unknown."

For the numerical parameters and thresholds, determining whether a "small" change in their values would have minor or large effects on the results will be addressed by conducting

simulation studies as part of the risk assessment. In the interim, we provide preliminary qualitative assessments of uncertainty in Table 8-1.

8.3 Reporting of Uncertainty

The detailed reporting of uncertainties will be presented in the risk assessment report (Lee et al., in progress). However, we provide here a preliminary report on the overall assessment of the uncertainties:

- There is less uncertainty in the biogeographical patterns of risk for a taxon overall and the taxonomic patterns of risks among taxa than for an individual species.
- Greatest uncertainty for risks is associated with ocean acidification.
- Least uncertainty is for risk associated with temperature (other than Magdalena and Cortezian ecoregions).
- The lack of sufficient spatial resolution in the available regional-scale climate predictions of temperature and pH changes in estuaries increases the uncertainty associated with estuarine organisms.
- The habitat thresholds are the greatest source of uncertainty in the SLR algorithm.
- For some species, the actual risks associated with low and moderate risk classifications may be underestimated because of stressor interactions and/or unmodeled effects (e.g., disease).
- Predictions are sufficient to identify the scope and patterns of risk and for regional-scale adaptation planning.
- Predictions are sufficient to flag high risk versus low risk commercial/recreational species but not sufficient for fisheries management.

8.4 EPA/ORD's Quality Assurance/Quality Control

This research falls under ORD's quality assurance Category B. The research presented in this report was conducted under the following Quality Assurance/Quality Control documents:

Standard Operating Procedure:

Lee II, H., Marko, K., Hanshumaker, M., Folger, C., and Graham, R. 2015. User's Guide & Metadata to Coastal Biodiversity Risk Analysis Tool (CBRAT): Framework for the Systemization of Life History and Biogeographic Information. EPA Report. EPA/601/B-15/001. 123 pages.

Quality Assurance Project Plans (QAPPs):

Secondary Data Collection and Analysis for Estuarine Ecosystem Services Research Project: Multi-Scalar Benthic Indicators, Estuary Scale, Regional Scale, and Estuarine Global Climate Change Tasks. QAPP-NHEERL/WED/PCEB/HL/2009-01-r0.

Coastal Biodiversity Risk Assessment Tool (CBRAT): Assessing impacts of individual and multiple climate stressors on near-coastal species at a regional scale Air Climate and Energy (ACE) Program. E-WED-0030833.

Quality Management Plan:

Quality Management Plan, Western Ecology Division (WED), National Health and Environmental Effects Research Laboratory (NHEERL), Office of Research and Development, United States Environmental Protection Agency. Corvallis, Oregon. QMP-NHEERL/WED/1995-01-r4.0.

Electronic Notebook:

This project archives significant project documents in an electronic notebook (MS OneNote) in accordance with Office of Research and Development (ORD) PPM 13.6, *Scientific Recordkeeping*: Electronic. The One Note electronic notebook is not intended to be inclusive of all electronic records used in the project but rather is seen as a starting point for an electronic records structure for consistency and as a valuable resource for all researchers involved with the project.

Quality Objectives and Criteria for Existing Measurement Data:

Nearly all the data entered into CBRAT will be existing information available from the scientific literature, published books, and scientific databases. Existing or secondary data is defined as information previously collected for other projects or intended applications. Potential limitations on the use of the existing data for CBRAT are best appreciated with respect to their original intended application. To facilitate this understanding, the source(s) of the information is documented for each species in CBRAT in the 'Comments' section including full references for each original data source. Every species also has a 'References' page that lists the papers, reports, databases, and personal communications that are linked to that particular species. Other data, including species relative abundance and population trends, are generated from key literature specific to each taxonomic group and potentially augmented by expert opinion. The result of this quality assurance effort is a transparent presentation of existing data sources and any limitations on their use in the context of the original study.

Audit Records:

CBRAT was the subject of an external audit review in 2015. Auditors external to the EPA reviewed the project's electronic notebook and interviewed Project staff and WED's QA Manager. The auditors found no deficiencies in the project and noted several best practices such as documentation of records.

Appendix A. Under The Hood – Hardware, Software, Access Levels, & Backups

A-1 Servers

CBRAT is a database backed website developed with Ruby on Rails web application framework. The biological information is stored in a PostgreSQL database. PostGIS provides spatial, geographic objects for the PostgreSQL database and interacts with MapServer to display species' geographic distributions and abundances.

The CBRAT Information system has three servers in its configuration: 1) maintenance server, 2) development server, and 3) public server. Each server plays an important role in the tools development cycle as described below. Each of the CBRAT servers has a Linux based operating system. On the development and public servers, Apache2 is installed as the web hosting software to host the development and public websites. These servers are currently located within the Northwest Knowledge Network (NKN) at the University of Idaho (https://www.northwestknowledge.net/).

Maintenance Server: The maintenance server provides the repository for backups (described below). It also has Git server software installed to provide project management for software development between multiple users. When changes to the code base are made, the changes are documented and pushed to the Git server. The Git server maintains version control so that code changes can be reversed if the changes create unresolvable errors. Once code changes are documented and pushed to the Git server, the code is then pushed to the development server.

Development Server: The development server provides a staging area to test new functionality and tools being designed to enhance CBRAT. The data on the development server can be changed or manipulated to test different risk scenarios without affecting the final data in the public server. It also provides a mirror copy of the public-facing CBRAT web server to evaluate compatibility between current versions and new software releases prior to upgrades on the public-facing server. The database on the development server is periodically updated with the most recent public database version, but the data on the development server is not backed up, and is never used to update the public server. It exists strictly for testing and training purposes. **Public Server:** The public-server hosts the website and current database, and is the version used by managers and researchers to conduct the risk assessments. The public server is the repository of all the biological, environmental, and geographical data as well as the rule sets used to calculated risk. Different access levels are managed by a website security certificate maintained by Digicert, as described below.

A-2 Software

- **Operating System:** Ubuntu 12.04.2 LTS (GNU/Linux 3.5.0-23-generic x86_64).
- Apache2 Server version: Apache/2.2.22.
- **Ruby:** Ruby 1.9.3p49 (2013-05-15 revision 40747 [x86 64-linux].
- **Rails:** Rails 3.0.11.
- **Git:** git version 1.7.9.5.
- **PostgreSQL:** PostgreSQL 9.1.9 on x86_64-unknown-linux-gnu, compiled by gcc (Ubuntu/Linaro 4.6.3-1ubuntu5) 4.6.3, 64-bit.
- **POSTGIS:** POSTGIS="2.0.0 r9605" GEOS="3.3.8-CAPI-1.7.8" PROJ="Rel. 4.8.0, 6 March 2012" LIBXML="2.8.0".
- **MapServer:** MapServer 6.2.1.

A-3 Access Levels

Depending on the user's expertise and interest, the administrator will assign an access level to each user's account from one of the following categories with the corresponding privileges. A summary of these privileges is displayed in Table A-1.

Public: The first level is public access. No login is required to view biological or environmental information that has been reviewed and released by the U.S. EPA. Information on individual species and/or taxonomic groups of species as well as risk assessments will be released to the public as the information is finalized through the review process. The public cannot change any data or run new risk assessments.

Manager: This level requires a user name and password to gain access to biological and environmental information that has not been released to the public. Users with this access level are able to view all information, test tools, and temporarily modify inputs into the risk analyses. Users with this access level are not able to edit information contained in the database but they do have the ability to submit issues related to any bugs encountered, incorrect information about a species, or suggestions on how to improve the website.

Expert User: This third level of access also requires a user name and password and provides the additional ability to add/edit all the information contained in CBRAT except user accounts and deleting or combing species. Experts can enter "Master" records, though they can be overwritten by Gatekeepers and Administrators.

Gatekeepers: This access level also requires a user name and password for access. Gatekeepers have all the access privileges of expert user/taxonomic experts and have the added ability to review information that has been entered by other expert users. Gatekeepers also have the ability to import data from spreadsheets with a linked PDF as well as delete or combine species.

Administrator: This access level also requires a user name and password for access. Administrators have all the access privileges of gatekeepers. Administrators can view user's statistics (e.g., hours logged-in) and can approve species for public viewing. Administrators also have access to the user management tools to edit and change access levels of all user accounts.

A-4 Backup Strategy

Cron is a time-based job scheduler software utility used to automate system administration tasks on Unix and Linux operating systems. A Linux *cron* job has been created to automatically back up the website database every evening at midnight and at the end of every month at midnight to the maintenance server. Each of the last seven days of backups is stored using the day of the week naming convention with each day overwriting the backup made seven days previous. Likewise, the monthly backups are stored using a month naming convention with each month overwriting the backup made the end of the month one year ago. This *cron* job is located on the public server and manages all the weekly, monthly and annual backups as outlined. Offsite backup storage of the database and website code is updated regularly in the event of a catastrophic hardware failure at University of Idaho.

Privileges	Public	Manager	Expert	Gatekeeper	Administrator
Login Required	no	х	х	Х	х
View Public Species	Х	х	х	Х	х
Generate Spreadsheet Summaries of Abundance and Life History Data for Public Species	х	х	х	x	х
Generate PDF Profile for a Single Public Species	Х	х	х	Х	X
View Non-Public Species (species that have not gone through final review)	no	х	х	x	х
Generate Spreadsheet Summaries of Abundance and Life History Data for Non-Public Species	no	x	х	x	х
Generate PDF Profiles for Multiple Public	no	×	×	v	×
& Non-Public Species	no	^	~	~	^
Test Tools	no	х	х	x	х
Submit Issues	no	х	х	Х	x
Enter Abundance and Trait Data	no		х	Х	х
Export Summaries from the Biotic Matrix	Х	х	х	Х	х
Modify Data in Biotic Matrix	no		х	Х	х
View Results from Default Risk Assessments	Х	х	х	Х	х
Modify Inputs into Risk Assessments	no	х	Х	Х	х
Run New Risk Assessments	no	х	х	Х	x
Create Master Records for Abundance	no	no	Х	Х	x
Site Management: Modify or Approve User Accounts	no	no	no	no	Х

Table A-1. Summary of the privileges associated with each level of access in CBRAT.

Privileges	Public	Manager	Expert	Gatekeeper	Administrator
Site Management: Manage Species	no	no	no	x	x
Site Management: View User Statistics	no	no	no	no	×
Site Management: Data Imports: Species Name Check	X	X	X	X	x
Site Management: Data Imports: Import PDFs, Link PDFs, Delete Links	no	no	no	х	x
Site Management: Output Data Reports (who entered specific data and when)	no	no	no	x	x
Site Management: Approve Species Public Viewing	no	no	no	no	Х

Appendix B. Outputting Risk Assessment Results

As described in this section, all users of CBRAT are able to download detailed results from the last risk assessment. Additionally, users with an access level of "manager" or above (see Section A-3) can modify biotic input data and conduct new risk assessments on all stressors (Section B-1) or individual climate stressors (Section B-2). Users are referred to the CBRAT User's Guide (Lee et al., 2015) for an overview of CBRAT.

B-1 Vulnerability Summary Output

The Output Vulnerability Summary page is available as part of the Risk Analysis tab in CBRAT (Figure B-1). Clicking on "Generate Results" generates a screen output of the risks, from which it is possible to output a CSV or XLS file. These output files list all the species within the chosen taxon, location, and depth range with all their risk and resilience factors listed by ecoregion (Figure B-2 and Figure B-3). The XLS file has color coded risks but it is easier to manipulate the numerical values and perform mathematical operations (e.g., summation of risks) with the CSV file.

The "Vulnerability" column in the output (Figure B-2) is the overall climate risk for the species within the ecoregion based on the greatest risk (lowest number) for all climate risks, using the temperature-adjusted ocean acidification risk for pH and aragonite saturation, and the climate-adjusted baseline/status risk. As detailed in Section 2.3, we contend that the single greatest risk is the most defensible approach to assigning overall climate vulnerability. However, with the CSV output, users can explore other approaches to setting overall vulnerability such as basing it on the number of high and moderate risks. Additionally, with basic spreadsheet manipulations, users can remove any particular risk factor to evaluate its importance.

The vulnerability summary output lists the risks generated from the last climate scenario analyzed. If any of the abundance classifications have been changed since the last risk analysis, it is necessary to click the "Make Abundance Reports", which updates the abundance classifications. This update takes approximately 15 minutes with the crabs. Then click on the "Run Vulnerability Summaries" to update the risks, which also takes approximately 15 minutes. If none of the abundances have been changed but there have been changes to any of the biotic traits, effects thresholds, or climate input values it is only necessary to click on the "Run Vulnerability Summaries", which also takes about 15 minutes. It is not necessary to click on either of these if there haven't been any changes to abundances, biotic traits, effects thresholds, or climate input values. After updating as needed, click on "Generate Results". To avoid the possibility of one user changing values while another user runs a risk assessment, CBRAT does not allow more than one user to run a risk assessment at a time. Further, it is not possible to change abundances, biotic traits, or climate values while a risk calculation is underway.

CBRAT -	Coastal	Biodiversity	Risk Analys	is Tool	
Home	Search	Risk Analysis	Data Export	Documents	Site Management
Output Vu Vulnerabilit Make Abundand Taxonomic R Values: Brac	ulnerabili cy Summary Inf ce Reports R Ranks: Infraord hyura	ity Summary Formation is updated ni un Vulnerability Summarie er •	ghtly (04:00am (PDT IS Locations: Groups: N ✓ Filter to Ber)). Single Ecoregion I.E. Pacific & U.S. Arc nthic (0-200m) valu	Ecoregion Group tic u es
Generate Resul	ts Reset	iltor bu			
Vulnerabil	ities	inter by.			

Figure B-1. Output Vulnerability Summary screen.

The Output Vulnerability Screen is accessed via the Risk Analysis tab. Choose the Taxonomic Rank and corresponding taxonomic Value. Then choose a single ecoregion or all the species in the NEP and U.S. Arctic. The default is to output results for benthic species that occur from 0 to 200 m; unclicking the filter box will output species at all depths. Clicking on Generate Results will output a screen with the risks, from which a CSV or XLS file can be generated (Figure B-2 and Figure B-3) Reset clears the input values on the page. Click on Make Abundance Reports if any abundance classifications have been changed followed by the Run Vulnerability Summaries. Click on the Run Vulnerability Summaries if any biotic traits, thresholds, or climate values have been changed. The Vulnerabilities checkbox allows outputs of individual risk or resilience factors (Figure B-4).

The Vulnerabilities checkbox at the bottom of the page allows users to output only species that have a specific risk or resilience factor (non-null, including 0 values) associated with it (Figure B-4). This function is useful for checking results for a specific stressor and to find species missing a particular risk because of missing data. The major difference between this function and outputting individual climate risks (Section B-2) is that the vulnerability checkbox under the Vulnerability Summary still calculates all climate and baseline/status risks and so is slower than outputting individual risks.

B-2 Outputting Individual Climate Risks

Risks associated with an individual climate driver can be analyzed separately using the "Test" function under the Temperature Increases, Ocean Acidification, and Sea Level Rise Risks links, which are under the Risk Analysis tab. The test screen for sea level rise is shown in Figure B-5. As with the vulnerability summary, the "Make Abundance Report" is clicked if abundance classifications have been changed. The "ReCalc SLR Values" is clicked to update the risks following the abundance update or if any of the biotic traits, thresholds or climate values have been changed. A portion of an output for the ETW SST risks is illustrated in Figure B-6. The test function is considerably faster than the vulnerability summary since only one family of risks is calculated. The increase in speed is particularly useful when conducting scenario modelling on a particular climate stressor and during quality assurance checks.

Species	Family	Location	Taxa- code	Vulner- ability	Abundance Class	Sea Level Rise	Sea Surface Temperature Annual Upper Mean	Sea Surface Temperature Summer Increase	Sea Surface Temperature Winter Increase	Within Ecoregion SST Risk	air_summer _temp	air_winter _temp	air_annual _temp	depth_100 _temp	depth_30 _temp	surface _temp	annual _ph	summer _ph	winter ara _ph	ite	Greatest Temperature Risk	Greatest OA Risk	Temperature Adjusted OA Risk
Herbstia parvifrons	Epialtidae	Southern California Bight	DEC	-2	Low Moderate	-2	0	0	0	-1	0	0	o	0	0	0	0	-1	o		0	-1	-1
Heteractaea Iunata	Xanthidae	Southern California Bight	DEC	-2	Very Rare	-2	o	o	o	-2	o	o	o		o	o	o	-1	o		o	-1	-1
Hexapanopeus rubicundus	Panopeidae	Southern California Bight	DEC	-1	Very Rare	o	o	o	0	-2	o	0	o		0	0	o	-1	o		0	-1	-1
Hoplocypode occidentalis	Ocypodidae	Southern California Bight	DEC	-1	Very Rare	-1	0	o	o	-2	o	0	o			o	o	-1	o		o	-1	-1
Inachoides laevis	Inachoididae	Southern California Bight	DEC	-1	Rare	-1	0	0	0	-3	0	0	0	0	o	o	0	-1	0		o	-1	-1
Latulambrus occidentalis	Parthenopidae	Southern California Bight	DEC	-1	High Moderate	-1	0	o	0	-2	0	0	0	0	o	o	0	-1	o		o	-1	-1
Libinia setosa	Epialtidae	Southern California Bight	DEC	-1	Rare	0	0	o	0	-2				0	0	0	o	-1	0		o	-1	-1
Lophopanopeus bellus	Panopeidae	Southern California Bight	DEC	-3	Rare	-2	-3	-2	-2	-8	-2	0	-2	-1	+2	-2	0	-1	o		-3	-1	-1
Lophopanopeus diegensis	Panopeidae	Southern California Bight	DEC	-3	Low Moderate	-2	-3	-2	-2	-3	-2	0	-2	-2	-2	-2	o	-1	0		-3	-1	-1

Figure B-2. Portion of Vulnerability Summary CSV - Output for climate risks.

Each species is listed by each ecoregion. "Vulnerability" is the overall climate risk calculated as the single greatest risk from the sea level rise risk, greatest temperature risk, temperature-adjusted ocean acidification risk, and the climate-adjusted baseline risk (see Figure B-3). The "Within Ecoregion SST Risk" is a worst-case scenario and is not included in calculating the overall risky. Climate risks are classified from minor (0) to high (-3). Aragonite is null in this case because pH and not aragonite saturation state was chosen as the major stressor for decapods. These are test data and do not represent the final risk assessment for these species.

Species	Family	Location	Taxa- code	Vulner- ability	Abundance Class	Greatest Climate Risk	Greatest Baseline Risk	Climate Adjusted Baseline Risk	Endemic	Restricted Distrib.	Wide Distribution	Arctic Endemic	Small Island Distrib.	Nonin- digenous Species	Hyper- Rare	Rare Every- where	Abundant Some- where	Population Decline	S.Rare-N. Mod/Abun.	Transient	Symbiotic Specializat ion	Habitat Specializa- tion	Trophic Specializa- tion	Anadromous / Catadromous	Slow Repro. / Long Lived
Herbstia parvifrons	Epialtidae	Southern California Bight	DEC	-2	Low Moderate	-2		o			2														
Heteractaea Iunata	Xanthidae	Southern California Bight	DEC	-2	Very Rare	-z	-3	-3					2								-2	-3			
Hexapanopeus rubicundus	Panopeidae	Southern California Bight	DEC	-1	Very Rare	-1	-1	0								-1									
Hoplocypode occidentalis	Ocypodidae	Southern California Bight	DEC	-1	Very Rare	-1		0					2												
Inachoides laevis	Inachoididae	Southern California Bight	DEC	-1	Rare	-1		o																	
Latulambrus occidentalis	Parthenopidae	Southern California Bight	DEC	-1	High Moderate	-1		0			2														
Libinia setosa	Epialtidae	Southern California Bight	DEC	-1	Rare	-1	-1	o								-1									
Lophopanopeus bellus	Panopeidae	Southern California Bight	DEC	-3	Rare	-3		0																	
Lophopanopeus diegensis	Panopeidae	Southern California Bight	DEC	-3	Low Moderate	-3	-1	-4										-1							

Figure B-3. Portion of Vulnerability Summary CSV - Output for baseline/status risks.

Each species is listed by each ecoregion. Both risks, classified from 0 to -3, and resilience factors, classified from 1 to 3, are output for the baseline/status traits. Null values indicate either that the risk is minor (0) or that there is missing data to calculate the risk. The overall value of the baseline/status risks are weighted for each species by the extent of climate risk, given in the "Greatest Climate Risk" column, with the "Climate Adjusted Baseline Risk" used in calculating the overall risk. These are test data and do not represent the final risk assessment for these species.

CBRAT - Coastal Bi	odiversity Ri	sk Analysis	; Tool											
Home Search	Risk Analysis	Data Export	Documents	Site Management										
Dutput Vulnerability Summary Vulnerability Summary information is updated nightly (04:00am (PDT)). Make Abundance Reports Run Vulnerability Summaries														
Taxonomic Ranks: Infraorder Values: Brachyura	Y	Locations: ○ Sir Groups: ● N.E ♂ Filter to Bent	ngle Ecoregion 💿 I E. Pacific & U.S. Arcti hic (0-200m) value	Ecoregion Group c										
Generate Results Reset Additional values to filte	r by:													
Only include Species with V	/ulnerability values o	ıf:												
 Abundant Somewhere Anadromous / Catadromous Arctic Endemic Endemic Habitat Specialization 	 Hyper-Rare Nonindigenous Sp. Ocean Acidification Declines Population Decline Rare Everywhere 	 Restrict Sea Le Sea Summer I Sea Summer Inc Sea Sumiter Inc Sea Suy Yearly Upp 	tted Distrib. evel Rise urface Temperature ncrease urface Temperature rease urface Temperature per Mean	 Slow Repro. / Long Lived Small Island Distrib. S.Rare-N.Mod/Abun. Symbiotic Specialization Air and Subsurface Temperature Transient Trophic Specialization Wide Distribution 										

Figure B-4. Outputting vulnerability summary limited to species with a specific risk or resilience factor.

Clicking on "Vulnerabilities" displays a list of the individual risk and resilience factors. Choose a single factor and click on "Generate Results". This will generate a vulnerability summary (Figure B-2 and Figure B-3) but only for species with a non-null value for the chosen factor. In this case, only species with a non-null risk for sea level rise are output.

CBRAT -	- Coastal	Biodiversity	Risk Analysi	is Tool			
Home	Search	Risk Analysis	Data Export	Documents	Site Management	About	Terms of Use
Isosta Habit. Sea Lev	tic / Eustatic Rates at Thresholds rel Rise Risks SLR Test	Make Abundance Re ReCalc SLR Values Sea Level Rise Input Taxonomic Ranks Values: Brachyura Locations: Sing Groups: • N.E. • Filter to Benthi	ports t Variables i Infraorder • e Ecoregion • Eco Pacific & U.S. Arctic c (0-200m) values	pregion Group		Sea Le	vel Rise Risk
		Export CSV F	Reset Filter				

Figure B-5. Screen for outputting risks associated with a specific climate stressor.

This test option is available under each of the climate stressor (shown here for SLR). Choose the Taxonomic Rank and corresponding Value. Then choose a single ecoregion or all the species in the NEP and U.S. Arctic. The default is to output results for benthic species that occur from 0 to 200 m; unclicking the filter box will output all species at all depths. Click on Make Abundance Reports if abundance values have been changed, and then the ReCalc SLR Values to update the risks. Click on the ReCalc button if any biotic traits, thresholds, or climate values have been changed. Click on "Export CSV" to generate an output (Figure B-6 is an example with ETW temperature risks).
species_id	species	taxa_code	meow_class	increment	incremental_ increase	projected_ increase	sst_range
2343	Pugettia gracilis	DEC	Gulf of Alaska	SUMMER	3.53	15.35	minor
2343	Pugettia gracilis	DEC	Aleutian Islands	SUMMER	3.63	12.07	minor
2343	Pugettia gracilis	DEC	North American Pacific Fjordland	SUMMER	3.18	16.4	low
2343	Pugettia gracilis	DEC	Puget Trough/Georgia Basin	SUMMER	3.12	16.71	low
2343	Pugettia gracilis	DEC	Oregon, Washington, Vancouver Coast and Shelf	SUMMER	2.9	17.02	moderate
2343	Pugettia gracilis	DEC	Northern California	SUMMER	2.83	18.02	high
2343	Pugettia gracilis	DEC	Puget Trough/Georgia Basin	WINTER	1.8	9.31	minor
2343	Pugettia gracilis	DEC	Northern California	WINTER	2.34	14.98	moderate
2343	Pugettia gracilis	DEC	Oregon, Washington, Vancouver Coast and Shelf	WINTER	2.41	11.75	minor
2343	Pugettia gracilis	DEC	Aleutian Islands	WINTER	2.53	6.21	minor
2343	Pugettia gracilis	DEC	Gulf of Alaska	WINTER	2.79	6.91	minor
2343	Pugettia gracilis	DEC	North American Pacific Fjordland	WINTER	2.53	9.21	minor
2343	Pugettia gracilis	DEC	Oregon, Washington, Vancouver Coast and Shelf	ANNUAL	2.62	14.13	minor
2343	Pugettia gracilis	DEC	Northern California	ANNUAL	2.54	16.09	high
2343	Pugettia gracilis	DEC	Aleutian Islands	ANNUAL	3.03	8.7	minor
2343	Pugettia gracilis	DEC	Gulf of Alaska	ANNUAL	3.1	10.52	minor
2343	Pugettia gracilis	DEC	North American Pacific Fjordland	ANNUAL	2.8	12.27	minor
2343	Pugettia gracilis	DEC	Puget Trough/Georgia Basin	ANNUAL	2.15	12.59	minor

Figure B-6. Portion of the output from an individual climate risk output.

Example for ETW temperature risks for the crab *Pugettia gracilis*. Full output includes each species listed by ecoregion. For ETW, the risk level is listed under "sst_range". The "incremental_increase" is the future increase in temperature while the "projected_increase" is the projected future temperature. The variables (columns) in the output are specific to each climate stressor. The pivot table function in spreadsheets can be used to organize the data. These are test data and do not represent the final risk assessment for these species.

B-3 Outputting Results for Northern Colonization

The Northern Colonization Test function (Figure B-7), located under the "Temperature Increases" page in CBRAT, outputs an analysis of whether currently unoccupied northern (cooler) ecoregions will become sufficiently warm to allow colonization (Section 5.5). The suitability of temperatures in northern ecoregions is determined using the BTL approach (Section 5.4). A portion of an output is shown in Figure B-8.

CBRAT -	Coastal	Biodiversity	Risk Analysi	is Tool			
Home	Search	Risk Analysis	Data Export	Documents	Site Management	About	Terms of Use
Predicted S	ST Increases T Thresholds SST Test	Mala Abundana Da			Те	mpera	ture Increases
Air an	d Subsurface Increases	ReCalc Northern Cold	onization Values				
Air and Sut Northern	Surface Test Colonization Test	Values: Brachyura	le Ecoregion Eco	pregion Group			
		 ✓ Filter to Benthi 	c (0-200m) values				
		Export CSV R	eset Filter				

Figure B-7. Northern Colonization Test screen.

Screen to evaluate suitability of temperatures in unoccupied northern ecoregions using the BTL approach. Choose the Taxonomic Rank and corresponding Value. Then choose a single ecoregion or the NEP and U.S. Arctic. The default is to output results for benthic species that occur from 0 to 200 m; unclicking the filter box will output all species at all depths. Click on Make Abundance Reports if abundance values have been changed, and then the ReCalc SLR Values to update the risks. Click on the ReCalc button if any biotic traits, thresholds, or climate values have been changed. Clicking on Export CSV will generate a CSV file with an analysis of the temperature suitability of all species within the chosen taxon in currently unoccupied northern (cooler) ecoregions. An example output is shown in Figure B-8.

species_id	species	taxa_code	eco_region	depth_class	suitability
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	air_summer	high
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	air_winter	moderate
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	air_yearly	high
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	depth_100	low
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	depth_30	minor
121	Metacarcinus magister	DEC	Beaufort Sea - continental coast and shelf	sst	moderate
121	Metacarcinus magister	DEC	Chukchi Sea	air_summer	high
121	Metacarcinus magister	DEC	Chukchi Sea	air_winter	moderate
121	Metacarcinus magister	DEC	Chukchi Sea	air_yearly	high
121	Metacarcinus magister	DEC	Chukchi Sea	depth_100	minor
121	Metacarcinus magister	DEC	Chukchi Sea	depth_30	minor
121	Metacarcinus magister	DEC	Chukchi Sea	sst	moderate

Figure B-8. Portion of the output from Northern Colonization Test.

The temperature suitability for northern colonization, as calculated using the BTL approach, is listed for all species for all northern (cooler) unoccupied ecoregions. The pivot table function in spreadsheets can be used to organize the data. Suitability is classified from minor (not suitable) to high (high suitability). These are test data and do not represent the final risk assessment for these species.

Appendix C. Near-Coastal Habitat Areas and GIS Metadata

C-1 Introduction

Over the last decade there has been a dramatic increase in the availability of georeferenced marine/estuarine landscape data for California, Oregon, and Washington. These GIS layers have been generated for a variety of purposes, including evaluating essential fish habitat, assessing potentially threatened habitat types (e.g., marshes, seagrasses, and kelps), and for assessing tsunami risks. We synthesized a number of these layers to generate estimates of major offshore and estuarine habitats for the Southern California Bight, Northern California, and Oregon, Washington, Vancouver Coast, and Puget Trough/Georgia Basin ecoregions. These areal estimates were then used as inputs in assigning relative abundance of species in these four ecoregions (Section 3) as well as a guide to the relative areas of major habitats in other ecoregions.

C-2 Near-Coastal Habitat Areas – Patterns of Offshore and Estuarine Habitats

Offshore habitats were split into those that occur from the shoreline to 30 m deep and those from >30 m to 200 m depth, which correspond to our shallow and deep subtidal depth classes. As our primary concern was evaluating broadly across habitat patterns, these two depth classes were combined for the current analyses. The resolution of the offshore data varied among ecoregions, with the greatest detail off the coasts of Oregon and Washington. At this time, we do not have areal estimates for coastal beaches, while the rocky intertidal was analyzed separately. The estuarine data were primarily derived from the National Wetland Inventory (NWI; USFWS, 2009; <u>http://www.fws.gov/wetlands/</u>) with additional sources for seagrass layers. Total estuary areas included unvegetated sediments, emergent marsh, submerged aquatic vegetation (SAV), tidal riverine areas, marine areas at the mouth of estuaries, hard substrates, and woody vegetation, which is the definition of estuary area used in Lee and Brown (2009). Offshore and estuarine data were available only for the United States so that the areas for the Puget Trough/Georgia Basin Ecoregion do not include Canada while the Southern California Bight Ecoregion areas do not include Mexico.

The key points relating to habitat area at an ecoregion scale are:

• Estuarine area is several-fold smaller in the Southern California Bight Ecoregion than in the other three ecoregions (Figure C-1). Inclusion of the Mexican portion of the

ecoregion would increase the estuarine area (e.g., Bahia San Quintin), though it is likely that the total estuarine area would still be substantially less than in the other three ecoregions. Puget Trough/Georgia Basin Ecoregion had the second smallest estuarine area; inclusion of Canada (e.g., Fraser River) would likely increase the area to be more comparable to Northern California and Oregon, Washington, Vancouver Coast and Shelf ecoregions.

- Intertidal and subtidal unconsolidated habitats combined constitute the major estuarine habitat types in all ecoregions (Figure C-2). The relative contribution of these unconsolidated habitats was smallest in the Southern California Bight Ecoregion. The area of estuarine hard substrates (not shown) was trivial in all ecoregions.
- The greatest area of emergent marshes occurs in Northern California and the smallest in the Southern California Bight (Figure C-2). Inclusion of Mexico would increase the area of marsh in the Southern California Bight, though it is likely that it would still be smaller than the other ecoregions because of the relatively smaller estuarine area in Southern California and northern Baja.
- Areas of intertidal and subtidal submerged aquatic vegetation (SAV) are substantially less than the areas of unvegetated unconsolidated sediments in the three northern ecoregions while more similar in the Southern California Bight Ecoregion (Figure C-2). *Zostera marina* is relatively abundant in Puget Sound, in which 200 km² (20,000 hectares) have been estimated (Mumford, 2007), though this is substantially smaller than the unconsolidated habitats in Puget Sound.
- Estuarine unconsolidated habitats constitute a small fraction (1% 3.1%) of the area of the offshore unconsolidated habitat (Figure C-3).
- Across the three ecoregions with offshore area estimates, unconsolidated habitat constitutes the greatest area, with the Southern California Bight showing a reduced percentage compared to the other ecoregions (Figure C-4 through Figure C-6).
- Rocks/boulders and rocks mixed with other substrate types occupied a moderate offshore area in Northern California and the Oregon, Washington, Vancouver Coast and Shelf ecoregions (Figure C-5 and Figure C-6). Rocks occupied both a greater absolute area and a greater proportion of the offshore area in the Southern California Bight Ecoregion (Figure C-4).
- Kelp occupied a small percentage of the area (0.09% 0.6%) in all three ecoregions with offshore data layers (Figure C-4 through Figure C-6). The area of floating kelp ranged from approximately 1900 to 4700 hectares in the Strait of Juan de Fuca, one of the

primary locations for floating kelp in Puget Sound (Puget Sound Action Team, 2007), representing a small percentage of unconsolidated habitats in Puget Sound.



• In the more detailed analysis off Oregon and Washington, cobble/gravel and shell substrates composed a small percentage of the total offshore area (Figure C-1).

Figure C-1. Total estuarine area in the Southern California Bight, Northern California, Oregon, Washington, Vancouver Coast and Shelf, and Puget Trough/Georgia Basin ecoregions. Values for Southern California do not include the Mexican portion of the ecoregion while values for Puget do not include the Canadian portion of the ecoregion. Estuarine areas are derived from the NWI.



Figure C-2. Areas of major estuarine habitats from Puget Trough/Georgia Basin to Southern California Bight ecoregions.

Values for Southern California do not include the Mexican portion of the ecoregion while values for Puget Trough do not include the Canadian portion of the ecoregion. Estuarine areas were derived from the NWI.



Figure C-3. Areas of offshore versus total estuarine unconsolidated habitats by ecoregion. Most of the substrate type around islands presumably consists of rock/boulders. Values for Southern California do not include the Mexican portion of the ecoregion.



Figure C-4. Area of major habitat types from 0-200 m offshore in the Southern California Bight Ecoregion. Most of the substrate type around islands presumably consists of rock/boulders. ND = no data. Values for Southern California do not include the Mexican portion of the ecoregion.



Figure C-5. Area of major habitat types from 0-200 m offshore in the Oregon, Washington, Vancouver Coast and Shelf Ecoregion.



Figure C-6. Area of major habitat types from 0-200 m offshore in the Northern California Ecoregion. Most of the substrate type around islands presumably consists of rock/boulders. ND = no data.

C-3 Near-Coastal Habitat Areas – Geospatial Analysis

The following summarizes the data sources and geospatial methodologies used to estimate nearcoastal habitat areas.

C-3.1 Deepwater (Offshore) Marine Habitat Data Compilation Method

Geographic Information Systems (GIS) software ArcMap v.10.1 tools were used to overlay geospatial data including surficial geological habitats (Romsos et al, 2007), canopy kelp forests (PSMFC, 2004), MEOW marine ecoregions (Spalding et al, 2007), and bathymetric depths (PFMC, 2004). These data were then cross-tabulated and summarized in a Microsoft ExcelTM pivot table.

<u>Sources:</u> The surficial geological habitat geospatial data layer was downloaded from the Pacific Coast Ocean Observing System (PaCOOS) West Coast Habitat Server maintained by Oregon State University's Active Tectonics & Seafloor Mapping Lab. The canopy kelp forest geospatial data were downloaded from the Oregon Ocean Information website maintained by the State of Oregon to support marine spatial planning in the Oregon Territorial Sea. The marine ecoregion geospatial data were downloaded from The Nature Conservancy's TNCMAPS website that provides The Nature Conservancy's core conservation datasets. Bathymetric depth geospatial data were downloaded from the Pacific Fishery Management Council's Pacific Coast Marine Habitat Information website. National Wetland Inventory (NWI) geospatial data downloaded from the U.S. Fish & Wildlife Survey's National Wetland Inventory (NWI) website in 2011 were also used in the process (Cowardin et al., 1979).

<u>GIS Overlay and Extraction</u>: The geospatial data layers above were downloaded in a variety of cartographic projections. All were projected into the Albers projection for compatibility in the overlay process. These data were all in the ESRI shapefile vector polygon format. The bathymetric data consisted of polygons representing 10-meter depth zones. The bathymetric data consisted of five shapefiles, one each for Oregon and Washington waters and three for California waters. The five layers were merged and polygons less than or equal to 200 m were extracted. The "identity" overlay tool was used to simultaneously overlay and extract surficial geologic habitat polygons less than or equal to 200 m deep. The specific vertical datum was not provided but it is assumed to be mean sea level. The "identity" overlay tool was again used to simultaneously overlay and extract marine ecoregion polygons. Canopy kelp polygons were similarly overlain. The final GIS overlay procedure was to use NWI polygons to erase estuarine polygons from the compiled shapefile in order to avoid duplication with a parallel West Coast estuarine habitat data compilation effort. The last step in the geospatial data compilation was to calculate the area of each resulting polygon in hectares.

C-3.2 Nearshore Marine, Estuarine and Tidal Riverine Habitat Data Compilation Method

Geographic Information Systems (GIS) software ArcMap v.10.1 tools were used to overlay geospatial data including NWI habitats (Cowardin et al. 1979), seagrass habitat (PFMC, 2005), and marine ecoregions (Spalding et al, 2007). These data were then cross-tabulated and summarized in a Microsoft ExcelTM pivot table.

<u>Sources:</u> Marine, estuarine and tidal riverine NWI polygons for Washington, Oregon and California were downloaded from the U.S. Fish & Wildlife Survey's NWI website in 2011 and compiled as part of a West Coast estuarine classification study (Lee and Brown, 2009). Seagrass habitat geospatial data were downloaded from the Pacific Fishery Management Council's (PFMC) Pacific Coast Marine Habitat Information website. These data were compiled in support of an Environmental Impact Statement (EIS) to consider the designation and conservation of Essential Fish Habitat (EFH) for Pacific Coast Groundfish. The marine ecoregion geospatial data were downloaded from The Nature Conservancy's TNCMAPS website described above.

GIS Overlay and Extraction: The wetlands and deepwater habitats classification codes termed "Attributes" by the NWI are alpha-numeric codes that provide detailed habitat descriptions for polygon areas in the shapefile. The codes, developed by Cowardin et al. (1979), represent a complex hierarchical classification of ecological taxa. Only three of the highest levels of classification were selected and extracted; marine, estuarine and riverine. Both subtidal and tidal polygons were used for the marine and estuarine systems, however for the riverine system only the tidal riverine subsystem polygons were used. The next levels of classification, classes and subclasses, are based on substrate material, flooding regime, or vegetation class. Special modifiers are also used. In order to enhance the usefulness of these data, a table was constructed and joined to the geospatial data that parses the NWI codes into 101 human-readable classes. An online NWI classification decoder tool was used to aid the construction of the join table. Because seagrasses or submerged aquatic vegetation may not be consistently mapped due the limitations of aerial imagery as the primary data source used to detect wetlands in the NWI mapping process (USFWS 2004), the PFMC seagrass shapefile was incorporated using the 'identity' overlay tool. The 'identity' overlay tool was again used to simultaneously overlay and clip marine ecoregion polygons to the extent of the extracted NWI polygons. The last step in the geospatial data compilation was to calculate the area of each resulting polygon in hectares.

C-3.3 GIS Data Links for Geospatial Analysis of Near-Coastal Habitats (Accessed 08/09-14/2013)

- Pacific Coast Ocean Observing System/ West Coast Habitat Server http://pacoos.coas.oregonstate.edu/index.htm
- Oregon Ocean Information
 http://www.oregonocean.info/index.php/ocean-data-and-resources
- TNCMAPS <u>http://maps.tnc.org/gis_data.html</u>
- Pacific Coast Marine Habitat Information <u>http://marinehabitat.psmfc.org/</u>
- U.S.FWS National Wetlands Inventory <u>http://www.fws.gov/wetlands/Data/Data-Download.html</u>
- NWI online Classification Code Decoder <u>https://www.fws.gov/wetlands/Data/Wetland-Codes.html</u>

C-4 Calculation and Metadata for Computing Habitat Thresholds for West Coat Intertidal Rocky Habitats due to Sea Level Rise using LiDAR Topobathy

GIS Methodology:

Within each ecoregion, topobathy LIDAR digital elevation models (DEMs) downloaded from NOAA's Digital Coast GIS data repository (Dept. Commerce, 2016) were used to estimate the percent change in the area of rocky intertidal habitat in 10 cm increments with different levels of eustatic sea level rise. Puget Sound topobathy LIDAR was released concurrent to this study and required conversion to digital elevation model (DEM) from LAZ compressed LIDAR point format (Isenburg, 2011). Environmental Sensitivity Index (ESI) Map Shoreline data were used to identify rocky shorelines (Dept. Commerce, 2013). Such stretches of shoreline were extracted for each of the four ecoregions and buffered by 100 m to include the intertidal and evaluate the potential area for upland habitat migration. All available LIDAR topobathy DEMs from Digital Coast were extracted using the resulting polygons and two rasters were synthesized from the results, a 10 cm increment zone raster and a non-planimetric surface area raster (Jenness, 2004) for zonal summation. Current rocky intertidal non-planimetric surface areas for each ecoregion were computed between Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels established from published datum sheets for tidal stations central to each MEOW ecoregion (Gill and Schultz, 2000). Percent change in non-planimetric surface area for the same relative ranges were calculated in 10 cm incremental steps of eustatic SLR from the zonal summation.

The sources and steps for each parameter are given below.

Marine Ecoregions of the World (MEOW):

http://www.marineregions.org/sources.php#meow

Marine Ecoregions of the World polygon shapefiles were downloaded. The four MEOW ecoregions on the US west coast were selected in ArcGIS 10.2.2 and exported to new shapefiles. They are: Puget Trough/Georgia Basin; Oregon, Washington, Vancouver Coast and Shelf; Northern California and; Southern California Bight.

Environmental Sensitivity Index (ESI) Map Shoreline data:

http://response.restoration.noaa.gov/maps-and-spatial-data/environmental-sensitivityindex-esi-maps.html

ESI shoreline data were downloaded. All shorelines with the term "Rocky" in their attributes were selected in ArcGIS 10.2.2 and exported to a new shapefile. The rocky shoreline was then buffered by 100 m using the ArcGIS 10.2.2 Analysis tool 'Buffer' to create a polygon shapefile. This shapefile then clipped by each ecoregion using the ArcGIS 10.2.2 Analysis tool 'Clip'.

Coastal Topobathy Lidar (JALBTCX) Digital Elevation Models:

https://coast.noaa.gov/dataregistry/search/dataset/C10406A4-FB7D-4D30-96D7-E036F6942EB6

Topobathy LiDAR digital elevation models were downloaded from NOAA's Digital Coast GIS data repository and mosaicked by ecoregion. Sub-dataset rasters were extracted by the buffered rocky shoreline for the ecoregions using the using the ArcGIS 10.2.2 Spatial Analyst tool 'Extract by Mask'. A second raster was derived from these data using the ArcGIS 10.2.2 Spatial Analyst tool 'Raster Calculator' by multiplying zvalues by ten and integerizing to serve as 10 cm elevation "zones". A third raster of nonplanimetric surface area was derived from these data by using the surface area tool in the DEM Surface Tools v. 2.1.375 created by Jenness Enterprises. http://www.jennessent.com/arcgis/arcgis extensions.htm

Non-planimetric surface areas were summarized in tabular format for each 10 cm elevation "zone" using the ArcGIS 10.2.2 Spatial Analyst tool 'Zonal Statistics as Table'. Puget Sound topobathy LiDAR was downloaded in .laz compressed LiDAR point format. These data were uncompressed into xyz ASCII format using the open source LASzip tool developed by Martin Isenburg.

https://rapidlasso.com/

These data were opened in ArcMap 10.2 and displayed as point events. The point events were turned into shapefiles using the ArcGIS 10.2.2 Analysis tool Clip using the buffered rocky shoreline and merged using the ArcGIS 10.2.2 Data Management tool 'Merge'. These data were then converted to raster via the ArcGIS 10.2.2 Spatial Analyst tool interpolation tool 'IDW' with the three nearest points at a maximum variable distance of 30 meters. Raster calculation and surface area procedures described above were then applied.

Tidal Datums:

Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels relative to NAVD88 (the LiDAR elevation datum) were computed from published datum sheets for tide stations representative of each MEOW ecoregion. The stations selected are: Santa Monica, CA (9410840) for Southern California Bight; Point Reyes, CA (9415020) for Northern California; South Beach, OR (9435380) for Oregon, Washington, Vancouver Coast and Shelf and; Port Townsend, WA (9444900) for the Puget Trough/Georgia Basin.

https://tidesandcurrents.noaa.gov/stations.html

Habitat Threshold Calculation:

Tabular data of the sum of non-planimetric surface area for each 10 cm elevation 'zone' was opened in an Excel spreadsheet. A new column was added and the zone number was multiplied by 10. This step restores elevation relative to NAVD88. A second sheet was added with the first column labeled MSL (mean sea-level rise). The second column is labeled 'Risk' and is formatted as percentage. Tidal datum sheets are consulted and a formula is entered as follows: =

1 -(SUM(LiDAR!E398:E423))/(SUM(LiDAR!E\$398:E\$423))

where 'LiDAR!' is the summary sheet 'E398' is the sum of the non-planimetric surface area at MLLW and 'E423' is the sum of the non-planimetric surface area at MHHW. This provides the percentage of the current non-planimetric surface area of the intertidal for each 0.1 m rise in sea level. Habitat Thresholds were assigned as follows: 0 - 10% loss = Minor; 11 - 29% loss = Low; 30 - 49% loss = Moderate; $\ge 50\%$ loss = High.

Results for percent habitat loss of rocky intertidal by ecoregion:

Figure C-7 shows the results of the GIS model by each ecoregion.

A)									B)				
Seal Level Rise (m)	Puget LiDAR	Puget Risk	OrWaLiDAR	OrWa Risk	NorCal LiDAR	NorCal Risk	SoCal LiDAR	SoCal Risk	Seal Level Rise (m)	Average risk	Percent Loss		
0	0.0%		0.0%	Minor	0.0%	Minor	0.0%	Minor		Minor	0-10%		
0.1	6.7%		-0.8%	Minor	3.0%	Minor	4.3%	Minor	0.4	Low	11-29%		
0.2	15.0%	Low	-1.3%	Minor	5.7%	Minor	17.6%	Low	0.8	Moderate	30-49%		
0.3	22.6%	Low	0.8%	Minor	9.4%	Minor	26.9%	Low	1.4	Hign	>=50%		
0.4	27.7%	Low	1.3%	Minor	13.7%	Low	34.2%	Moderate					
0.5	30.8%	Moderate	2.3%	Minor	18.2%	Low	39.6%	Moderate					
0.6	33.4%	Moderate	4.0%	Minor	22.4%	Low	43.9%	Moderate	C)				
0.7	34.9%	Moderate	6.4%	Minor	26.8%	Low	47.7%	Moderate	Ecoregion	Tidal Range (m)	High	Moderate	Low
0.8	35.5%	Moderate	9.6%	Minor	31.2%	Moderate	50.7%	Hign	Puget	2.60	1.4	0.5	0.2
0.9	36.3%	Moderate	13.4%	Low	35.0%	Moderate	51.5%	Hign	OrWa	2.54	2.0	1.4	0.9
1	38.2%	Moderate	17.5%	Low	38.4%	Moderate	52.1%	Hign	NorCal	1.79	1.5	0.8	0.4
1.1	40.7%	Moderate	21.5%	Low	41.3%	Moderate	51.5%	Hign	SoCal	1.65	0.8	0.4	0.3
1.2	43.2%	Moderate	25.3%	Low	44.2%	Moderate	49.2%	Hign					
1.3	47.0%	Moderate	29.0%	Low	46.8%	Moderate	47.9%	Hign					
1.4	50.0%	Hign	32.6%	Moderate	49.0%	Moderate	47.4%	Hign					
1.5	52.4%	Hign	35.9%	Moderate	50.9%	Hign	46.9%	Hign					
1.6	54.5%	Hign	38.9%	Moderate	52.6%	Hign	46.9%	Hign					
1.7	56.5%	Hign	42.0%	Moderate	54.1%	Hign	47.7%	Hign					
1.8	57.9%	Hign	44.9%	Moderate	55.5%	Hign	48.6%	Hign					
1.9	59.3%	Hign	47.7%	Moderate	56.7%	Hign	49.4%	Hign					
2	60.8%	Hign	50.1%	Hign	57.9%	Hign	50.1%	Hign					
2.1	61.8%	Hign	52.2%	Hign	59.1%	High	50.8%	Hign					
2.2	62.6%	High	54.1%	High	60.2%	High	51.5%	High					
2.3	63.3%	High	55.9%	High	61.3%	High	52.8%	High					
2.4	64.1%	High	57.4%	High	62.2%	High	53.3%	High					
2.5	64.7%	High	59.0%	High	03.2%	High	53.8%	rign					
2.6	65.3%	High	62.0%	High	65.0%	High	54.8%	High					
2./	66.0%	High	62.0%	Hign	65.0%	High	57.8%	High					
2.0	66.2%	High	65.0%	High	66.7%	High	64.1%	High					
2.9	66.2%	High	66.6%	Hign	67.5%	High	60.1%	High					

Figure C-7. Calculation of habitat thresholds by ecoregion for rocky intertidal habitats.

In Part A), the first column lists the average sea level rise for US CONUS West Coast while the columns labeled LIDAR are the predicted percent habitat loss by SLR within each ecoregion. The color coded columns are the habitat threshold class for each SLR value. Part B) shows the percent habitat losses used to define each habitat threshold class. Part C) first lists the tide range within each ecoregion and then the SLR values for each habitat threshold class calculated by each ecoregion.

Appendix D. Evaluation of Temperature as Determinant for Warm-Edge Range Limits of Marine Species

The logic to predict the species' risk to increased temperatures inherently assumes that species do not exist in southern (warmer) unoccupied ecoregions because they are too warm (Section 5). It is known that factors other than temperature can affect species' range limits (Gaston, 2003), including food supply, interspecific competition, and interactions between biotic and abiotic variables (e.g., Helmuth et al., 2006; Sexton et al., 2009; Gaston, 2009). Temperature, however, is the most important determinant of species' warm-edge range limits. Strong support for this contention comes from Cahill et al. (2013) who reported that temperature was supported 68.8% of the time as the factor limiting the warm-edge of distributions (i.e., southern limits in the northern hemisphere and northern limits in the southern hemisphere).

Cahill et al.'s review included 48 marine species. To further evaluate marine species, we reviewed studies not included in Cahill et al. (Table D-1). Based on this review, we identified four lines of evidence that support the critical role of temperature in setting warm-edge range limits:

- Physiological
- Range Shifts
- Impaired Fecundity/Recruitment
- Trophic Dynamic Shift

D-1 Physiological

Physiological limits to temperature affect species' distributions directly and were the most supported proximate cause of warm-edge range limits in the Cahill et al. review. We reviewed nine papers that found that increases in temperature affect aerobic scope, growth, and protein synthesis/denaturation (Table D-1). Increases in water temperature reduce the capacity of water to hold oxygen and other dissolved gases. The resulting combination of high temperature and low oxygen concentration is very stressful to many fishes and aquatic invertebrates because high temperatures also cause elevated metabolic rates and increased demand for oxygen (Lomolino et

al., 1953). In *Maja squinado, Zoarces viviparous, Gadus morhua, Ostorhinchus cyanosoma* and *Ostorhinchus doederleini*, limited circulation and ventilation at high temperatures caused insufficient oxygen supply, thus limiting aerobic scope, thermal tolerance, and even growth performance (Frederich and Pörtner, 2000; Pörtner and Knust, 2007; Pörtner et al., 2008; Nilsson et al., 2009). Studies have shown that growth performance for *Acanthochromis polyacanthus* and *Cheilodactylus spectabilis* declined at the warmest sea surface temperatures experienced at their warm range boundary, respectively (Munday et al., 2008; Neuheimer et al., 2011). High temperatures in the natural habitat of *Mytilus edulis* caused protein denaturation, suggesting that the species' distribution is restricted by its thermal limit (Chapple et al., 1998).

D-2 Range Shifts

Range shifts are a key example of temperature's effect at the population level. They appear as direct evidence, displayed by contractions of lower latitude limits, and suggestive evidence, displayed by expansions of higher latitude limits. In marine ectotherms, species' ranges conform closely to their limits of thermal tolerance, thus both range boundaries have been equally responsive to warming temperatures (Sunday et al., 2012). Physiological limitations to rising temperatures are the likely cause of such range shifts (Somero, 2012; Cahill et al., 2013).

Eleven papers reviewed in Table D-1 support this line of evidence. Two-thirds of North Sea fish species' distributions have shifted in response to increased temperatures (Perry et al., 2005). The Atlantic cod's expansion poleward is likely due to temperature's effects on reproductive performance and reduced food availability (Pörtner et al., 2008). In addition, intertidal communities on the California coast have shifted poleward in response to elevated temperatures (Barry et al., 1995). Studies have shown that the lower latitude range boundary of *Semibalanus balanoides* has shifted poleward 350 km (Jones et al., 2012); transplant experiments and thermal modelling revealed mortality in transplanted barnacles due to high temperatures during aerial exposure, suggesting that temperature is driving contraction of the lower latitude range boundary (Jones et al., 2012; Wethey and Woodin, 2010). A special case of a range shift is the northern colonization of the southern wood borer *Teredo bartschi* near a thermal discharge (Hoagland and Turner, 1980). Marine species shift at different rates because they follow local climate velocities (Pinsky et al., 2013, also see Molinos et al., 2016).

In addition to long-term changes, extreme temperature events affect population distribution, potentially resulting in range shifts (Wethey et al., 2011). It is clear that temperature plays a major role in defining the southern range limits, though the pattern may be "messy" if the number and severity of extreme events increases along with changes in mean temperatures.

D-3 Impaired Fecundity/Recruitment

The direct effect of temperature on recruitment is also an important line of evidence. We reviewed six papers which supported this line of evidence (Table D-1). In Atlantic cod, it has been found that as temperatures warm, recruitment decreases in stocks inhabiting the uppermost part of their temperature range (Planque and Frédou, 1999; Sundby, 2000). This indicates that temperature is an important factor limiting the southern distribution of this species. The same effect was observed in Macoma balthica in which increased temperatures resulted in a decrease in reproductive output, recruitment, and growth, with effects detected in populations approximately 1000 km poleward of the warm edge of the species' range (Beukema et al., 2009). Studies of this clam have also found that rising seawater temperature affected recruitment by a decrease in reproductive output and by spring advancement of bivalve spawning (Philippart et al., 2003). In flatfish, temperature during gonadal maturation affects recruitment and distribution through its influence on the rate of gonadal maturation and spawning time (Lange and Greve, 1997). There is a negative correlation between temperature and abundance of plaice, suggesting that as temperature rises, recruitment decreases (Lange and Greve, 1997). Additionally, it has been found in fish that high temperatures shorten the time before the larva experiences irreversible starvation, or the time it takes before the larva exhausts all its yolk reserves and becomes too weak to feed on exogenous food supplies, negatively affecting recruitment (Blaxter, 1992; McGurk, 1984). It appears that warm temperatures are generally important to successful larval and juvenile development (Sundby, 2000; Rutherford and Houde, 1996), but past a certain threshold, high temperatures are detrimental to recruitment and limit a species' distribution.

D-4 Trophic Dynamic Shifts

Changes in trophic dynamics of marine ecosystems are an indirect effect of temperature on warm-edge range boundaries. Marine organisms exist in a thermal niche and interact in a food web specific to that niche. When warming temperatures shift ranges of species, the trophic dynamics are potentially affected. We reviewed seven articles (Table D-1) that support this line of evidence. For example, in the eastern North Atlantic Sea and European shelf seas, warm-water copepod species have experienced a northward extension by more than 10 degrees latitude while colder-water species have decreased in numbers (Beaugrand et al., 2002). Because copepods are prey for many larger marine organisms, these shifts could have substantial effects on the entire ecosystem, especially on fish abundances, with a possible decline or collapse in the stock of boreal species such as cod (Beaugrand et al., 2002; Sundby, 2000). Temperature can also impact trophic dynamics because each species has different temperature sensitivities; thus, when temperatures rise, predator-prey interactions can be altered based on the thermal sensitivities of the species involved. Studies have found that in temperate estuaries, crustaceans are more readily able to cope with an increase in temperature, even increasing their growth potential, than their predators (fish species) and bivalve prey. As a result, bivalve recruitment could be negatively affected due to higher predation pressure (Freitas et al., 2007).

Table D-1. Summary of studies supporting the assumption that temperature sets the warm-edge range limits of marine species. Studies are limited to references not included in the Cahill et al. (2013) review.

Species	Taxon	Experiment/Approach	Evidence Type	Species' Response/Main finding	Citation
Mytilus edulis	Bivalve	Tested levels of stress-70 protein isoforms of 70, 72 and 78 kDa	Physiological/Biochemica I: Protein synthesis and denaturation	High temperature caused protein denaturation, suggesting that the mussels' distribution is restricted by temperature	Chapple et al., 1998
Maja squinado	Crustacean	Measured physiological limitations of thermal tolerance	Physiological: Aerobic scope	Limited circulation and ventilation at high temperatures caused insufficient oxygen supply, thus limiting aerobic scope and thermal tolerance	Frederich and Pörtner, 2000
Five coral reef fishes	Fish	Tested the effect of increased water temperatures on the resting and maximum rates of oxygen consumption	Physiological: Aerobic scope	Aerobic scope decreased in all species due to increased temperature increases of 2-4 °C, but varied across species, suggesting changes in community composition with climate change	Nilsson et al., 2009
Zoarces viviparus	Fish	Examined thermally limited oxygen delivery in southernmost distribution area	Physiological: Aerobic scope/growth	Growth performance decreased and heat-induced mortality occurred as a result of thermally limited oxygen delivery in higher temperatures	Pörtner and Knust, 2007
Gadus morhua, Zoarces viviparus	Fish	Reviewed and analyzed temperature-dependent metabolic adaptation, energy budgets, biogeography, and fitness	Physiological: Aerobic scope/Range shift: Expansion of higher latitude limit/Trophic effects	Population declined due to high temperatures as a result of oxygen limitation, range shifted poleward, loss of larger copepod species, changing trophic dynamics	Pörtner et al., 2008
Acanthochromis polyacanthus	Fish	Tested the effect of temperature on growth	Physiological: Growth	Growth performance of juveniles and adults declined at maximum sea surface temperature experienced at location	Munday et al., 2008
NA	Marine invertebrates	Examine the effect of temperature on larval development	Physiological: Growth	Temperature best explained latitudinal differences in developmental rates in marine invertebrates, increased temperature affected developmental rates and time to hatching	Hoegh- Guldberg and Pearse, 1995

Species	Taxon	Experiment/Approach	Evidence Type	Species' Response/Main finding	Citation
Engraulis japonicus, Sardinops melanostictus	Fish	Examined the optimal temperature for growth of larva	Physiological: Growth	Japanese anchovy and Japanese sardine regime shift occurred due to different optimal temperature for larval growth (optimal growth rate for anchovy larvae occurred at 22.0 °C, whereas that for sardine larvae occurred at 16.2 °C)	Takasuka et al., 2007
Cheilodactylus spectabilis	Fish	Examined effect of warming sea water on growth and metabolism using changes in otoliths over 90 years	Physiological: Growth	Reduced growth as a result of high temperatures at the warm boundary, suggesting increased metabolic costs	Neuheimer et al., 2011
360 species or species groups	Fish and invertebrates	Measured range shifts to understand how marine species respond to climate velocity	Range shift: Climate velocities	Marine taxa follow climate velocities, thus variation in species range shifts can be explained by local variation in temperature, species tended to shift deeper when experiencing increased sea surface temperature	Pinsky et al., 2013
Semibalanus balanoides	Crustacean	Transplant experiments and thermal modelling to investigate role of climate on poleward contraction of southern range	Range shift: Contraction of lower latitude limit	Southern limit contracted 350 km northward, mortality occurred in transplanted barnacles in the sun due to high temperatures during aerial exposure	Jones et al., 2012
NA	Fish	Examined shifts in species' boundaries and centers of distribution in response to increased temperature	Range shift: Contraction of lower latitude limit and expansion of higher latitude limit	>2/3 of species' distributions shifted in response to climatic warming (shifted poleward or moved deeper in the water column), southern boundaries of ½ of the fish shifted north	Perry et al., 2005
Semibalanus balanoides, Diopatra neapolitana	Crustacean, polychaete	Comparing distribution changes with temperature changes	Range shift: Contraction of lower latitude limit and expansion of higher latitude limit	Southern geographic limit of the barnacle retreated 300 km, northern geographic limit of the polychaete shifted poleward 300 km	Wethey and Woodin, 2010

Species	Taxon	Experiment/Approach	Evidence Type	Species' Response/Main finding	Citation
NA	Marine ectotherms and terrestrial species	Test predictions of thermal tolerance in relation to range and range shifts	Range shift: Contraction of lower latitude limit and expansion of higher latitude limit	Marine ectotherm ranges expanded northward and contracted at the southern boundary due to thermal tolerance, latitudinal ranges correspond to thermal tolerance	Sunday et al., 2012
Arctica islandica, Spisula solidissima	Bivalves	Examined effects of rising temperature on distribution	Range shift: Contraction of lower latitude limit	Lower growth rate and tissue weight occurred at high density at southern edge of range, predicted contraction of southern range limit	Weinberg et al., 2002
9 species	Crustacean, polychaete	Examined the effect of extreme temperature events and tested mechanistic geographic hypothesis on the factor that sets range	Range shift: Extreme temperature event	Extreme temperature events affect population distributions, climate change is punctuated by extreme episodes and the rate of change of temperature is highly variable, thus the spatial pattern of range shifts varies	Wethey et al., 2011
9 species categories	Coral	Examined 80 years of SST data and range changes of coral	Range shift: Expansion of higher latitude limit	Four major coral species categories shifted poleward at 14 km/year since 1930	Yamano et al., 2011
Teredo bartschi	Bivalve	Evaluated species in the thermal effluent of a nuclear generating station	Range shift: Expansion of higher latitude limit	The southern wood borer, <i>Teredo bartschi,</i> was found in New Jersey only in the thermal effluent. The northern distributions of another wood borer, <i>Teredo furcifera,</i> and polychaete, <i>Ficopomatus enigmaticus,</i> also appear to be related to the thermal effluent.	Hoagland and Turner, 1980
45 species	Invertebrate intertidal species	Reported changes in abundance/distribution of 45 species over 61 years	Range shift: Expansion of higher latitude limit	Ranges shifted northward and community structure was altered due to relative changes of abundances of species	Barry et al., 1995
NA	Crustacean	Examined copepod range shifts and ecosystem changes due to temperature increases	Range shift: Expansion of higher latitude limit /Trophic effects	Northward extension occurred of more than 10° latitude of warm-water species associated with a decrease in the number of colder water species, negatively affects boreal species due to food web changes	Beaugrand et al., 2002, 2009
Gadus morhua	Fish	Examined the effect of temperature on recruitment	Impaired fecundity/Recruitment	Negative relationship between temperature and recruitment of Atlantic cod stocks located in warm water	Planque and Frédou, 1999

Species	Taxon	Experiment/Approach	Evidence Type	Species' Response/Main finding	Citation
Limanda, Microstomus kitt, Pleuronectes platessa	Fish	Examined the effect of temperature on spawning time, recruitment, and distribution of fish	Impaired fecundity/Recruitment	Temperature during gonadal maturation affects recruitment and distribution through influence of rate of gonadal maturation and spawning time, negative correlation between temperature and abundance	Lange and Greve, 1997
Macoma balthica	Bivalve	Studied the population responses to warmer than average temperatures	Studied the population responses to warmer than average temperaturesImpaired fecundity/RecruitmentWarming temperatures caused a reduction of reproductive output and recruitment, decreased growth, and increased mortality due to low BMI condition valuesE a		Beukema et al., 2009
NA	Fish	Examined the effect of temperature on recruitment, growth, and trophic dynamics	Impaired fecundity/Recruitment /Trophic effects	Temperature affected body size, growth, differentiation of muscle and meristic characters, predicted a mismatch of larvae with their food supply	Blaxter, 1992
Macoma balthica	Bivalve	Examined temperature- induced effects on reproduction, onset of spawning, and juvenile mortality rate	Impaired fecundity/Recruitment /Trophic effects	Rising seawater temperature affected recruitment by a decrease in reproductive output and by spring advancement of bivalve spawning, rising temperature causes a mismatch of spawning, phytoplankton bloom, and settlement of juvenile shrimp	Philippart et al., 2003
Calanus finmarchicus, Gadus morhua	Fish, crustacean	Examined the effect of temperature on recruitment and trophic dynamics	Impaired fecundity/Recruitment /Trophic effects	Atlantic cod in the uppermost part of the temperature range show a decrease in recruitment with increasing temperature due to effects on vital rates and food web	Sundby, 2000
NA	Phytoplankton	Examined relationships between temperature and biomass of primary producers	Trophic effects	Temperature explained 73% of variance in the relative contribution of small cells to total phytoplankton biomass, predicting a shift toward smaller primary producers in warmer ocean, changing trophic dynamics	Morán et al., 2010
NA	Benthic intertidal species	Examined temperature sensitivity of predators versus prey	Trophic effects	Different thermal tolerances in predator/prey changed trophic dynamics (more predator pressure) and negatively affected prey recruitment	Freitas et al., 2007

Appendix E. Metadata of GIS Analysis of Temperature and Ocean Acidification Values

E-1 Aragonite Saturation State Projections by MEOW Ecoregion GIS Process

Aragonite saturation state projections to 2100 (Cao and Caldeira, 2008) in netCDF format were obtained from Long Cao on 7/19/2014. These data were outputs from a coarse resolution model coupled with a climate-carbon cycle model that had a horizontal resolution of 1.8° latitude and 3.6° longitude (approximately 200 km X 400 km at the equator).

The ArcGIS 10.2.2 Multi-dimension tool MAKE NetCDF RASTER LAYER was used to convert aragonite saturation state netCDF formatted data into ArcInfo grid format rasters for RCP8.5 scenarios for 2010 (baseline), 2050 and 2100. In order to overlay these data with the marine and estuarine portions of the Marine Ecoregions of the World (MEOW) ecoregion polygons, the ArcGIS 10.2.2 Raster Projection SHIFT tool was used to shift their x coordinates by -180 degrees so that the Prime Meridian was -180 degrees (International Date Line). The ArcGIS 10.2.2 Spatial Analyst tool EXTRACT BY MASK was then used to 'clip' the aragonite saturation state grids to the MEOW marine ecoregions.

The values in the resulting grid cells were multiplied by 100, integerized and converted to vector polygon shapefiles. The resulting shapefiles were overlaid with the marine and estuarine portion of the MEOW polygons using the INTERSECT tool and projected into an Albers equal area projection. Items were created in the resulting shapefile's attribute tables, to: 1) calculate area in square meters, 2) to divide the GRIDCODE item by 100 to restore the projected aragonite saturation state values and 3) to calculate the product of area and aragonite saturation values.

These attribute tables (.dbf files) were then opened in Excel and saved as Excel files. Pivot tables were inserted in each file and the area values and area X aragonite saturation values were summarized by MEOW ecoregion. The final step to calculate the mean aragonite saturation state projected values by ecoregion for 2010, 2050, and 2100 was to divide the sum of aragonite saturation state projected values by the sum of the areas of each ecoregion.

E-2 NOAA Climate Projections by MEOW Ecoregion GIS Process

Historical climate (1956-2005) and Anomaly (2050-2099) data were downloaded from NOAA's Climate Data Portal (Table E-1) as netCDF files using the "Average of all Models" data selection variable. The data variables available when the statistic selected is anomaly includes: anomaly, histclim, histstddev, and varratio. We used the 'histclim', which represents the average historical 1956-2005 values as stated in http://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html:

"If the user selects "Anomaly" as the statistic: The climate change panel (upper right) will show the difference in the mean climate in the future time period (RCP8.5) compared to the historical reference period. The climate variability panel (lower left) will show the average inter-annual (de-trended)

standard deviation for the historical reference period (1956-2005) (or just a single model's historical variability). The change in variability (lower right panel) is expressed as a ratio of the de-trended variance (average or single model) in the future, divided by the past."

The Marine Geospatial Ecology Toolkit (MGET) and zonal statistics tools were used to streamline the GIS process that was used to extract aragonite saturation data from the netCDF format files. These tools are available from these two websites:

http://mgel.env.duke.edu/mget

and

http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/zonal-statistics.htm.

Headers for each netCDF file were extracted in ArcMap 10.2.2 using the MGET tool 'Find netCDFs and Extract Headers' then copied and pasted into the Header Files Tab of the MGET tool 'Convert 2D Variable in NetCDF to ArcGIS raster.

Data were summarized from the resulting rasters using the marine and estuarine portion of the Marine Ecoregions of the World (MEOW) polygons by the Spatial Analyst tool 'Zonal Statistics as table' which calculated the following statistics: AREA, MIN, MAX, RANGE, MEAN, STD and SUM. Thirteen MEOW ecoregions were analyzed from the Mexican Tropical Pacific to the Beaufort - continental coast and shelf.

Table E-1. Historical climate (1956-2005) and Anomaly (2050-2099) data. Data were downloaded from NOAA's Climate Change Web Portal at: <u>http://www.esrl.noaa.gov/psd/ipcc/ocn/</u>. The downloaded data were analyzed by MEOW ecoregion

CALCULATED VALUES	SEASON	21 st CENTURY PERIOD
Average historical SST AND projected SST by ecoregion	Entire Year	2005-2099
Average historical SST AND projected SST by ecoregion	July-AugSept.	2005-2099
Average historical SST AND projected SST by ecoregion	JanFebMarch	2005-2099
Average historical air temp. AND projected air temp. by ecoregion	Entire Year	2005-2099
Average historical air temp. AND projected air temp. by ecoregion	July-AugSept.	2005-2099
Average historical air temp. AND projected air temp. by ecoregion	JanFebMarch	2005-2099
Average historical pH AND projected pH by ecoregion	Entire Year	2005-2099
Average historical pH AND projected pH by ecoregion	July-AugSept.	2005-2099
Average historical pH AND projected pH by ecoregion	JanFebMarch	2005-2099
Average historical ChI AND projected ChI by ecoregion	Entire Year	2005-2099
Average historical ChI AND projected ChI by ecoregion	July-AugSept.	2005-2099
Average historical ChI AND projected ChI by ecoregion	JanFebMarch	2005-2099
Average historical 30-m temp. AND projected 30-m temp. by ecoregion	Entire Year	2005-2099
Average historical 30-m temp. AND projected 30-m temp. by ecoregion	July-AugSept.	2005-2099
Average historical 30-m temp. AND projected 30-m temp. by ecoregion	JanFebMarch	2005-2099
Average historical 50-m temp. AND projected 50-m temp. by ecoregion	Entire Year	2005-2099
Average historical 100-m temp. AND projected 100-m temp. by ecoregion	Entire Year	2005-2099

CALCULATED VALUES	SEASON	21 st CENTURY PERIOD
Average historical 200-m temp. AND projected 200-m temp. by ecoregion	Entire Year	2005-2099

Glossary of Terms

Term	Definition
Absent	Term previously used in CBRAT to indicate the <i>Error/Extinct</i> classification.
Abyssal	A vertical depth zone in the ocean between ≥2000 to 6000 m.
Albers projection	Albers equal-area conic projection. A conic, equal area map projection that uses two standard parallels. Although scale and shape are not preserved, distortion is minimal between the standard parallels. See http://desktop.arcgis.com/en/arcmap/latest/map/projections/albers-equal-area-conic.htm .
Algorithm-based risk assessment	Risk assessment based on a knowledge base (database) and a rule set, with no expert intervention in calculating final risks. Used to avoid the limitations of expert solicitations, include potential sources of bias.
Anadromous	Species that spend most of their lives in saltwater and migrate to freshwater to breed.
Aragonite	A highly soluble form of calcium carbonate.
Aragonite saturation state (Ωa)	The ratio of the concentration of aragonite present in sea water compared to the total amount of aragonite that sea water could hold when saturated, symbolized by Ωa . When $\Omega a < 1$, the seawater is undersaturated with respect to aragonite, and aragonite shells will tend to dissolve.
Arctic endemic	Native to the Arctic region and not occurring naturally anywhere else.
Area of occupancy (AOO)	Area of the outermost limits over which a species actually occurs; total area of all patches occupied by a species.
Baseline/Status Risk	Baseline risks are inherent biotic traits of species that increase vulnerability to climate change. Status risks are changes in a species' viability (e.g., population decline) due to external factors, such as overfishing that increase vulnerability to climate change.
Bathyal	> 200 – 2000m. This benthic zone is below the euphotic zone and extends down the continental slope.
Benthic larvae	Larvae that remain on the bottom or within the tubes of adults.
Benthopelagic	Animals living all or part of their life in the water column directly above but not on the bottom.
Binary fission	Reproduction by splitting into two approximately equal parts.
Brachyuran crabs	Decapod crustaceans of the infraorder Brachyura. True crabs not to be confused with similarly named animals such as hermit crabs, king crabs, porcelain crabs, or horseshoe crabs.
Brackish	Salinity 0.5 – < 30 psu.
Broadcast spawner	Both males and females discharge gametes into the water column.
Brooded	The larval or juvenile phase is brooded within the adult or tube of the adult; ovoviviparous.

Term	Definition
Budding and fragmentation	Splitting into unequal parts. Buds may form on the body of the "parent".
Calcite	Carbonate mineral CaCO ₃ .
Catadromous	Species that spend most of their lives in freshwater and migrate to saltwater to breed.
CBRAT	Coastal Biodiversity Risk Analysis Tool (<u>http://www.cbrat.org</u>).
Chemoautotrophic	Organisms, typically bacteria, that derive their energy from inorganic sources, including sulfides and ferrous iron. Chemoautotrophic bacteria live symbiotically with certain organisms, providing nutrients to their host. Chemosynthetic.
Climate-adjusted baseline/status risk	Greatest baseline/status risks weighted by the greatest climate risk.
Coastal acidification	Reduction in pH in near-coastal waters, including estuaries, as opposed to reductions in pH in ocean waters.
Coastal Biogeographic Risk Analysis Tool (CBRAT)	Ecoinformatic tool synthesizing life history, habitat, distributional, and abundance data on near-coastal species. Predict vulnerability to climate change, including temperature increases, ocean acidification, and sea level rise. Available at <u>http://www.cbrat.org</u> .
Coolest Occupied Ecoregion (COE)	In CBRAT, the COE is the coolest ecoregion in which the species maintains a viable population. Different ecoregions may be defined as the COE depends upon the specific temperature measurement (air, SST, subsurface).
Cold temperate province	In the MEOW biogeographical schema, provinces are the unit larger than ecoregions and smaller than realms. In the NEP, the Cold Temperate Northeast Pacific Province is composed of the Aleutian Islands, Gulf of Alaska, North American Pacific Fjordland, Puget Trough/Georgia Basin, Oregon, Washington, Vancouver Coast and Shelf, and Northern California ecoregions.
Constrained	As used in CBRAT, SLR predictions of habitat loss in which the habitat is not allowed to migrate inland due to anthropogenic or natural barriers. See Unconstrained.
Coupled Model Inter- comparison Project Phase 5 (CMIP5)	A climate model based on an international effort (<u>http://cmip-pcmdi.llnl.gov/</u>). CMIP5 was used in IPCC Fifth Assessment. Results are served by the NOAA's Climate Web Portal (<u>http://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html</u>).
Cryptic species	Two or more distinct species classified as a single species.
Cryptofauna	Sessile and vagile organisms living in the interstices and crevices formed by epibenthic organisms or their structures, such as formed by mussel beds, living corals, and coral rubble.
Decomposer	Organisms that breakdown and digest dead organisms. Bacteria and fungi are major decomposer groups.
Deep subtidal	> 30 – 200 m depth.
Deposit feeder	Animal that ingests sediment particles, feeding on the associated detritus, microflora, and microorganisms.

Term	Definition
Detritivore	Animals that feed on small detritus (i.e., plant and animal remains). Q.v. scavenger.
Direct development	Development without a larval phase.
Dominance normalized relative abundance (DNRA)	As defined in this document, abundance of a species divided by the average abundance of the dominant species in the sample, where dominant species are defined as those constituting ≥75% of the individuals.
Ecoregion	In the Marine Ecoregions of the World (MEOW) biogeographic schema, ecoregions are the smallest coastal unit. They are defined as areas "of relatively homogeneous species composition, clearly distinct from adjacent systems." Globally, there are 232 ecoregions. See http://www.worldwildlife.org/publications/marine-ecoregions-of-the-world-a-bioregionalization-of-coastal-and-shelf-areas .
Ectoparasite	External parasite, including gill parasites.
Endemic	Species only located in a restricted location. In CBRAT, defined as species occurring in only one ecoregion.
Endoparasite	Internal parasite.
Epibiotic	Organisms living on surface of a living or dead organism. Relationship may be mutualistic, parasitic, or commensal.
Epiphytic	Living on surface of living or dead plant.
Epizoic	Living on surface of a living or dead animal.
Error/Extinct	Species that have been reported to occur in an ecoregion but do not actually occur, either because they were incorrectly reported or because they went extinct in the ecoregion See <i>Hierarchical abundance classification schema</i> .
Eustatic sea level rise (ESLR)	Worldwide change in sea level primarily caused by thermal expansion of sea water and melting of glaciers and ice sheets.
Expert solicitation	A formal or informal synthesis of opinions from experts on a designated topic. Also referred to as expert opinion.
Extent of occurrence (EOO)	Distance or area between the outermost limits of the occurrence of a species. The broad range of a species.
Folivore	Feeds on leaves.
Free scale pH (pH _F)	See pH
Freecast spawners	In animals, males and/or females discharge gametes directly into the water column.
Gonochoristic / Dioecious	Having separate sexes. In plants, male and female flowers are produced on different individuals.
Grazer	An organism that feeds by rasping benthic algae from sediment, rocks, or leaf surfaces. May consume some smaller benthic organisms, but if animals are dominant food source, the species is classified as a predator.
Hadal	> 6000 m. The deepest areas of the sea, including ocean trenches.

Term	Definition
Haploid/diploid phases	In plants, fungi, kelp, and some microorganisms, an alternation of multicellular haploid and diploid phases.
Hermaphrodite/ Monoecious	Organisms having both male and female sexual organs.
Heterogamy	Alternation between sexual and asexual (parthenogenetic) reproductive phases.
Hierarchical abundance classification schema	In CBRAT, a classification schema for species' relative abundance within an ecoregion. The abundance classifications are arranged in three levels according to the amount of available data: Level I: <i>Present, Not Reported, Error/Extinct, and Transient.</i> Level II: <i>Abundant, Moderate, Rare.</i> Level III: <i>Very Abundant, Moderately Abundant; High Moderate, Low Moderate; Moderately Rare, Very Rare, Hyper-rare.</i>
Holoplankton	Species that are planktonic for their entire life cycle.
Hybrid approach to estimating relative	A systematic approach to combining multiple lines of evidence to assign relative abundances. The following sources are listed in order of the weight assigned them:
abundance	Regional scale, randomized surveys such as the previous EMAP surveys.
	Regional-scale, non-randomized quantitative surveys, such as NOAA's RACE surveys.
	Expert opinion addressing the ecoregional abundance of a taxon.
	Local randomized and non-randomized surveys.
	Natural history and taxonomic texts.
	Frequency of occurrence data such as from OBIS and GBIF.
Hyperbenthos	Benthic animals that make periodic forays from the bottom into the water column, such as some of the corophiid amphipods.
Hyper-rare species	Species that have not been observed in \geq 50 years assuming at least a minimal sampling effort.
Intrinsic rate of increase (r)	The theoretical maximum rate of increase of a population per individual, assuming no density-dependent effects.
Island ecoregion	In CBRAT, a MEOW ecoregion that is surrounded by water with no direct contact with the mainland. Small island ecoregions have a land area of ≤200 km².
Isostatic adjustment	Vertical movement of the earth's plates resulting in local uplift or subsidence and the raising or lowering of sea level.
Kleptoparasite	Parasites that feed on the food items that the host has collected; symbionts that "steal" food from their hosts.
Lecithotrophy	Larvae that derive nourishment from yolk.
LIDAR	Light Detection and Ranging; a remote sensing method that uses light from a pulsed laser to accurately measure distance to the Earth, from which precise three-dimensional maps can be generated. See http://oceanservice.noaa.gov/facts/lidar.html .

Term	Definition
Lithodid crabs	Crabs of the families Lithodidae and Hapalogastridae. King crabs, not "true" crabs of the Infraorder Brachyura.
Marine Ecoregions of the World (MEOW)	The Marine Ecoregions of the World (MEOW) is a global biogeographic system for coastal and shelf areas consisting of a nested system of 12 realms, 62 provinces, and 232 ecoregions. See http://www.worldwildlife.org/publications/marine-ecoregions-of-the-world-a-bioregionalization-of-coastal-and-shelf-areas .
Maximum acceptable toxicant concentration (MATC)	In toxicology, the MATC is the greatest acceptable concentration, calculated as geometric mean of the "no observed adverse effects level" (NOAEL) and the "lowest observed adverse effects level" (LOAEL). When applied to pH and aragonite saturation state, the MATC is the <i>lowest</i> acceptable level.
Medusa/polyp phases	In Cnidaria, an alternation between a polypoid benthic stage and a free-living medusoid stage.
Meroplankton	Species that are planktonic for only part of their life cycle, usually the larval phase.
Mixed fines	Combination of mud and sand, where the two classes constitute >95% of the weight. Do not confuse with "mixed sediments", a mixture of mud/sand and cobble/gravel/rock.
Mixed sediments	Unconsolidated sediment composed of both sand and mud with gravel or cobble, where gravel and cobble constitute >5% but <75% of the sediment weight. Do not confuse with "mixed fines".
Monoecious (plants)	Plants having separate male and female flowers on the same individual plant.
Near coastal	As used in CBRAT, the region from the supratidal down to 200 m depth. Includes both estuaries and offshore areas.
Negative evidence	Evidence based on not observing an expected event. In CBRAT, absence or a limited number of reports of a species is used as potential evidence for rarity in an ecoregion.
Neritic	> 0 – 200m. Subtidal zone extending from the low water mark to the approximate edge of the continental shelf. Also referred to as the sublittoral zone or coastal waters.
Network Common Data Form (netCDF)	Data formats that support the creation, access, and sharing of array-oriented scientific data. Often used for oceanographic data. See <u>http://www.unidata.ucar.edu/software/netcdf/</u> .
Next Coolest Unoccupied Ecoregion (NCUE)	In CBRAT, the MEOW ecoregion that is not occupied by the target species and is the next coolest ecoregion compared to the coolest occupied ecoregion (COE). Assumed that the temperature in the NCUE is too cool for the species is to maintain a viable population.
Next Warmest Unoccupied Ecoregion (NWUE)	In CBRAT, the MEOW ecoregion that is not occupied by the target species and is the next warmest ecoregion compared to the warmest occupied ecoregion (WOE). Assumed that the temperature in the NWUE is too warm for the species is to maintain a viable population.
Nonindigenous species (NIS)	Species introduced outside of their natural range via anthropogenic vectors, such as ballast water discharges. Also referred to as exotic species or invaders.
Northeast Pacific (NEP)	As used in CBRAT, the near-coastal region from the Aleutians Islands through the Gulf of California.

Term	Definition
Ocean acidification (OA)	A reduction in the pH of the ocean caused primarily by uptake of carbon dioxide (CO ₂) from the atmosphere. Q.v. Coastal acidification.
Oceanic	As used in CBRAT, > 200 m depth. Includes the benthos and water above the continental slope and ocean floor. Also includes deeper portion of inland seas like Puget Sound and Gulf of California.
Osmotrophy	Uptake of dissolved organic compounds by osmosis for nutrition. Can be the sole source of nutrition or a supplemental source.
Oviparous	Eggs are laid by the female and develop outside of either parent. Crabs are considered oviparous rather than ovoviviparous.
Ovoviviparous	Eggs develop within the female, or male in some cases, but the embryo derives no nourishment from the parent. A brooder.
Parthenogenesis / Agamospermy	In animals, parthenogenesis is the development of an unfertilized egg. In plants, agamospermy (apomixes) is the production of fertile seeds without pollination.
рН	Measure of the acidity (pH <7) or basicity (pH >7) of a solution. Theoretically, the negative of the logarithm to base 10 of the activity of the hydrogen ion. Operationally, pH in seawater has been measured by four different scales that can differ by more than 0.1 pH unit.
	Free scale pH (pH _F): pH = $-\log_{10}[H+]$. This measures the free H ⁺ ion concentration, which corresponds to the theoretical definition of pH. However, it is difficult to measure free ion concentration in seawater. Further, it does not include other ions, such as sulfate, that affect the "acidity" of seawater.
	NBS scale pH (pH _{NBS}): pH obtained with glass electrodes when calibrated against an NBS or NIST buffer. NBS buffers have a low ionic strength (ca. 0.1 mol kg ^{-1}) compared to full-strength seawater (ca. 0.72 mol kg $_{-1}$), and the use of such dilute buffers are not generally recommended for seawater.
	Total scale pH (pH $_{\rm T}$): The total scale pH includes both hydrogen ions and sulfate ions in the calculation.
	Seawater scale pH (pH _{SWS}): The seawater scale pH includes hydrogen ions, sulfate ions, and fluoride ions in the calculation.
Planktonic larvae	Larvae that spend at least part of the larval phase in the water column.
Planktotrophic larvae	Larvae that feed on other organisms.
Primary producer	Organism whose metabolic energy is derived from sunlight or chemosynthesis in contrast to consumption of other organisms.
Protandry	Initially a male and changes to a female.
Protogyny	Initially a female and changes to a male.
Rare	See "Hierarchical abundance classification schema".
Red List	List of threatened and endangered plant and animal species produced by the IUCN. See https://www.iucn.org/resources/conservation-tools/iucn-red-list-threatened-species .

Term	Definition
Relative abundance	Abundances normalized to some measure of the abundances of other species in the taxon or guild. Values depend upon what taxon or guild is used to relativize the abundances. In CBRAT, quantitative abundances are normalized to the average abundance of the dominant species within major taxa in a sample (see Dominance normalized relative abundance). See "Hierarchical abundance classification schema" for relative abundance classes used in CBRAT.
Relative sea level rise (RSLR)	The net change in sea level at a particular location due to both eustatic SLR and local factors.
Representative Concentration Pathways (RCP)	A set of four climate pathways (scenarios) expressed in radiative forcing value (W/m2). RCP 2.6 reflects the lowest emissions while RCP 8.5 reflects continuing emission increases through the 21st century as a result of both high population growth and a slower rate of technology development (van Vuuren et al., 2011).
Rhodoliths / Maerl	Free-living masses of coralline algae forming a hard substrate. Large aggregations of rhodoliths can form beds covering hectares. Referred to as maerl in Europe.
Rule-based system	A system of representing human expert knowledge in an automated system by coding logical assertions as IF-THEN statements. Approach used in CBRAT to automatically calculate risks to climate change as an alternative to expert solicitation.
Scavenger	Feeds on dead organic material. Usually used for species feeding on larger particles or animal remains.
Scenario modelling	Evaluation of how risks change under different climate scenarios.
Seawater scale pH (pHsws):	See pH.
Sequential hermaphrodite	Animals that change their sex, from male to female or from female to male.
Shallow subtidal	> 0 – 30 m depth.
Specialized systems	As used in CBRAT, ecosystems composed of benthic and pelagic habitats with physical and/or chemical characteristics distinct from surrounding ecosystems (e.g., saline lagoons, hydrothermal vents).
Spermcast spawner	Only male discharges gametes into the water column.
Sporogenesis	Reproduction and dispersal through formation of spores. Spores differ from seeds in having little food reserves. Most spores are haploid and may be part of an alternation of haploid and diploid life history stages. Red algae have both diploid and haploid spores.
Subsurface deposit feeder	Deposit feeder that ingests subsurface particles.
Summer temperatures (months used)	July, August and September: used in modeling the effects of summer temperature increases.
Supralittoral	Area above the high water level that is periodically wetted by breaking waves or during extreme storms. The splash zone.

Term	Definition
Surface deposit feeder	Animals that ingests particles at the sediment interface.
Suspension feeder	Feeds on phytoplankton, zooplankton, and/or suspended particles in the water column.
Symbiont	Organisms living in direct contact or close physical proximity with another organism, including commensal (+/0), neutral (0/0, and negative (-/+) relationships.
Symbiotic algae	Microflora living in association with other organisms, supplying nutrition to the host (e.g., hermatypic corals).
Synchronous hermaphrodite	Animals having both male and female sexual organs at the same time (i.e., simultaneous hermaphrodites).
Temperature-adjusted ocean acidification risk	Risk due to reduced pH or aragonite saturation state incorporating interaction with enhanced temperatures.
TopoBathy	GIS layers that combine topography (land elevation) and bathymetry (water depths).
Total scale pH (pH $_{\rm T}$)	see pH.
Transient	A species that temporarily inhabits an ecoregion beyond its normal range due to unusual climatic or oceanographic events. By definition, transients are unable to maintain a long-term viable population in the new ecoregion under present conditions.
Uncertainty Analysis	Evaluation of how risks change with different effects thresholds and/or model assumptions. Less formal than a sensitivity analysis.
Unconstrained	In CBRAT, SLR predictions of habitat loss in which the habitat is allowed to migrate inland; absence of anthropogenic or natural barriers to landward migration of intertidal habitats. See Constrained.
Vegetative propagation	Formation of new individuals in plants without the production of spores or seeds by stolons (runners) or formation of bulbs.
Viviparous	Development takes place within the female and embryo derives nourishment from the mother.
von Bertalanffy growth coefficient (k)	In the von Bertalanffy growth equation, k is the rate (1/year) at which the asymptotic length (size) is approached.
Warm temperate province	In the MEOW biogeographical schema, provinces are the unit larger than ecoregions and smaller than realms. In the NEP, the Warm Temperate Northeast Pacific Province is composed of the Southern California Bight, Magdalena Transition and Cortezian ecoregions.
Warmest occupied ecoregion (WOE)	In CBRAT, the WOE is the warmest ecoregion in which the species maintains a viable population. Different ecoregions may be defined as the WOE depends upon the specific temperature measurement (air, SST, subsurface).
Winter temperatures (months)	January, February, and March: used in modeling the effects of winter temperature increases in CBRAT.

Term	Definition
Wrack	Phytodetritus, including kelp, other macroalgae and SAV, deposited in the upper intertidal on both coastal shores and in estuaries.

THIS PAGE INTENTIONALLY BLANK

Bibliography

- Abele, L.G. 1976. Comparative species composition and relative abundance of decapod crustaceans in marine habitats of Panama. Marine Biology 38: 263–278.
- Aburto-Oropeza, O., Ezcurra, E., Danemann, G., Valdez, V., Murray, J. and Sala, E. 2008. Mangroves in the Gulf of California increase fishery yields. Proceedings of the National Academy of Sciences 105: 10456–10459.
- Ægisdóttir, S., White, M.J., Spengler, P.M., Maugherman, A.S., Anderson, L.A., Cook, R.S., Nichols, C.N., Lampropoulos, G.K., Walker, B.S., Cohen, G., and Rush, J.D. 2006. The meta-analysis of clinical judgment project: Fifty-six years of accumulated research on clinical versus statistical prediction. The Counseling Psychologist 34: 341–382.
- Agnalt, A.L., Grefsrud, E.S., Farestveit, E., Larsen, M., and Keulder, F. 2013. Deformities in larvae and juvenile European lobster (*Homarus gammarus*) exposed to lower pH at two different temperatures. Biogeosciences 10: 7883–7895.
- Akçakaya, H.R., Butchart, S.H.M., Mace, G.M., Stuart, S.N., and Hilton-Taylor, C. 2006. Use and misuse of the IUCN Red List Criteria in projecting climate change impacts on biodiversity. Global Change Biology 12: 2037–2043.
- Allen, J.D. and Pernet, B. 2007. Intermediate modes of larval development: bridging the gap between planktotrophy and lecithotrophy. Evolution and Development 9: 643–653.
- Allen, L.G., Yoklavich, M.M., Cailliet, G.M., and Horn, M.H. 2006. Bays and Estuaries. The Ecology of Marine Fishes – California and Adjacent Waters. (Eds. Allen, L.G., Pondella, D.J., and Horn, M.H.) 119–148. University of California Press. Berkeley 671 pages.
- Alongi, D.M. 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Coastal and Shelf Science. 76: 1–13.
- Alongi, D.M. 2015. The impact of climate change on mangrove forests. Current Climate Change Reports 1:30-39.
- Angulo, E.A., Deves, L., Saint Jalmes, M., and Courchamp, F. 2009. Fatal attraction: rare species in the spotlight. Proceedings of the Royal Society of London B: Biological Sciences 276: 1331–1337.
- Anlauf, H., D'Croz, L., O'Dea, A. 2011. A corrosive concoction: the combined effects of ocean warming and acidification on the early growth of a stony coral are multiplicative. Journal of Experimental Marine Biology and Ecology 397: 13–20.
- Appelhans, Y.S., Thomsen, J., Pansch, C., Melzner, F., and Wahl, M. 2012. Sour times: seawater acidification effects on growth, feeding behaviour and acid–base status of *Asterias rubens* and *Carcinus maenas*. Inter-Research Marine Ecology Progress Series 459: 85–98.

- Arnberg, M., Calosi, P., Spicer, J.I., Tandberg, H.S., Nilsen, M., Westerlund, S., and Bechmannm, R.K. 2013.
 Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (*Pandalus borealis*) larvae. Marine Biology 160: 2037–2048.
- Arnold, K.E., Findlay, H.S., Spicer, J.I., Daniels, C.L., and Boothroyd, D. 2009. Effect of CO₂-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.). Biogeosciences 6: 1747–1754.
- Babyak, M.A. 2004. What you see may not be what you get: a brief, nontechnical introduction to overfitting in regression-type models. Psychosomatic Medicine 66: 411–421.
- Bálint, M., Domisch, S., Engelhardt, C.H.M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S.U., and Nowak, C. 2011. Cryptic biodiversity loss linked to global climate change. Nature Climate Change 1: 313– 318.
- Barboza, F.R. and Defeo, O. 2015. Global diversity patterns in sandy beach macrofauna: a biogeographic analysis. Scientific Reports 5: 14515, doi: 10.1038/srep14515.
- Barry, J.P., Baxter, C.H., Sagarin, R.D., and Gilman, S.E. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. Science 267: 672–675.
- Beaugrand, G., Luczak, C., and Edwards, M. 2009. Rapid biogeographical plankton shifts in the North Atlantic Ocean. Global Change Biology 15: 1790–1803.
- Beaugrand, G., Reid, P.C., Ibanez, F., Lindley, J.A., and Edwards, M. 2002. Reorganization of North Atlantic marine copepod biodiversity and climate. Science 296: 1692–1694.
- Bechmann, R.K., Taban, I.C., Westerlund, S., Godal, B.F., Arnberg, M., Vingen, S., Ingvarsdottir, A., and Baussant,
 T. 2011. Effects of ocean acidification on early life stages of shrimp (*Pandalus borealis*) and mussel
 (*Mytilus edulis*). Journal of Toxicology and Environmental Health, Part A 74: 424–438.
- Belan, T.A. 2003. Benthos abundance pattern and species composition in conditions of pollution in Amursky Bay (the Peter the Great Bay, the Sea of Japan). Marine Pollution Bulletin 46: 1111–1119.
- Bellard, C., Bertelesmeier, C., Leadley, P., Thuiller, W., and Courchamp, F. 2012. Impacts of climate change on the future of biodiversity. Ecology Letters 15: 365–377.
- Berkeley, S.A., Chapman, C., and Sogard, S.M. 2004. Maternal age as a determinant of larval growth and survival in a marine fish, *Sebastes melanops*. Ecology 85: 1258–1264.
- Bernhardt, J.R. and Leslie, H.M. 2013. Resilience to climate change in coastal marine ecosystems. Annual Review of Marine Science 5: 371–392.
- Beukema, J.J., Dekker, R., and Jansen, J.M. 2009. Some like it cold: populations of the tellinid bivalve Macoma balthica (L.) suffer in various wars from a warming climate. Marine Ecology Progress Series 384: 135– 145.
- Bickford, D., Lohman, D.J., Sodhi, N.S., Ng, P.K.L., Meier, R., Winker, K., Ingram, K.K., and Das, I. 2006. Cryptic species as a window on diversity and conservation. Trends in Ecology & Evolution 22: 148–155.
- Blackburn, T.M. and Gaston, K.J. 1997. Who is rare? Artifacts and complexities in rarity determination. The Biology of Rarity. (Eds. Kunin, W.E. and Gaston, K.J.) Chapman & Hall, London. Pages 48–60.
- Blankespoor, B., Dasgupta, S., and Laplante, B. 2012. Sea-level rise and coastal wetlands: impacts and costs. Policy Research working paper number WPS 6277. Washington, DC: World Bank Group. 27 pages. <u>http://documents.worldbank.org/curated/en/375251468323964212/Sea-level-rise-and-coastal-wetlands-impacts-and-costs</u>.
- Blaxter, J.H.S. 1992. The effect of temperature on larval fishes. Netherlands Journal of Zoology 42: 336–357.
- Blunden, J. and Arndt, D.S. (eds.) 2016. State of the climate in 2015. Bulletin of the American Meteorological Society 97: S1–S275.
- Bopp, L., Resplandy, L., Orr, J.C., Doney, S.C., Dunne, J.P., Gehlen, M., Halloran, P., Heinze, C., Ilyina, T., Séférian, R., Tjiputra, J., and Vichi, M. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. Biogeosciences 10: 6225–6245.
- Branch, T.A., Dejoseph, B.M., Ray, L.J., and Wagner, C.A. 2013. Impacts of ocean acidification on marine seafood. Trends in Ecology & Evolution 28: 178–186.
- Breitburg, D.L., Salisbury, J., Bernhard, J.M., Cai, W.-J., Dupont, S., Doney, S.C., Kroeker, K.J., Levin, L.A., Long, C., Milke, L.M., Miller, S.H., Phelan, B., Passow, U., Seibel, B.A., Todgham, A.E., and Tarrant, A.M. 2015. And on top of all that...: Coping with ocean acidification in the midst of many stressors. Oceanography 28: 48–61.
- Brown, C.J., Schoeman, D.S., Sydeman, W., Brander, K., Buckley, L., Burrows, M., Duarte, C.M., Moore, P.J.,
 Pandolfi, J.M., Poloczanska, E., Venables, W., and Richardson, A.J. 2011. Quantitative approaches in climate change ecology. Global Change Biology 17: 3697–3713.
- Buckley, L.B., Urban, M.C., Angilletta, M.J., Crozier, L.G., Rissler, L.J., and Sears, M.W. 2010. Can mechanism inform species' distribution models? Ecology Letters 13: 1041–1054.
- Bulling, M.T., Hicks, N., Murray, L., Paterson, D.M., Raffaelli, D., White, P.C.L., and Solan, M. 2010. Marine biodiversity–ecosystem functions under uncertain environmental futures. Philosophical Transactions of the Royal Society B: Biological Sciences 365: 2107–2116.
- Busch, D.S. and McElhany, P. 2016. Estimates of the direct effect of seawater pH on the survival rate of species groups in the California current ecosystem. PLoS ONE 11(8): e0160669. https://doi.org/10.1371/journal.pone.0160669.
- Bustamante, R.H., Branch, G.M., and Eekhout, S., 1995. Maintenance of an exceptional intertidal grazer biomass in South Africa: subsidy by subtidal kelps. Ecology 76: 2314–2329.

- Byrne, M. 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: Vulnerabilities and potential for persistence in a changing ocean. Oceanography and Marine Biology: An Annual Review (Eds. Gibson, R.N., Atkinson, R.J.A., Gordon, J.D.M., Hughes, R.N., Hughes, D.J., and Smith, I.P.) 49: 1–42.
- Cadien, D.C. and Lovell, L.L. 2012. Expert Workshops: An Approach to CBRAT Data Acquisition, Correction, and Finalization. Los Angeles, CA: Southern California Association of Marine Taxonomists. 14 pages.
- Cahill, A.E., Aiello-Lammens, M.E., Fisher-Reid, M.C., Hua, X., Karanewsky, C.J., Ryu, H.Y., Sbeglia, G.C., Spagnolo,
 F., Waldron, J.B., and Wiens, J.J. 2013. Causes of warm-edge range limits: systematic review, proximate factors and implications for climate change. Journal of Biogeography 41: 429–442.
- California Natural Resources Agency. 2014. Safeguarding California: Reducing Climate Risk. An Update to the 2009 California Climate Adaptation Strategy. <u>http://resources.ca.gov/docs/climate/Final_Safeguarding_CA_Plan_July_31_2014.pdf</u>
- Cao, L. and Caldeira, K. 2008. Atmospheric CO₂ stabilization and ocean acidification. Geophysical Research Letters 35: 1–5.
- Carter, H.A., Ceballos-Osuna, L., Miller, N.A., and Stillman, J.H. 2013. Impact of ocean acidification on metabolism and energetics during early life stages of the intertidal porcelain crab *Petrolisthes cinctipes*. The Journal of Experimental Biology 216: 1412–1422.
- Ceballos–Osuna, L., Carter, H.A., Miller, N.A., and Stillman, J.H. 2013. Effects of ocean acidification on early life– history stages of the intertidal porcelain crab *Petrolisthes cinctipes*. Journal of Experimental Biology 216: 1405–1411.
- Chan, N. and Connolly, S.R. 2013. Sensitivity of coral calcification to ocean acidification: a meta–analysis. Global Change Biology 19: 282–290.
- Chapple, J.P., Smerdon, G.R., Berry, R.J., and Hawkins, A.J.S. 1998. Seasonal changes in stress–70 protein levels reflect thermal tolerance in the marine bivalve *Mytilus edulis* L. Journal of Experimental Marine Biology and Ecology 229: 53–68.
- Charrette, N.A., Cleary, D.F.R., and Mooers, A.O. 2006. Range restricted, specialist Bornean butterflies are less likely to recover from ENSO–induced disturbance. Ecology 87: 2330–2337.
- Chavez, F.P., Collins, C.A., Huyer, A., and Mackas, D.L. 2002. El Nino along the west coast of North America. Progress in Oceanography 54: 1–5.
- Chenelot, H., Jewett, S., and Hoberg, M. 2008. Invertebrate communities associated with various substrates in the nearshore Eastern Aleutian Islands, with emphasis on thick crustose coralline algae. In: Brueggeman, P., Pollock, N.W. (eds). Diving for science 2008. Proc. Am. Acad. Underwater Sci. 27th Annual Diving Symp., Dauphin Island, Ala., pp 13-36.

- Cheung, W.W.L., Lam, V.W.Y. and Pauly, D. 2008. Modelling present and climate–shifted distribution of marine fishes and invertebrates. Fisheries Centre Research Reports. Vancouver, BC: University of British Columbia 16. 72 pages.
- Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R., and Pauly, D. 2009. Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries 10: 235–251.
- Cheung, W.W.L., Sarmiento, J.L., Dunne, J., Frölicher, T.L., Lam, V.W.Y., Deng Palomares, M.L., Watson, R., and Pauly, D. 2012. Shrinking of fishes exacerbates impact of global ocean changes on marine ecosystems. Nature Climate Change 3: 254–258.
- Christmas, A.-M.F. 2013. Effects of ocean acidification on dispersal behavior in the larval stage of the Dungeness crab and the Pacific Green Shore crab. Western Washington University, Master Thesis. 72 pages.
- Chown, S.L. 2012. Trait–based approaches to conservation physiology: forecasting environmental change risks from the bottom up. Philosophical Transactions of the Royal Society of London Series B: Biological Sciences 367: 1615–1627.
- Chu-Agor, M.L., Muñoz–Carpena, R., Kikera, G.A., Aiello–Lammens, M.E., Akçakaya, H.R., Convertino, M., and Linkov, I. 2012. Simulating the fate of Florida Snowy Plovers with sea–level rise: Exploring research and management priorities with a global uncertainty and sensitivity analysis perspective. Ecological Modeling 224: 33–47.
- Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva, S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., and Unnikrishnam, A.S. 2013. Sea level change. Climate Change 2013: The Physical Basis, Contribution of Working Group I to The Fifth Assessment Report of the Intergovernmental Panel On Climate Change (Eds. Stocker, T.F., Qin, D., Plattner, G.–K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M.). Cambridge. Pages 1029–1136.
- Clark, K.B. 1994. Ascoglossan (=Sacoglossa) molluscs in the Florida Keys: Rare marine invertebrates at special risk. Bulletin of Marine Science 54: 900–916.
- Clinton, P.J. and Lee II, H. 2016. Computing risk to West Coast intertidal rocky habitat due to sea level rise using LiDAR topobathy. ESRI Ocean GIS Forum, Redlands, California, November 01 - 03, 2016. <u>https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=331151</u>.
- Clinton, P.J., Frazier M.R., McCoy, L., Reusser, D., and Lee II, H. 2012. Predicting change in eelgrass distribution due to sea level rise in three Pacific Northwest estuaries. Presented at ESRI Users Conference, San Diego, CA, July 23–27, 2012. <u>https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=240860.</u>
- Clough, J.S., 2008. SLAMM 5.0.2 Technical Documentation. Warren Pinnacle Consulting, Inc. 37 pages.
- Coan, E.V. and Valentich–Scott, P. 2012. Bivalve Seashells of Tropical West America: Marine Bivalve Mollusks from Baja California to Northern Peru. Santa Barbara, Ca. Santa Barbara Museum of Natural History. 1258 pages.

- Coan, E.V., Valentich–Scott, P., and Bernard, F.R. 2000. Bivalve Seashells of Western North America: Marine Bivalve Mollusks from Arctic Alaska to Baja California. Santa Barbara, Ca: Santa Barbara Museum of Natural History. 764 pages.
- Cohen, A. and Holcomb., M. 2009. Why corals care about Ocean Acidification: uncovering the mechanism. Oceanography 22: 118–127.
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.–L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski Jr., W.J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A.J., and Wehner, M. 2013. Long–term climate change: projections, commitments and irreversibility. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the International Panel on Climate Change (Eds. Stocker, T.F., Qin, D., Plattner, G.–K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M.), Cambridge University Press, Cambridge. Pages 1029–1136. http://www.climatechange2013.org/images/report/WG1AR5_Chapter12_FINAL.pdf.
- Committee on Assessing Numeric Limits for Living Organisms in Ballast Water; National Research Council. 2011. Assessing the relationship between propagule pressure and invasion risk in ballast water. Washington, DC: National Academies Press. 144 pages. <u>http://www.nap.edu/catalog/13184/assessing-the-</u> <u>relationship-between-propagule-pressure-and-invasion-risk-in-ballast-water</u>.
- Cooper, N., Bielby, J., Thomas, G.H., and Purvis, A. 2008. Macroecology and extinction risk correlates of frogs. Global Ecology and Biogeography 17: 211–221.
- Cornwall, C.E. and Hurd, C.L. 2016. Experimental design in ocean acidification research: problems and solutions. ICES Journal of Marine Science 73: 572–581.
- Costello, M.J., Bouchet, P., Boxshall, G., Fauchald, K., Gordon, D., et al. 2013. Global coordination and standardization in marine biodiversity through the World Register of Marine Species (WoRMS) and related databases. PLoS ONE 8(1): e51629. doi:10.1371/journal.pone.0051629.
- Cowardin, L.M., Carter, V., Golet, F.C., and LaRoe, E.T. 1979. Classification of wetlands and deepwater habitats of the United States. Washington, D.C: U.S. Fish and Wildlife Service Report FWS/OBS/–79/31. <u>http://mawwg.psu.edu/docs/resources/ClassificationWetlandsDeepwaterHabitatsUS.pdf</u>.
- Craft, C., Clough, J., Ehman, J., Joye, S., Park, R., Pennings, S., Guo, H., and Machmuller, M. 2009. Forecasting the effects of accelerated sea–level rise on tidal marsh ecosystem services. Frontiers in Ecology and the Environment 7: 73–78.
- Crisp, D.J. and Southward, A.J. 1958. The distribution of intertidal organisms along the coasts of the English Channel. Journal of the Marine Biological Association of the United Kingdom 37: 157-208.
- Darwin, C. R. 1854. A monograph on the sub-class Cirripedia, with figures of all the species. The Balanidae, (or sessile cirripedes); the Verrucidae, etc. etc. etc. London: The Ray Society. Volume 2.

- Dasher, D., Lomax, T., Jewett, S., Norcross, B., Holladay, B., and Blanchard, A. 2015. Alaska Monitoring and Assessment Program 2010 and 2011 Chukchi Sea Coastal Survey Environmental Status. Alaska Department of Environmental Conservation Division of Water, Water Quality Standards, Assessment and Restoration, Anchorage, AK, DEC AKMAP Chukchi Sea/2015. 43 pages.
- Davies, K.F., Margules, C.R., and Lawrence, J.F. 2000. Which traits of species predict population declines in experimental forest fragments? Ecology 81: 1450–1461.
- Davies, K. F., Margules, C. R., and Lawrence, J. F. 2004. A synergistic effect puts rare, specialized species at greater risk of extinction. Ecology 85: 265–271.
- Dawes, R.M., Faust, D., and Meehl, P.E. 1989. Clinical versus actuarial judgment. Science 243: 1668–1674.
- De la Haye, K.L., Spicer, J., Widdicombe, S., and Briffa, M. 2011. Reduced sea water pH disrupts resource assessment and decision making in the hermit crab *Pagurus bernhardus*. Animal Behaviour 82: 495–501.
- Delefosse, M., Banta, G.T., Canal–Verges, P., Penha–Lopes, G., Quintana, C.O., Valdemarsen, T., and Kristensen,
 E. 2012. Macrobenthic community response to the *Marenzelleria viridis* (Polychaeta) invasion of a
 Danish estuary. Marine Ecology Progress Series 461: 83–94.
- Denney, N.H., Jennings, S., and Reynolds, J.D. 2002. Life–history correlates of maximum population growth rates in marine fishes. Proceedings of the Royal Society B– Biological Sciences 269: 2229–2138.
- Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Office of Response and Restoration (ORR), Emergency Response Division (ERD). 2013. NOAA Shoreline Assessment Manual 4th edition. Office of Response and Restoration, Emergency Response Division, Seattle, Washington. 154 pages. http://response.restoration.noaa.gov/sites/default/files/manual_shore_assess_aug2013.pdf.
- Department of Commerce, National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Office for Coastal Management (OCM). 2016. United States Interagency Elevation Inventory (USIEI). NOAA's Ocean Service, Office for Coastal Management (OCM), Charleston, SC. <u>https://coast.noaa.gov/digitalcoast/tools/inventory</u>.
- Di Nitto, D., Neukermans, G., Koedam, N., Defever, H., Pattyn, F., Kairo, J.G., and Dahdouh–Guebas, F. 2014. Mangroves facing climate change: landward migration potential in response to projected scenarios of sea level rise. Biogeosciences 11: 857–871.
- Diamond, S.E., Frame, A.M., Martin, R.A., and Buckley, L.B. 2011. Species' traits predict phenological responses to climate change in butterflies. Ecology Letters 92: 1005–1012.
- Dijkstra, J.A., Lambert, W.J., and Harris, L.G. 2013. Introduced species provide a novel temporal resource that facilitates native predator population growth. Biological Invasions 15: 911–919.

- Dissanayake, A. and Ishimatsu, A. 2011. Synergistic effects of elevated CO₂ and temperature on the metabolic scope and activity in a shallow–water coastal decapod (*Metapenaeus joyneri*; Crustacea: Penaeidae). ICES Journal of Marine Science 68: 1147–1154.
- Dodd, L.F., Grabowski, J.H., Piehler, M.F., Westfield, I., and Ries, J.B. 2015. Ocean acidification impairs crab foraging behavior. Proceedings of the Royal Society B 282: 1–9.
- Doney, S.C., Fabry, V.J., Feely, R.A., and Kleypas, J.A. 2009. Ocean acidification: The other CO₂ problem. Annual Review of Marine Science 1: 169–192.
- Donohue, P.J.C., Calosi, P., Bates, A.H., Laverock, B., Rastrick, S., Mark, F.C., Strobel, A., and Widdicombe, S. 2012. Impact of exposure to elevated pCO₂ on the physiology and behavior of an important ecosystem engineer, the burrowing shrimp *Upogebia deltaura*. Aquatic Biology 15: 73–86.
- Drake, J.S., Berntson, E.A., Cope, J.M., Gustafson, R.G., Holmes, E.E., Levin, P.S., Tolimieri, N., Waples, R.S.,
 Sogard, S.M., and Williams, G.D. 2010. Status review of five rockfish species in Puget Sound,
 Washington: bocaccio (*Sebastes paucispinis*), canary rockfish (*S. pinniger*), yelloweye rockfish (*S. ruberrimus*), greenstriped rockfish (*S. elongatus*), and redstripe rockfish (*S. proriger*). U.S. Department of
 Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 247
 pages.
- Drescher, M., Perera, A.H., Johnson, C.J., Buse, L.J., Drew, C.A., and Burgman, M.A. 2013. Toward rigorous use of expert knowledge in ecological research. Ecosphere 4: 83. <u>http://dx.doi.org/10.1890/ES12–00415.1.</u>
- Drolet, D., Locke, A., Lewis, M.A., and Davidson, J. 2015. Evidence–based tool surpasses expert opinion in predicting probability of eradication of aquatic nonindigenous species. Ecological Applications 25: 441–450.
- Ducks Unlimited. No date. Sea Level Rise Providing Nature A-Right-of Way. Online presentation, http://www.ecy.wa.gov/programs/sea/shorelines/smp/toolbox/docs/winter11_marshes_model.pdf.
- Dugan, J.E. and Hubbard, D.M. 2010. Ecological effects of coastal armoring: a summary of recent results for exposed sandy beaches in southern California. Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop. May, 2009. (Eds. Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, L., and Dinicola, R.S.), U.S. Geological Survey Scientific Investigations Report 2010. Pages 187–194.
- Dulvy, N.K., Ellis, J.R., Goodwin, N.B., Grant, A., Reynolds, J.D., and Jennings, S. 2004. Methods of assessing extinction risk in marine fishes. Fish and Fisheries 5: 255–276.
- Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., and Skjoldal, H.R. 2008. Climate change and deepening of the North Sea fish assemblage: A biotic indicator of warming seas. Journal of Applied Ecology 45: 1029–1039.
- Dulvy, N.K., Sadovy, Y., and Reynolds, J.D. 2003. Extinction vulnerability in marine populations. Fish and Fisheries 4: 25–64.

- Dumbauld, B.R., Chapman, J.W., Torchin, M.E., and Kuris, A.M. 2011. Is the collapse of mud shrimp (*Upogebia pugettensis*) populations along the Pacific coast of North American caused by outbreaks of a previously unknown bopyrid isopod parasite (*Orthione griffensis*)? Estuaries and Coasts 34: 336–350.
- Duncan, R.P. and Young, J.R. 2000. Determinants of plant extinction and rarity 145 years after European settlement of Auckland, New Zealand. Ecology 81: 3048–3061.
- Dupont, S., Lundve, B., and Thorndyke, M. 2010. Near future ocean acidification increases growth rate of the lecithotrophic larvae and juveniles of the sea star *Crossaster papposus*. Journal of Experimental Zoology Part B, Molecular and Developmental Evolution 314: 382–389.
- Edgar, G.J., Bates, A.E., Bird, T.J., Jones, A.H., Kininmonth, S., Stuart–Smith, R.D., and Webb, T.J. 2016. New approaches to marine conservation through the scaling up of ecological data. Annual Review of Marine Science 8: 435–461.
- Edmunds, P. J., Brown, D., and Moriarty, V. 2012. Interactive effects of ocean acidification and temperature on two scleractinian corals from Moorea, French Polynesia. Global Change Biology, 18: 2173–2183.
- Eisenlord, M.E., Groner, M.L., Yoshioka, R.M., Elliot, J., Maynard, J., Fradkin, S., Turner, M., Pyne, K., Rivlin, N., van Hooidonk, R., Harvell, C.D. 2016. Ochre star mortality during the 2014 wasting disease epizootic: role of population size structure and temperature. Philosophical Transactions of the Royal Society B Biological Sciences 371: <u>http://dx.doi.org/10.1098/rstb.2015.0212</u>.
- Elith, J. and Leathwick, J.R. 2009. Species distribution models: ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics 40: 677-697.
- Ellison, J., 2000. How South Pacific mangroves may respond to predicted climate change and sea level rise. In: Gillespie, A., Burns, W. (Eds.), Climate Change in the South Pacific: Impacts and Responses in Australia, New Zealand, and Small Islands States. Kluwer Academic Publishers, Dordrecht, Netherlands, (Chapter 15), pp. 289–301.
- Ellison, J.C. and Stoddart, D.R. 1991. Mangrove ecosystem collapse during predicted sea level rise Holocene analogs and implications. Journal of Coastal Research 7: 151–165.
- Engle, J.M., and Richards, D.V. 2001. New and unusual marine invertebrates discovered at the California Channel Islands during the 1997–1998 El Niño. Bulletin of the Southern California Academy of Sciences 100: 186– 198.
- Fairchild, J.F., Allert, A.L., Feltz, K.P., Nelson, K.J., and Valle, J.A. 2009. An ecological risk assessment of the acute and chronic effects of the herbicide Clopyralid to rainbow trout (*Oncorhynchus mykiss*). Archives of Environmental Contamination and Toxicology 57: 725–731.
- Fehsenfeld, S., Kiko, R., Appelhans, Y., Towle, D.W., Zimmer, M., and Melzner, F. 2011. Effects of elevated seawater pCO₂ on gene expression patterns in the gills of the green crab *Carcinus maenas*. BMC Genomics 12: 488.

- Flather, C.H. and Seig, C.H. 2007. Species rarity: Definition, causes and classification. Conservation of Rare or Little–Known Species. Biological, Social, and Economic Considerations (Eds. Raphael, M.G. and Molina, R.) 40–66. Washington D.C: Island Press. 392 pages.
- Foden, W., Mace, G., Vié, J.–C., Angulo, A., Butchart, S., DeVantier, L., Dublin, H., Gutsche, A., Stuart, S., and Turak, E. 2008. Species susceptibility to climate change impacts. An analysis of the IUCN Red List of Threatened Species (Eds: Vié, J.–C., Hilton–Taylor, C., and Stuart, S.) 77–87. Gland, Switzerland: IUCN. 180 pages.
- Foden, W.B., Butchart, S.H.M., Stuart, S.N., Vié, J.–C., Akçakaya, H.R., Angulo, A., DeVantier, L.M., Gutsche, A., Turak, E., Cao, L., Donner, S.D., Katariya, V., Bernard, R., Holland, R.A., Hughes, A.F., O'Hanlon, S.E., Garnett, W.T., Şekercioğlu, Ç.H., and Mace, G.M. 2013. Identifying the World's Most Climate Change Vulnerable Species: A Systematic Trait–Based Assessment of all Birds, Amphibians and Corals. PLoS ONE 8(6): e65427. doi: 10.1371/journal.pone.0065427.
- Foo, S.A. and Byrne, M. 2016. Acclimatization and adaptive capacity of marine species in a changing ocean. Advances in Marine Biology 74: 69–116.
- Food and Agriculture Organization of the United Nations (FAO). 2007. The world's mangroves 1980–2005. FAO Forestry Paper 153. Rome, 77 pages.
- Frederich, M. and Pörtner, H.O. 2000. Oxygen limitation of thermal tolerance defined by cardiac and ventilatory performance in spider crab, *Maja squinado*. American Journal of Physiology Regulatory, Integrative and Comparative Physiology 279: R1531–R1538.
- Freitas, V., Campos, J., Fonds, M., and Van der Veer, H.W. 2007. Potential impact of temperature change on epibenthic predator—bivalve prey interactions in temperate estuaries. Journal of Thermal Biology 32: 328–340.
- Fujimoto, K., Miyagi, T., Kikuchi, T., and Kawana, T. 1996. Mangrove habitat formation and response to Holocene sea–level changes on Kosrae Island, Micronesia. Mangroves and Salt Marshes 1: 47–57.
- Füssel, H.-M. 2009. An updated assessment of the risks from climate change based on research published since the IPCC Fourth Assessment Report. Climatic Change 97: 469–482.
- Galbraith, H., Jones, R., Park, R., Clough, J., Herrod–Julius, S., Harrington, B. and Page, G. 2002. Global climate change and sea level rise: potential losses of intertidal habitat for shorebirds. Waterbirds 25: 173–183.
- Galbraith, H. and Price, J., 2009. A Framework for Categorizing the Relative Vulnerability of Threatened and Endangered Species to Climate Change. EPA/600/R-09/011. National Center for Environmental Assessment, Washington, D.C. 113 pages.
- Gallagher, A.J., Kyne, P.M., and Hammerschlag, N. 2012. Ecological risk assessment and its application to elasmobranch conservation and management. Journal of Fish Biology 80: 1727–1748.

Gaston, K.J. 1994. Rarity. London, UK: Chapman and Hall. 205 pages.

- Gaston, K.J. 1997. What is rarity? The Biology of Rarity (Eds. Kunin, W.E. and Gaston, K.J.) 30–47. London, UK: Chapman & Hall. 280 pages.
- Gaston, K.J. 2003. The Structure and Dynamics of Geographic Ranges. Oxford Series in Ecology and Evolution. New York, Oxford University Press Inc. 266 pages.
- Gaston, K.J. 2009. Geographic range limits: achieving synthesis. Proceedings of the Royal Society B 276: 1395–1406.
- Gaston, K.J. 2011. Common ecology. Bioscience 61: 354–362.
- Geselbracht, L.L., Freeman, K., Birch, A.P., Brenner, J. and Gordon, D.R. 2015. Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida's Gulf Coast: Implications for adaptation planning.
 PLoS ONE 10(7): e0132079. doi:10.1371/journal.pone.0132079.
- Gill, S.K. and Schultz, J.R. (eds). 2000. Tidal Datums and their Applications. Department of Commerce (DOC), National Oceanic and Atmospheric Administration (NOAA), National Ocean Service (NOS), Center for Operational Oceanographic Products and Services, Silver Springs, Maryland. 132 pages. <u>http://tidesandcurrents.noaa.gov/publications/tidal_datums_and_their_applications.pdf</u>.
- Gilman, E., Ellison, J.C., Duke, N.C., Field, C., and Fortuna, S. 2008. Threats to mangroves from climate change and adaptation options: a review. Aquatic Botany 89: 237–250.
- Glenn, E.P., Nagler, P.L., Brusca, R.C., and Hinojosa–Huerta, O. 2006. Coastal wetlands of the northern Gulf of California: inventory and conservation status. Aquatic Conservation: Marine and Freshwater Ecosystems 16: 5–28.
- Glick, P., Clough, J., and Nunley, B. 2007. Sea-level Rise and Coastal Habitats in the Pacific Northwest: An Analysis for Puget Sound, Southwestern Washington, and Northwestern Oregon. National Wildlife Federation, Seattle, Washington. 106 pages.
- Glynn, P.W. 2012. Global warming and widespread coral mortality: evidence of first coral reef extinctions. Saving a Million Species: Extinction Risk from Climate Change. (Ed. Hannah, L.) Island Press, Washington, DC. Pages 103–119.
- Godoy, M.D.P. and de Lacerda, L.D. 2015. Mangroves response to climate change: a review of recent findings on mangrove extension and distribution. Anais da Academia Brasileira de Ciências 87: 651-67.
- Gollasch, S. 2006. Assessment of the introduction potential of aquatic alien species in new environments.
 Assessment and Control of Biological Invasion Risks (Eds. Koike, F., Clout, M., Kawamichi, M., De Poorter, M., and Iwatsuki, K.) Kyoto, Japan and Gland, Switzerland: Shoukadoh Book Sellers, IUCN. Pages 88–91.
- Graham, N.A.J. 2007. Ecological versatility and the decline of coral feeding fishes following climate driven coral mortality. Marine Biology 153: 119–127.

- Gray, J.S., Bjørgesæter, A., Ugland, K.I. 2005. The impact of rare species on natural assemblages. Journal of Animal Ecology 74: 1131–1139.
- Greene, K.E., Zimmerman, J.L., Laney, R.W., and Thomas–Blate, J.C. 2009. Atlantic coast diadromous fish habitat: A review of utilization, threats, recommendations for conservation, and research needs. Washington, DC: Atlantic States Marine Fisheries Commission. 464 pages.
- Griffen, B.D. 2009. Effects of a newly invasive parasite on the burrowing mud shrimp, a widespread ecosystem engineer. Marine Ecology Progress Series 391: 73–83.
- Grove, W.M., Zald, D.H., Lebow, B.S., Snitz, B.E., and Nelson, C. 2000. Clinical versus mechanical prediction: A meta–analysis. Psychological Assessment 12: 19–30.
- Gutowska, M.A. and Melzner, F. 2009. Abiotic conditions in cephalopod (*Sepia officinalis*) eggs: embryonic development at low pH and high *p*CO₂. Marine Biology 156: 515–519.
- Gynther, I., Waller, N., and Leung, L.K.–P. 2016. Confirmation of the extinction of the Bramble Cay melomys *Melomys rubicola* on Bramble Cay, Torres Strait: results and conclusions from a comprehensive survey in August–September 2014. Unpublished report to the Department of Environment and Heritage Protection, Queensland Government, Brisbane. <u>https://www.ehp.qld.gov.au/wildlife/threatened–</u> <u>species/documents/bramble-cay-melomys-survey-report.pdf</u>.
- Haer, T., Kalnay, E., Kearney, M., and Moll, H. 2013. Relative sea–level rise and the conterminous United States: Consequences of potential land inundation in terms of population at risk and GDP loss. Global Environmental Change 23: 1627–1636.
- Haigh, R., Ianson, D., Holt, C.A., Neate, H.E., and Edwards, A.M. 2015. Effects of ocean acidification on temperate coastal marine ecosystems and fisheries in the Northeast Pacific. PLoS ONE 10(2): e0117533. doi:10.1371/journal.pone.0117533.
- Hale, S.S. and Heltshe, J.F. 2008. Signals from the benthos: development and evaluation of a benthic index for the nearshore Gulf of Maine. Ecological Indicators 8: 338-350.
- Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Steneck, R., and Watson, R. 2008. A global map of human impact on marine ecosystems. Science 319: 948–952.
- Hannah, L. (Ed.) 2012. Saving a Million Species: Extinction Risk from Climate Change. Island Press, Washington. 432 pages.
- Hans, S., Fehnsefeld, S., Treberg, J.R., and Weihrauch, D. 2014. Acid–base regulation in the Dungeness crab (*Metacarcinus magister*). Marine Biology 161: 1179–1193.

- Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C.T., Milke, L.M., Richardson, D.E., Robillard, E., Walsh, H.J., McManus, M.C., Marancik, K.E., and Griswold, C.A. 2016. A vulnerability assessment of fish and invertebrates to climate change on the northeast U.S. continental shelf. PLoS ONE 11(2): e0146756. doi:10.1371/ journal.pone.0146756.
- Harley, C.D., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J., Thornber, C.S., Rodriguez, L.F.,
 Tomanek, L., and Williams, S.L. 2006. The impacts of climate change in coastal marine systems. Ecology
 Letters 9: 228–241.
- Harrell, F.E., Lee, K.L., and Mark, D.B. 1996. Multivariable prognostic models: Issues in developing models, evaluating assumptions and adequacy, and measuring and reducing errors. Statistics in Medicine 15: 361–387.
- Hart, J. 1982. Crabs and their relatives of British Columbia. Victoria, British Columbia, Canada. British Columbia Provincial Museum Handbook 40. 267 pages.
- Hartley, S. and Kunin, W. 2003. Scale dependency of rarity, extinction risk, and conservation priority. Conservation Biology 17: 1559-1570.
- Harvey, B.P., Gwynn–Jones, D., and Moore, P. J. 2013. Meta–analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecology and Evolution 3: 1016–1030.
- Hawkins, S.J. and Jones, H.D. 1992. Marine Field Course Guide 1. Rocky Shores. Marine Conservation Society, Immel Publishing. 112 pages.
- Heinrich, D.D.U., Watson, S.–A., Rummer, J.L., Brandl, S.J., Simpfendorfer, C.A., Heupel, M.R., and Munday, P.L.
 2016. Foraging behaviour of the epaulette shark *Hemiscyllium ocellatum* is not affected by elevated CO₂.
 ICES Journal of Marine Science 73: 633–640.
- Helmuth, B. and Hofmann, G.E. 2001. Microhabitats, thermal heterogeneity, and patterns of physiological stress in the rocky intertidal zone. Biological Bulletin 201: 374–384.
- Helmuth, B., Broitman, B.R., Yamane, L., Gilman, S.E., Mach, K., Mislan, K.A.S., and Denny, M.W. 2010.
 Organismal climatology: analyzing environmental variability at scales relevant to physiological stress.
 Journal of Experimental Biology 213: 995–1003.
- Helmuth, B., Mieszkowska, N., Moore, P., and Hawkins, S.J. 2006. Living on the edge of two changing worlds:
 Forecasting the responses of rocky intertidal ecosystems to climate change. Annual Review of Ecology,
 Evolution, and Systematics 37: 373–404.
- Hendriks, I.E., Duarte, C.M., Álvarez, M. 2010. Vulnerability of marine biodiversity to ocean acidification: a metaanalysis. Estuarine, Coastal and Shelf Science 86: 157–164.

- Herborg, L.M., O'Hara, P., and Therriault, T.W. 2009. Forecasting the potential distribution of the invasive tunicate *Didemnum vexillum*. Journal of Applied Ecology 46: 64–72.
- Hercos, A.P., Sobansky, M., Queirozl, H.L., and Magurran, A.E. 2012. Local and regional rarity in a diverse tropical fish assemblage. Proceedings of the Royal Society B Biological Sciences 280: 20122076. http://dx.doi.org/10.1098/rspb.2012.2076.
- Hewitt, J.E., Ellis, J.L., and Thrush, S.F. 2016. Multiple stressors, nonlinear effects and the implications of climate change impacts on marine coastal ecosystems. Global Change Biology 22: 2665-2775.
- Hiddink, J. G., Burrows, M.T. and Molinos, J.G. 2015. Temperature tracking by North Sea benthic invertebrates in response to climate change. Global Change Biology 21: 117–129.
- Hines, A.H. 1982. Coexistence in a kelp forest: Size, population dynamics, and resource partitioning in a guild of spider crabs (*Brachyura, Majidae*). Ecological Monographs 52: 179–182.
- Hoagland, K.E. and Turner, R.D. 1980. Range extensions of teredinids (shipworms) and polychaetes in the vicinity of a temperate-zone nuclear generating station. Marine Biology 58: 55-64.
- Hobbs, J.–P.A., Jones, G.P., and Munday, P.L. 2011. Extinction risk in endemic marine fishes. Conservation Biology 25: 1053–1055.
- Hoegh–Guldberg, O. and Pearse, J.S. 1995. Temperature, food availability, and the development of marine invertebrate larvae. American Zoologist 35: 415–425.
- Hofmann, G.E. and Todgham, A.E. 2010. Living in the now: physiological mechanisms to tolerate a rapidly changing environment. Annual Review of Physiology 72: 127–145.
- Hollenbeck, J.P., Olsen, M.J., and Haig, S.M. 2014. Using terrestrial laser scanning to support ecological research in the rocky intertidal zone. Journal of Coastal Conservation 18: 701–714.
- Horn, H.G., Boersma, M., Garzke, J., Löder, M.G., Sommer, U., and Aberle, N. 2016. Effects of high CO₂ and warming on a Baltic Sea microzooplankton community. ICES Journal of Marine Science 73: 772–782.
- Hubbard, D.M., Dugan, J.E., Schooler, N.K., and Viola, S.M. 2014. Local extirpations and regional declines of endemic upper beach invertebrates in southern California. Estuarine, Coastal and Shelf Science 150: 67– 75.
- Hyland, J.L., Balthis, W.L., Posey, M.H., Hackney, C.T. and Alphin, T.D. 2004. The soft-bottom macrobenthos of North Carolina estuaries. Estuaries 27: 501-514.
- Inger, R., McDonald, R., Rogowski, D., Jackson, A., Parnell, A., Preston, S., Harrod, C., Goodwin, C., Griffiths, D., Dick, J., Elwood, R., Newton, J., and Bearhop, S. 2010. Do non-native invasive fish support elevated lamprey populations? J. Appl. Ecol. 47: 121-129.

- IPCC, 2007. Summary for Policymakers. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L.) Cambridge, UK and New York, NY, USA: Cambridge University Press. 18 pages. <u>http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf</u>.
- IPCC, 2014: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds Pachauri, R.K. and Meyer, L.). IPCC, Geneva, Switzerland, 151 pages. <u>http://ar5-</u> <u>syr.ipcc.ch/ipcc/resources/pdf/IPCC_SynthesisReport.pdf</u>.
- Isenburg, M. 2011. LASzip: lossless compression of LiDAR data. European LiDAR Mapping Forum. Salzburg, Austria. 9 pages. <u>http://www.cs.unc.edu/~isenburg/lastools/download/laszip.pdf.</u>
- IUCN Species Survival Commission. 2001. International Union for Conservation of Nature red list categories and criteria Version 3.1. Second edition. Gland, Switzerland: International Union for Conservation of Nature.
 33 pages. <u>http://s3.amazonaws.com/iucnredlist-</u>
 newcms/staging/public/attachments/3097/redlist_cats_crit_en.pdf.
- IUCN Standards and Petitions Subcommittee 2016. Guidelines for using the IUCN Red List Categories and Criteria. Version 12. 101 pages. <u>http://cmsdocs.s3.amazonaws.com/RedListGuidelines.pdf.</u>
- Iyengar, E.V. 2005. Seasonal feeding–mode changes in the marine facultative kleptoparasite *Trichotropis cancellata* (Gastropoda, Capulidae): trade–offs between trophic strategy and reproduction. Canadian Journal of Zoology 83: 1097–1111.
- Jackson, A.C. and McIlvenny, J. 2011. Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. Journal of Experimental Marine Biology and Ecology 400: 314–321.
- Janousek, C.N. and Folger, C.L. 2012. Patterns of distribution and environmental correlates of macroalgal assemblages and sediment chlorophyll A in Oregon tidal wetlands. Journal of Phycology 48: 1448–1457.
- Jenness, J.S. 2004. Calculating landscape surface area from digital elevation models. Wildlife Society Bulletin 32: 829–839.
- Jensen, G.C. 1995. Pacific Coast Crabs and Shrimps. Monterey, California: Sea Challengers. 87 pages.
- Jensen, G.C. 2014. Crabs and Shrimps of the Pacific Coast: A Guide to Shallow–Water Decapods from Southeastern Alaska to the Mexican Border. Mola Marine. 240 pages.

- Jiguet, F., Gadot, A.–S., Julliard, R., Newson, S.E., Couvet, D. 2007. Climate envelope, life history traits and the resilience of birds facing global change. Global Change Biology 13: 1672–1684.
- Johansen, J.L. and Jones, G.P. 2011. Increasing ocean temperature reduces the metabolic performance and swimming ability of coral reef damselfishes. Global Change Biology 17: 2971–2979.
- Jones, M.C., Dye, S.R., Fernandes, J.A., Frolicher, T.L., Pinnegar, J.K. et al. 2013. Predicting the Impact of Climate Change on Threatened Species in UK Waters. PLoS ONE 8(1): e54216. doi: 10.1371/journal.pone.0054216.
- Jones, M.J., Fielding, A., and Sullivan, M. 2006. Analysing extinction risk in parrots using decision trees. Biodiversity and Conservation 15: 1993-2007.
- Jones, S.J., Southward, A.J., and Wethey, D.S. 2012. Climate change and historical biogeography of the barnacle *Semibalanus balanoides*. Global Ecology and Biogeography 21: 716–724.
- Jørstad, K.E., Farestveit, E., Rudra, H., Agnalt, A.–L., and Olsen, S. 2002. Studies on red king crab (*Paralithodes camtschaticus*) introduced to the Barents Sea. Crabs in Cold Water Regions: Biology, Management and Economics; Alaska Sea Grant Collage Program. AK–SG–02–01. Pages 425–437.
- Josefson, A.B. and Mokievsky, V., 2013. Marine invertebrates. Arctic Biodiversity Assessment. Status and Trends in Arctic Biodiversity. (Ed. Meltofte, H.). Conservation of Arctic Flora and Fauna, Akureyri, Iceland. Pages. 276–309.
- Jumars, P.A., Dorgan, K.M., Lindsay, S.M. 2015. Diet of worms emended: an update of polychaete feeding guilds. Ann. Rev. Mar. Sci. 7: 497–520.
- Kairis, P.A. and Rybczyk, J.M. 2010. Sea level rise and eelgrass (*Zostera marina*) production: A spatially explicit relative elevation model for Padilla Bay. Ecological Modeling 221: 1005–1016.
- Kaldy, J.E. 2006. Production ecology of the non-indigenous seagrass, dwarf eelgrass (Zostera japonica Ascher. & Graeb.), in a Pacific Northwest Estuary, USA. Hydrobiologia 553: 201–217.
- Keller, V. and Bollmann, K. 2004. From red lists to species of conservation concern. Conservation Biology 18: 1636–1644.
- Kendall, M.A., Burrows, M.T., Southward, A.J., and Hawkins, S.J. 2004. Predicting the effects of marine climate change on invertebrate prey of the birds of rocky shores. Ibis 146: 40–47.
- Keppel, E.A., Scrosati, R.A., and Courtenay, A.C. 2012. Ocean acidification decreases growth and development in American lobster (Homarus americanus) larvae. Journal Northwest Atlantic Fish Science 44: 61–66.
- Kim, K.C. and Byrne, L.B. 2006. Biodiversity loss and the taxonomic bottleneck: emerging biodiversity science. Ecological Research, 21: 794–810.
- Kim, T.W., Taylor, J., Lovera, C., and Barry, J.P. 2015. CO2 driven decrease in pH disrupts olfactory behavior and increases individual variation in deep–sea hermit crabs. ICES Journal of Marine Science 73: 613–619.

- Kinlan, B.P. and Gaines, S.D. 2003. Propagule dispersal in marine and terrestrial environments: a community perspective. Ecology 84: 2007–2020.
- King, P.G., McGregor, A.R. and Whittet, J.D., 2011. The economic costs of sea-level rise to California beach communities. Report from the California Department of Boating and Waterways and San Francisco State University. California Department of Boating and Waterways, San Francisco State University. 82 pages.
- Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L., and Robbins, L.L. 2006. Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of a workshop sponsored by National Science Foundation, National Oceanic and Atmospheric Administration, and the US Geological Survey and held April, 2005, St. Petersburg, Florida. Contribution No. 2897 from NOAA/Pacific Marine Environmental Laboratory. 97 pages.
 <u>https://www.researchgate.net/publication/248700866 Impacts of Ocean Acidification on Coral Ree fs and Other Marine Calcifiers A Guide for Future Research</u>.
- Ko, G.W.K., Dineshram, R., Camoanati, C., Chan, V.B.S., Havenhand, J. and Thiyagarajan, V. 2015. Interactive effects of ocean acidification, elevated temperature, and reduced salinity on early-life stages of the Pacific oyster. Environ. Sci. Technol. 48:10079–10088.
- Kohl, W.T., McClure, T.I., and Miner, B.G. 2016. Decreased temperature facilitates short–term sea star wasting disease survival in the keystone intertidal sea star Pisaster ochraceus. PLoS ONE 11(4): e0153670. doi:10.1371/journal.pone.0153670.
- Kriegler, E., Hall, J.W., Held, H., Dawson, R., and Schellnhuber, H.J. 2009. Imprecise probability assessment of tipping points in the climate system. Proceedings of the National Academy of Sciences 106: 5041–5046.
- Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.P. 2013.
 Impacts of ocean acidification of marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology 19: 1884–1896.
- Kuhnert, P.M., Hayes, K., Martin, T.G., and McBride, M.F. 2009. Expert opinion in statistical models. In 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation: 4262–4268. <u>http://www.mssanz.org.au/modsim09/J2/kuhnert_J2.pdf.</u>
- Kuncel, N.R., Klieger, D.M., Connelly, B.S., and Ones, D.S. 2013. Mechanical versus clinical data combination in selection and admissions decisions: a meta–analysis. Journal of Applied Psychology 98: 1060–1072.
- Kurihara, H., Matsui, M., Furukawa, H., Hayashi, M., and Ishimatsu, A. 2008. Long–term effects of predicted future seawater CO₂ conditions on the survival and growth of the marine shrimp *Palaemon pacificus*. Journal of Experimental Marine Biology and Ecology 367: 41–46.
- Kynn, M. 2008. The 'heuristics and biases' bias in expert elicitation. Journal of the Royal Statistical Society: Series A (Statistics in Society) 171: 239–264.

- Laffoley, D. and Baxter, J.M. (Eds.) 2016. Explaining ocean warming: Causes, scale, effects and consequences. IUCN, Gland, Switzerland Full report: 456 pages. http://www.obs–vlfr.fr/~gattuso/files/Magnan_Gattuso_2016.pdf.
- Landes, A. and Zimmer, M., 2012. Acidification and warming affect both a calcifying predator and prey but not their interaction. Inter–Research Marine Ecology Progress Series 450: 1–10.
- Lange, U. and Greve, W. 1997. Does temperature influence the spawning time, recruitment and distribution of flatfish via its influence on the rate of gonadal maturation? German Journal of Hydrography 49: 251–263.
- Lawrence, A.J. and Soame, J.M. 2004. The effects of climate change on the reproduction of coastal invertebrates. Ibis 146: 29–39.
- Lea, R.N., and Rosenblatt, R.H. 2000. Observations on fishes associated with the 1997–98 El Niño off California. CalCOFI Report 41:117-129.
- Lee II, H. and Brown, C.A. (eds). 2009. Classification of regional patterns of environmental drivers and benthic habitats in Pacific Northwest estuaries. U.S. EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Newport OR. EPA/600/R– 09/140. 225 pages. <u>http://nepis.epa.gov/Adobe/PDF/P1006Q2H.PDF.</u>
- Lee II, H. and Reusser, D.A., 2012. Atlas of nonindigenous marine and estuarine species in the north Pacific. Office of Research and Development, National Health and Environmental Effects Research Laboratory, EPA/600/R/12/631. 1915 pages.
- Lee II, H., Marko, K., Hanshumaker, M., Folger, C., and Graham, R. 2015. User's guide & metadata to Coastal Biodiversity Risk Analysis Tool (CBRAT): Framework for the systemization of life history and biogeographic information. EPA Report. EPA/601/B–15/001. 123 pages. http://www.cbrat.org/pdfs/general/cbrat_users_guide_and_metadata.pdf.
- Lee II, H., Reusser, D.A., Frazier, M.R., McCoy, L.M., Clinton, P.J., and Clough, J.S. 2014. Sea Level Affecting Marshes Model (SLAMM) - New functionality for predicting changes in distribution of submerged aquatic vegetation in response to sea level rise. Version 1.0. U.S. EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Western Ecology Division. EPA/600/R–14/007. 50 pages. http://warrenpinnacle.com/prof/SLAMM6/SLAMM_6.3_final_release.pdf.
- Loarie, S.R., Carter, B.E., Hayhoe, K., McMahon, S., Moe, R., Knight, C.A., and Ackerly, D.D. 2008. Climate change and the future of California's endemic flora. PLoS ONE 3(6): e2502.doi:10.1371/journal.pone.0002502.
- Lomolino, M.V. and Weiser, M.D. 2001. Towards a more general species–area relationship: diversity on all islands, great and small. Journal of Biogeography 28: 431–445.
- Lomolino, M.V., Riddle, B.R., and Brown, J.H. 1953. Biogeography, Third Edition. Massachusetts: Sinauer Associates, Inc. 845 pages.

- Long, E.R., MacDonald, D.D., Smith, S.L., and Calder, F.D. 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. Environmental Management 19: 81–97.
- Long, W.C., Swiney, K.M., Harris, C., Page, H.N., and Foy, R.J. 2013. Effects of ocean acidification on juvenile red king crab (*Paralithodes camtschaticus*) and Tanner crab (*Chionoecetes bairdi*) growth, condition, calcification and survival. PLoS ONE 8(4): e60959. doi:10.1371/journal.pone.0060959.
- Long, W.C., Swiney, K.M., and Foy, R.J. 2016. Effects of high pCO₂ on Tanner crab reproduction and early life history, Part 2: carryover effects on larvae from oogenesis and embryogenesis are stronger than direct effects. ICES Journal of Marine Science 73: 836–848.
- López–Medellín, X., Castillo, A. and Ezcurra, E. 2011. Contrasting perspectives on mangroves in arid Northwestern Mexico: Implications for integrated coastal management. 2011. Ocean & Coastal Management 54: 318–329.
- Lord, J.P., Barry, J.P. and Graves, D. 2017. Impact of climate change on direct and indirect species interactions. Marine Ecology Progress Series 571:1–11.
- Love, M.S. 2011. Certainly more than you want to know about the fishes of the Pacific coast. San Francisco, CA: Really Big Press. 672 pages.
- Love, M.S., Mecklenburg, C.W., Mecklenburg, T.A., and Thorsteinson, L.K. 2005. Resource inventory of marine and estuarine fishes of the West Coast and Alaska: a checklist of North Pacific and Arctic Ocean species from Baja California to the Alaska-Yukon border. Dept. Int., USGS, Biol. Res. Div., Seattle, WA, OCS Study MMS 2005-030 and USGS/NBII 2005-001. 276 pages.
- Love, M.S. and Yoklavich, M.M. 2006. Deep rock habitats. The ecology of marine fishes: California and adjacent waters (Eds. Allen, L.G., Pondella, D.J., and Horn, M.H.) 253–266. University of California Press. Berkley, California. 670 pages.
- Love, M.S., Yoklavich, M., Thorsteinson, L., and Butler, J. 2002. The rockfishes of the northeast Pacific. Berkley and Monterey, California: University of California Press and Monterey Bay Aquarium Press. 416 pages.
- Lovell, L.L. and Cadien, D.C. 2013. Coastal Biogeographic Risk Analysis Tool (CBRAT): Further contributions to CBRAT data acquisition and correction: Second Expert Workshop 14–16 May, 2013. Los Angeles, CA: Southern California Association of Marine Taxonomists. 13 pages.
- Lucey, N.M., Lombardi, C., DeMarchi, L., Schulze, A., Gambi, M.C., and Calosi, P. 2015. To brood or not to brood: are marine invertebrates that protect their offspring more resilient to ocean acidification? Scientific Reports 5: 1–7 12009; doi: 10.1038/srep12009.
- Maclean, I.M.D. and Wilson, R.J. 2012. Recent ecological responses to climate change support predictions of high extinction risk. Proceedings of the National Academy of Sciences 108: 12337–12342.

- Malcolm, J.R., Liu, C., Neilson, R.P., Hansen, L., and Hannah, L. 2006. Global warming and extinctions of endemic species from biodiversity hotspots. Conservation Biology 20: 538–548.
- Marcot, B.G. and Molina, R. 2007. Special considerations for the science, conservation, and management of rare or little–known species. Conservation of Rare or Little–Known Species: Biological, Social, and Economic Considerations. (Eds. Raphael, G.M. and Molina, R.). 93-124. Island Press, Washington D.C. 389 pages.
- Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, B.-K., Yohe, G.W., and Zwiers, F.W. 2010. Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. Intergovernmental Panel on Climate Change (IPCC), 7 pages. https://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.
- Mathis, J.T., Cooley, S.R., Lucey, N., Colt, S., Ekstrom, J., Hurst, T., Hauri, C., Evans, W., Cross, J.N., and Feely, R.A. 2015. Ocean acidification risk assessment for Alaska's fishery sector. Progress in Oceanography 136: 71–91.
- Matozzo, V., Chinellato, A., Munari, M., Finos, L., Bressan, M., and Marin, M.G., 2012. First evidence of immunomodulation in bivalves under seawater acidification and increased temperature. PLoS ONE 7(3): e33820. doi:10.1371/journal.pone.0033820
- Maul, G.A. and Martin, D.M. 1993. Sea level rise at Key West, Florida, 1846-1992: America's longest instrument record? Geophysical Research Letters 20: 1955-1958.
- McAfee, A. 2013. Big data's biggest challenge? Convincing people NOT to trust their judgment. Harvard Business Review: 9. <u>https://hbr.org/2013/12/big-datas-biggest-challenge-convincing-people-not-to-trust-their-judgment#comment-1156190677.</u>
- McBride, M.F., Fidler, F., and Burgman, M.A. 2012. Evaluating the accuracy and calibration of expert predictions under uncertainty: predicting the outcomes of ecological research. Diversity and Distributions 18: 782– 794.
- McCune, B. 2011. Nonparametric multiplicative regression for habitat modeling. <u>http://www.pcord.com/NPMRintro.pdf</u>.
- McDowell, W.G., McDowell, W.H., and Byers, J.E. 2017. Mass mortality of a dominant invasive species in response to an extreme climate event: implications for ecosystem function. Limnology and Oceanography 62: 177–18.
- McGurk, M.D. 1984. Effects of delayed feeding and temperature on the age of irreversible starvation and on the rates of growth and mortality of Pacific herring larvae. Marine Biology 84: 13–26.

- McIvor, A.L., Spencer, T., Möller, I. and Spalding. M. 2013. The response of mangrove soil surface elevation to sea level rise. Natural Coastal Protection Series: Report 3. Cambridge Coastal Research Unit Working Paper 42. Published by The Nature Conservancy and Wetlands International. 59 pages. https://repository.tudelft.nl/islandora/object/uuid:6655e6c9-14c8-4660-9262-7d42e6bf73e1?collection=research.
- McKee, K.L., Cahoon, D.R, and Feller, I.C. 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Global Ecology and Biogeography 16: 545–556.
- McKinney, M.L. 1997. How do rare species avoid extinction? A paleontological review. The Biology of Rarity (Eds. Kunin, W.E. and Gaston, K.J.): 110–129. Chapman & Hall, London, UK. 280 pages.
- McLaughlin, J.F., Hellmann, J.J., Boggs, C.L., and Ehrlich, P.R. 2002. Climate change hastens population extinctions. Proceedings of the National Academy of Sciences of the United States of America 99: 6070– 6074.
- Mecklenburg, C.W., Mecklenburg, T.A., and Thorsteinson, L.K. 2002. Fishes of Alaska. American Fisheries Society, Bethesda, Maryland. 1116 pages.
- Meehl, G.A., Covey, C., Delworth, T., Latif, M., McAvaney, B., Mitchell, J.F.B., Stouffer, R.J., and Taylor, K.E. 2007. The WCRP CMIP3 multimodel dataset – a new era in climate change research. Bulletin of the American Meteorological Society 88: 1383–1394.
- Mellin, C., Russell, B.D., Connell, S.D., Brook, B.W., and Fordham, D.A. 2012. Geographic range determinants of two commercially important marine molluscs. Diversity and Distributions 18: 133–146.
- Meseck, S.L., Alix, J.H., Swiney, K.M., Long, W.C., Wikfors, G.H., and Foy, R.J. 2016. Ocean acidification affects hemocyte physiology in the Tanner Crab (*Chionoecetes bairdi*). PLoS ONE 11(2): e0148477.doi:10.1371/journal.pone.0148477.
- Metzger, R., Sartoris, F.J., Langenbuch, M., and Pörtner, H.O. 2007. Influence of elevated CO₂ concentrations on thermal tolerance of the edible crab *Cancer pagurus*. Journal of Thermal Biology 32: 144–151.
- Meyer, C.A. 2013. Evaluating habitat vulnerability and sustainability of urban seagrass resources to sea level rise. Graduate Theses and Dissertations, University of South Florida, 147 pages. <u>http://scholarcommons.usf.edu/etd/4918.</u>
- Miller, J.J., Maher, M., Bohaboy, E., Friedman, C.S., and McElhany, P. 2016. Exposure to low pH reduces survival and delays development in early life stages of Dungeness crab (*Cancer magister*). Marine Biology 163: 118.
- Miller, S.H., Zarate, S., Smith, E.H., Gaylord, B., Hosfelt, J.D., and Hill, T.M. 2014. Effect of elevated pCO₂ on metabolic responses of porcelain crab (*Petrolisthes cinctipes*) larvae exposed to subsequent salinity stress. PLoS ONE 9(10): e109167. doi: 10.1371/journal.pone.0109167.

- Molinos, J.G., Halpern, B.S., Schoeman, D.S., Brown, C.J., Kiessling, W., Moore, P.J., Pandolfi, J.M., Poloczanska,
 E.S., Richardson, A.J., and Burrows, M.T. 2016. Climate velocity and the future global redistribution of marine biodiversity. Nature Climate Change 6: 83–88.
- Molnar, J.L., Gamboa, R.L., Revenga, C., and Spalding, M.D. 2008. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment 6: 485–492.
- Monte–Luna, P., Lluch–Belda, D., Serviere–Zaragoza, E., Carmona, R., Reyes–Bonilla, H., Aurioles–Gamboa, D., Castro–Aguirre, J.L., del Proo, S.A.G., Trujillo–Milan, O., and Brook, B.W. 2007. Marine extinctions revisited. Fish and Fisheries 8: 107–122.
- Morán, X.A.G., López–Urrutia, A., Calvo–Díaz, A., and Li, W.K.W. 2010. Increasing importance of small phytoplankton in a warmer ocean. Global Change Biology 16: 1137.
- Morissette, S. and Himmelman, J.H. 2000. Subtidal food thieves: interactions of four invertebrate kleptoparasites with the sea star *Leptasterias polaris*. Animal Behavior 60: 531–543.
- Morris, J.T., Sundareshwar, P.V., Nietch, C.T., Kjerfve, B., and Cahoon, D.R. 2002. Responses of coastal wetlands to rising sea level. Ecology 83: 2869–2877.
- Morrison, W., Nelson. M., Howard, J., Teeters, E., Hare, J.A., Griffis, R., Scott, J.D., and Alexander, M.A. 2015. Methodology for assessing the vulnerability of marine fish and shellfish to a changing climate. NOAA Technical Memorandum NMFS–OSF–3. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 48 pages.
- Morueta–Holme, N., Fløjgaard, C., and Svenning, J.–C. 2010. Climate change risks and conservation implications for a threatened small–range mammal species. PLoS ONE 5(4): e10360. doi:10.1371/journal.pone.0010360.
- Moyle, P.B., Kiernan, J.D., Crain, P.K., and Quiñones, R.M. 2013. Climate change vulnerability of native and alien freshwater fishes of California: A systematic assessment approach. PLoS ONE 8(5): e63883 doi: 101371/journal.pone.0063883.
- Mumford, T.M. 2007. Kelp and eelgrass in Puget Sound: Seattle, Wash., U.S. Army Corps of Engineers, Puget Sound Nearshore Partnership Report No. 2007-05. 27 pages. <u>http://www.pugetsoundnearshore.org/technical_papers/kelp.pdf</u>.
- Munday, P.L., Crawley, N.E, and Nilsson, G.E. 2009. Interacting effects of elevated temperature and ocean acidification on the aerobic performance of coral reef fishes. Marine Ecology Progress Series 388:235-242.
- Munday, P.L., Kingsford, M., O'Callaghan, M., and Donelson, J.M. 2008. Elevated temperature restricts growth potential of the coral reef fish *Acanthochromis polyacanthus*. Coral Reefs 27: 927–931.

Musick, J.A. 1999. Criteria to define extinction risk in marine fishes. Fisheries 24: 6–14.

- Musick, J.A., Harbin, M.M., Berkeley, S.A., Burgess, G.H., Eklund, A.M., Findley, L., and Wright, S.G. 2000. Marine, estuarine, and diadromous fish stocks at risk of extinction in North America (exclusive of Pacific salmonids). Fisheries 25: 6–30.
- Myers, D., 2010, Shoreline development on Puget Sound. Puget Sound Shorelines and the Impacts of Armoring—Proceedings of a State of the Science Workshop, May 2009. (Eds. Shipman, H., Dethier, M.N., Gelfenbaum, G., Fresh, K.L., and Dinicola, R.S.). 43-48. U.S. Geological Survey Scientific Investigations Report 2010-5254. 262 pages.
- Nabholz, J.V. 1991. Environmental hazard and risk assessment under the United States Toxic Substances Control Act. The Science of the Total Environment 109/110 649–665.
- National Research Council. 2012. Sea–level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. The National Academies Press, Washington D.C. 201 pages.
- Nelson, W.G., Hyland, J.L., Lee II, H., Cooksey, C.L., Lamberson, J.O., Cole, F.A., and Clinton, P.J. 2008. Ecological Condition of Coastal Ocean Waters along the U.S. Western Continental Shelf: 2003. EPA 620/R-08/001, U.S. EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Western Ecology Division, Newport OR, 97365; and NOAA Technical Memorandum NOS NCCOS 79, NOAA National Ocean Service, Charleston, SC 29412-9110. 137 pages.
- Nelson, W.G., Lee II, H., and Lamberson, J.O. 2005. Condition of Estuaries of California for 1999: A Statistical Summary. EPA/620/R–05/004. U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC. 154 pages.
- Nelson, W.G., Lee II, H., Lamberson, J.O., Cole, F.A., Weilhoefer, C.L., and Clinton, P.J. 2007. The condition of tidal wetlands of Washington, Oregon and California –2002. U.S. Environmental Protection Agency, Washington D.C. EPA620/R–07/002. 102 pages.
- Nelson, W.G., Lee II, H., Lamberson, J.O., Engle, V., Harwell, L., and Smith, L.M. 2004. Condition of estuaries of western United States for 1999: a statistical summary. U.S. Environmental Protection Agency, Washington D.C EPA/620/R–04/200. 154 pages.
- Neuheimer, A.B., Thresher, R.E., Lyle, J.M., and Semmens, J.M. 2011. Tolerance limit for fish growth exceeded by warming waters. Nature Climate Change 1: 110–113.
- Nicholls, R.J., Hanson, S.E., Lowe, J.A., Warrick, R.A., Lu, X., Long, A.J. and Carter, T.R. 2011: Constructing sea– level scenarios for impact and adaptation assessment of coastal area: a guidance document. Supporting Material, Intergovernmental Panel on Climate Change Task Group on Data and Scenario Support for Impact and Climate Analysis (TGICA). 47 pages.
- Nilsson, G.E., Crawley, N., Lunde, I.G., and Munday, P.L. 2009. Elevated temperature reduced the respiratory scope of coral reef fishes. Global Change Biology 15: 1405–1412.

- NOAA. 2012. Status of stocks 2012 annual report to congress on the status of U. S. fisheries. National Oceanic and Atmospheric Association. 8 pages. http://www.nmfs.noaa.gov/sfa/statusoffisheries/2012/2012_SOS_RTC.pdf.
- NOAA. 2013. Shoreline Assessment Manual. 4th Edition. U.S. Dept. of Commerce. Seattle, WA: Emergency Response Division, Office of Response and Restoration, National Oceanic and Atmospheric Administration. 73 pp + appendices.
- Noisette, F., Comtet, T., Legrand, E., Bordeyne, F., Davoult, D., and Martin, S. 2014. Does encapsulation protect embryos from the effects of ocean acidification? the example of crepidula fornicata. PLoS ONE 9(3): e93021. doi:10.1371/journal.pone.0093021
- Norman, K., Sepez, J., Lazrus, H., Milne, N., Package, C., Russell, S., Grant, K., Lewis, R.P., Primo, J., Springer, E., Styles, M., Tilt, B., and Vaccaro, I. 2007. Community profiles for West Coast and North Pacific fisheries–Washington, Oregon, California, and other U.S. states. U.S. Department of Commerce, NOAA Tech. Memo. NMFS-NWFSC-85. 602 pages.
 <u>https://www.nwfsc.noaa.gov/assets/25/499_01082008_153910_CommunityProfilesTM85WebFinalSA.p</u> df.
- NRC. 2012. National Research Council. Sea–Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future. The National Academies Press, Washington, DC. 201 pages. http://www.ecy.wa.gov/climatechange/docs/ipa_slr_nrcfullreport.pdf.
- Nygren, A. 2014. Cryptic polychaete diversity: a review. Zoologica Scripta 43: 172–183.
- Olden, J.D., Poff, N.L., and Bestgen, K.R. 2008. Trait synergisms and the rarity, extirpation, and extinction risk of desert fishes. Ecology 89: 847–856.
- O'Leary, R.A., Choy, S.L., Murray, J.V., Kynn, M., Denham, R., Martin, T.G., and Mengersen, K. 2008. Comparison of three expert elicitation methods for logistic regression on predicting the presence of the threatened brush–tailed rock–wallaby *Petrogale penicillata*. Environmetrics 20: 379–98.
- Pacific States Marine Fisheries Commission (PSMFC). 2004. Risk Assessment for the Pacific Groundfish FMP. Page 15. <u>ftp://ftp.streamnet.org/pub/marinehabitat/DraftEFHEIS/AppendixA/crav4.pdf</u>
- Paganini, A.W., Miler, N.A., and Stillman, J.H. 2014. Temperature and acidification variability reduce physiological performance in the intertidal zone porcelain crab *Petrolisthes cinctipes*. Journal of Experimental Biology 217: 3974–3980.
- Pansch, C., Schaub. I., Havenhand, J., and Wahl, M. 2014. Habitat traits and food availability determine the response of marine invertebrates to ocean acidification. Global Change Biology 20: 765–777.
- Parkinson, R.W. 1989. Decelerating Holocene sea level rise and its influence on southwest Florida coastal evolution: A transgressive/regressive stratigraphy. Journal of Sedimentary Petrology 59: 960-972.

- Parker, S.J., Berkeley, S.A., Golden, J.T., Gunderson, D.R., Heifetz, J., Hixon, M.A., Larson, R., Leaman, B.M., Love, M.S., Musick, J.A., O'Connell, V.M., Ralston, S., Weeks, H.J., and Yoklavich, M.M. 2000. Management of Pacific Rockfish. Fisheries 25: 22–30.
- Parris, A., Bromirski, P., Burkett, V., Cayan, D., Culver, M., Hall, J., Horton, R., Knuuti, K., Moss, R., Obeysekera, J., Sallenger, A., and Weiss, J. 2012. Global Sea Level Rise Scenarios for the U.S. National Climate Assessment. NOAA Technical Report OAR CPO <u>https://scenarios.globalchange.gov/sites/default/files/NOAA_SLR_r3_0.pdf</u>
- Payne, M.C., Brown, C.A., Reusser, D.A., and Lee II, H. 2012a. Ecoregional analysis of nearshore sea-surface temperature in the North Pacific. PLoS ONE 7(1): e30105. doi:10.1371/journal.pone.0030105.
- Payne, M.C., Reusser, D.A., and Lee II, H. 2012b. Moderate–resolution sea surface temperature data and seasonal pattern analysis for the Arctic Ocean ecoregions: U.S. Geological Survey Open–File Report 2011–1246, 20 pages. <u>http://pubs.usgs.gov/of/2011/1246/.</u>
- Payne, M.C., Reusser, D.A., Lee II, H., and Brown, C.A. 2011. Moderate–resolution sea surface temperature data for the nearshore North Pacific: U.S. Geological Survey Open–File Report: 2010–1251. <u>http://pubs.usgs.gov/of/2010/1251/.</u>
- Pearson, R.G. 2010. Species' Distribution Modeling for Conservation Educators and Practitioners. Synthesis. American Museum of Natural History, Lessons in Conservation. Pages 54-89. <u>https://pdfs.semanticscholar.org/66db/947ee1a6ab91c408f489d17cfb6e068931a6.pdf.</u>
- Pearson, R.G., Stanton, J.C., Shoemaker, K.T., Aiello–Lammens, M.E., Ersts, P.J., Horning, N., Fordham, D.A., Raxworthy, C.J., Ryu, H.Y., McNees, J., and Akçakaya, H.R. 2014. Life history and spatial traits predict extinction risk due to climate change. Nature Climate Change 4: 217–221.
- Pechenik, J.A. 1999. On the advantages and disadvantages of larval stages in benthic marine invertebrate life cycles. Marine Ecology Progress Series 177: 269–297.
- Pedersen T.M., Hansen J.L., Josefson, A.B., and Hansen, B.W. 2008. Mortality through ontogeny of soft-bottom marine invertebrates with planktonic larvae. Journal of Marine Systems 73:185–207.
- Perry, A.L., Low, P.J., Ellis, J.R., and Reynolds, J.D. 2005. Climate change and distribution shifts in marine fishes. Science 308: 1912–1915.
- PFMC (Pacific Fishery Management Council). 2004. 10–meter Bathymetry Polygons for Washington, Oregon and California. Downloadable data: Data Source Information: The Active Tectonics and Seafloor Mapping Lab, College of Oceanic and Atmospheric Sciences, Oregon State University developed the data for Oregon and Washington. The Center for Habitat Studies, Moss Landing Marine Laboratories developed the data for California. Data compiled by TerraLogic GIS, Inc. http://marinehabitat.psmfc.org/.

- PFMC (Pacific Fishery Management Council). 2005. Pacific Coast Groundfish Fishery Management Plan for the California, Oregon, and Washington groundfish fishery. Appendix B, Part 1. Assessment methodology for groundfish essential fish habitat. Pacific Fishery Management Council. Portland, OR. <u>http://www.westcoast.fisheries.noaa.gov/publications/nepa/groundfish/groundfish_efh_eis/fmp-appendix-b1.pdf</u>.
- Philippart, C., van Aken, H., Beukema, J., Bos, O., Cadee, G., and Dekker, R. 2003. Climate–related changes in recruitment of the bivalve *Macoma balthica*. Limnology and Oceanography 48: 2171–2185.
- Piepenburg, D., Archambault, P., Ambrose Jr., W.G., Blanchard, A.L., Bluhm, B.A., Carroll, M.L., Conlan, K.E., Cusson, M., Feder, H.M., Grebmeier, J.M., Jewett, S.C., Lévesque, M., Petryashev, V.V., Sejr, M.K., Sirenko, B.I., Włodarska–Kowalczuk, M. 2011. Towards a pan–Arctic inventory of the species diversity of the macro– and megabenthic fauna of the Arctic shelf seas. Marine Biodiversity 41: 51–70.
- Pilgrim, E.M., Blum, M.J., Reusser, D.A., Lee II, H., and Darling, J.A. 2013. Geographic range and structure of cryptic genetic diversity among Pacific North American populations of the non–native amphipod *Grandidierella japonica*. Biological Invasions 15: 2415–2428.
- Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, JL., and Levin, S.A. 2013. Marine taxa track local climate velocities. Science 341: 1239–1242.
- Planque, B. and Frédou, T. 1999. Temperature and the recruitment of Atlantic cod (*Gadus morhua*). Canadian Journal of Fisheries and Aquatic Sciences 56: 2069–2077.
- Planque, B., Bellier, E., and Loots, C. 2011. Uncertainties in projecting spatial distributions of marine populations. ICES Journal of Marine Science 68: 1045–1050.
- Polidoro, B.A., Carpenter, K.E., Collins, L., Duke, N.C., Ellison, A.M., et al. 2010. The Loss of species: Mangrove extinction risk and geographic areas of global concern. PLoS ONE 5(4): e10095. doi:10.1371/journal.pone.0010095.
- Polidoro, B.A., Brooks, T., Carpenter, K.E., Edgar, G.J., Henderson, S., Sanciangco, J. and Robertson, D.R. 2012. Patterns of extinction risk and threat for marine invertebrates and habitat–forming species in the Tropical Eastern Pacific. Marine Ecology Progress Series 448: 93–104.
- Pondella, D.J. and Allen, M.J. 2001. Proceedings of special symposium: new and rare fish and invertebrate species to California during the 1997–1998 El Nino sponsored by the Southern California Academy of Sciences May 20, 2000. Bulletin Southern California Academy of Science 100: 129–130.
- Poore, R.Z., Williams, R.S., Jr., and Tracey, C. 2000. Sea level and climate: U.S. Geological Survey Fact Sheet 002– 00, 2 pages. <u>https://pubs.usgs.gov/fs/fs2-00/</u>.
- Pörtner, H.O. 2008. Ecosystem effects of ocean acidification in times of ocean warming: A physiologist's view. Marine Ecology Progress Series 373: 203–217.

- Pörtner, H.O. and Knust, R. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315: 95–97.
- Pörtner, H.O., Bock, C., Knust, R., Lannig, G., Lucassen, M., Mark, F.C., and Sartoris, F.J. 2008. Cod and climate in a latitudinal cline: physiological analyses of climate effects in marine fishes. Climate Research 37: 253– 270.
- Pörtner, H.O., Karl, D.M., Boyd, P.W., Cheung, W., Lluch–Cota, S.E., Nojiri, Y., Schmidt, D.N., Zavialov, P.O., Alheit, J., Aristegui, J., Armstrong, C., Beaugrand, G., Belkovich, V., Bowler, C., Brewer, P., Church, M., Cooley, S.R., del Monte-Luna, P., Edwards, M., Flint, M., Follows, M.J., Frölicher, T., Fulton, E.A., Gattuso, J.P., Hoegh-Guldberg, O., Hofmann, E.E., Knoll, A.H., Levin, L.A., Menzel, L., Moloney, C.L., Perry, R.I., Poloczanska, E.S., Roberts, J.M., Rost, B., Sarmiento, J.L., Sedlacek, J., Storch, D., Wiencke, C., and Wittmann, A.C. 2014. Ocean systems. Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. Field, C., Barros V., Dokken D., Mach K., Mastrandrea, P., and White, L.). Cambridge University Press, Cambridge, UK and New York, NY, USA. Pages 411–484. <u>http: //epic.awi.de/37501/.</u>
- Pörtner, H.O., Karl, D.M., Boyd, P.W., Cheung, W.W.L., Lluch–Cota, S.E., Nojiri, Y., Schmidt, D.N., and Zavialov, P.O. 2014. Ocean systems. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Eds. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L.) Cambridge, UK and New York, NY: Cambridge University Press. 411–484. <u>https://www.ipcc.ch/pdf/assessment-report/ar5/wg2/WGIIAR5-Chap6_FINAL.pdf</u>.
- Prather, C.M., Pelini, S.L., Laws, A., Rivest, E., Woltz, M., Bloch, C.P., Del Toro, I., Ho, C.–K., Kominoski, J., Newbold, T.A.S., Parsons, S. and Joern, A. 2013. Invertebrates, ecosystem services and climate change. Biological Reviews 88: 327–348.
- Proshutinsky, A.I., Ashik, M., Dvorkin, E.N., Häkkinen, S., Krishfield, R.A., and Peltier, W.R. 2004. Secular sea level change in the Russian sector of the Arctic Ocean. Journal of Geophysical Research: Oceans 109. doi: 10.1029/2003JC002007.
- PSMFC (Pacific States Marine Fisheries Commission). 2004. Risk Assessment for the Pacific Groundfish FMP. p. 15. <u>ftp://ftp.streamnet.org/pub/marinehabitat/DraftEFHEIS/AppendixA/crav4.pdf</u>.
- Puget Sound Action Team. 2007. 2007 Puget Sound Update: Ninth Report of the Puget Sound Assessment and Monitoring Program. Olympia, Washington: Puget Sound Action Team. 260 pages. <u>http://wdfw.wa.gov/publications/01051/wdfw01051.pdf.</u>
- Punt, A.E., Foy, R.J., Dalton, M.G., Long, W.C., and Swiney, K.M. 2016. Effects of long-term exposure to ocean acidification conditions on future southern Tanner crab (*Chionoecetes bairdi*) fisheries management. ICES Journal of Marine Science 73: 849–864.

- Ramsar. 2008. Resolution X.2.0. Biogeographic regionalization in the application of the strategic framework for the List of Wetlands of International Importance: scientific and technical guidance. Ramsar, Changwon, Republic of Korea. <u>http://archive.ramsar.org/pdf/res/key_res_x_20_e.pdf</u>.
- Raphael, M.G. and Molina, R. (Eds.) 2007. Conservation of Rare or Little Known Species. Biological, Social, and Economic Considerations. Island Press. 375 pages.
- Rastrick, S.P.S., Calosi, P., Calder–Potts, R., Foggo, A., Nightingale, G., Widdicombe, S., and Spicer, J.I. 2014. Living in warmer, more acidic oceans retards physiological recovery from tidal emersion in the velvet swimming crab, *Necora puber*. Journal of Experimental Biology 217: 2499–2508.
- Reusser, D.A. and Lee II, H. 2008. Predictions for an invaded world: a strategy to predict the distribution of native and non–indigenous species at multiple scales. ICES Journal of Marine Science 65: 742–745.
- Reusser, D.A. and Lee II, H. 2011. Evolution of natural history information in the 21st century developing an integrated framework for biological and geographical data. Journal of Biogeography 38: 1225–1239.
- Reusser, D.A., Frazier, M.L., Loiselle, R.A., Lee II, H., and Thorsteinson, L.K. 2016. Chapter 5. Arctic climate change—a tale of two cods. Alaska Arctic Marine Fish Ecology Catalog (Thorsteinson, L.K., and Love, M.S., Eds.). U.S. Geological Survey Scientific Investigations Report 2016–5038 (OCS Study, BOEM 2016–048). Pages 659–677.
- Revell, D.L., Battalio, R., Spear, B., Ruggiero, P., and Vandever, J. 2011. A methodology for predicting future coastal hazards due to sea–level rise on the California Coast. Climatic Change 109: 251–276.
- Reynolds, J.D., Dulvy, N.K., Goodwin, N.B., and Hutchings, J.A. 2005. Biology of extinction risk in marine fishes. Proceedings of the Royal Society B – Biological Sciences 272: 2337–2344.
- Rahmstorf, S. 2007. A semi-empirical approach to projecting future sea-level rise. Science. 315: 368-370.
- Richards, Z.T., Garcia, R.A., Wallace, C.C., Rosser, N.L., and Muir, P.R. 2015. A diverse assemblage of reef corals thriving in a dynamic intertidal reef setting (Bonaparte Archipelago, Kimberley, Australia). PLoS ONE 10(2): e0117791. doi:10.1371/journal.pone.0117791.
- Ries, J.B. 2011. Skeletal mineralogy in a high–CO₂ world. Journal of Experimental Marine Biology and Ecology 403: 54–64.
- Ries, J.B., Cohen, A.L., and McCorkle, D.C., 2009. Marine calcifiers exhibit mixed responses to CO₂–induced ocean acidification. Geology 37: 1131–1134.

Roberts, C.M. and Hawkins, J.P. 1999. Extinction risk in the sea. Trends in Ecology & Evolution 14: 241–246.

- Robertson, D.R. 2008. Global biogeographical data bases on marine fishes: caveat emptor. Diversity and Distributions 14: 891–892.
- Rodrigues, A.S.L. and Gaston, K.J. 2002. Rarity and conservation planning across geopolitical units. Conservation Biology 16: 674–682.

- Romsos, C., Goldfinger, C., Robison, R., Milstein, R.L., and Wakefield, W.W. 2007. Development of a regional seafloor surficial geologic habitat map for the continental margins of Oregon and Washington, USA.
 Mapping the Seafloor for Habitat Characterization (Eds. Todd, B.J. and Greene, H.G.) 229. Geological Association of Canada, Special Paper 47: 219–243.
- Ross, P.M., Parker, L., and Byrne, M. 2016. Transgenerational responses of molluscs and echinoderms to changing ocean conditions. ICES Journal of Marine Science 73: 537–549.
- Ross, P.M., Parker, L., O'Connor, W.A., and Bailey, E.A. 2011. The impact of ocean acidification on reproduction, early development and settlement of marine organisms. Water 3: 1005–1030.
- Rowe, G. and Wright, G. 2011. The Delphi technique: Past, present, and future prospects—introduction to the special issue. Technological Forecasting and Social Change 78: 1487–1490.
- Rudnick, D., Veldhuizen, T., Tullis, R., Culver, C., Hieb, K., and Tsukimura, B. 2005. A life history model for the San Francisco estuary population of the Chinese mitten crab, *Eriocheir sinensis* (Decapoda: Grapsoidea). Biological Invasions 7: 333–350.
- Ruiz, G.M., Fofonoff, P.W., Carlton, J.T., Wonham, M.J., and Hines, A.H. 2000. Invasion of coastal marine communities in North America: apparent patterns, processes, and biases. Annual Review of Ecology and Systematics 31: 481–531.
- Rumrill, S.S., 1990. Natural mortality of marine invertebrate larvae. Ophelia 32 (1–2), 163–198.
- Rutherford, E.S. and Houde, E.D. 1996. The influence of temperature on cohort–specific growth, survival, and recruitment of striped bass, *Morone saxatilis*, larvae in Chesapeake Bay. Oceanographic Literature Review 43: 73.
- Salway, R. and Shaddick, G. No date. Implementation of Qualitative Uncertainty Guidance: A Worked Example. <u>http://www.integrated-</u> <u>assessment.eu/eu/sites/default/files/Example%20of%20qualitative%20uncertainty%20analysis.pdf.</u>
- Scott, J.D., Alexander, M.A., Murray, D.R., Swales, D., and Eischeid, J. 2016. The climate change web portal a system to access and display climate and earth system model output from the CMIP5 archive. Bulletin of the American Meteorological Society 97: 523–530.
- Seddon, A.W., Froyd, C.A., Leng, M.J., Milne, G.A., and Willis, K.J. 2011. Ecosystem resilience and threshold response in the Galapagos Coastal Zone. PLoS ONE E 6(7): e22376. doi:10.1371/journal.pone.0022376.
- Selkoe, K.A. and Toonen, R.J. 2011. Marine connectivity: a new look at pelagic larval duration and genetic metrics of dispersal. Marine Ecology Progress Series 436: 291-305.
- Sexton, J.P., McIntyre, P.J., Angert, A.L., and Rice, K.J. 2009. Evolution and ecology of species range limits. Annual Review of Ecology, Evolution, and Systematics 40: 415–436.

- Shaughnessy, F.J., Gilkerson, W., Black, J.M., Ward, D.H., and Petrie, M. 2012. Predicted eelgrass response to sea level rise and its availability to foraging black Brant in Pacific Coast estuaries. Ecological Applications 22: 1743–1761.
- Schiffer, M., Harms, L., Lucassen, M., Mark, F.C., Pörtner, H.O., Storch, D. 2014. Temperature tolerance of different larval stages of the spider crab Hyas araneus exposed to elevated pCO2. Frontiers in Zoology 11:87 DOI 10.1186/s12983-014-0087-4.
- Sheridan, J.A. and Bickford, D. 2011. Shrinking body size as an ecological response to climate change. Nature Climate Change 1: 401–406.
- Short, F.T. and Neckles, H.A. 1999. The effects of global climate change on seagrasses. Aquatic Botany 63: 169–196.
- Short, F.T., Kosten, S., Morgan, P.A., and Malone, S. 2016. Impacts of climate change on submerged and emergent wetland plants. Aquatic Botany 135: 3–17.
- Small, D., Calosi, P., White, D., Spicer, J.I., and Widdicombe, S. 2010. Impact of medium–term exposure to CO₂ enriched seawater on the physiological functions of the velvet swimming crab *Necora puber*. Aquatic Biology 10: 11–21.
- Small, D.P., Calosi, P., Boothroyd, D., Widdicombe, S., and Spicer, J.I. 2016. The sensitivity of the early benthic juvenile stage of the European lobster *Homarus gammarus* (L.) to elevated pCO2 and temperature. Marine Biology 163: 53. doi:10.1007/s00227-016-2834-x
- Snedaker, S.C., Meeder, J.F., Ross, M.S., and Ford, R.G 1994. Discussion of Ellison, Joanna C. and Stoddart, David R., 1991. Mangrove ecosystem collapse during predicted sea–level rise: Holocene analogues and implications. Journal of Coastal Research, 7(1), 151–165. Journal of Coastal Research 10: 497–498.
- Snover, A.K., Mauger, G.S., Binder, L.W., Krosby, M., and Tohver, I. 2013. Climate change impacts and adaptation in Washington State: Technical summaries for decision makers. State of Knowledge Report prepared for the Washington State Department of Ecology. Climate Impacts Group, University of Washington, Seattle.
- Sodhi, N.S. and Ehrlich, P.R. 2010. Conservation Biology for All. Oxford University Press. 350 pages.
- Somero, G.N. 2012. The physiology of global change: linking patterns to mechanisms. Annual Review of Marine Science 4: 39–61.
- Sorte, C.J.B., Williams, S.L., and Carlton, J.T. 2010. Marine range shifts and species introductions: comparative spread rates and community impacts. Global Ecology and Biogeography 19: 303–316. Snover, A.K, G.S. Mauger, L.C. Whitely Binder, M. Krosby, and I. Tohver. 2013. Climate Change Impacts and Adaptation in Washington State: Technical Summaries for Decision Makers. State of Knowledge Report prepared for the Washington State Department of Ecology. Climate Impacts Group, University of Washington, Seattle.

- Spalding, M., Fox, H.H., Allen, G.R., Davidson, N., Ferdaña, Z.A., Finlayson, M., Halpern, B.S., Jorge, M.A.,
 Lombana, A., Lourie, S.A., Martin, K.D., McManus, E., Molnar, J., Recchia, C.A., and Robertson, J. 2007.
 Marine ecoregions of the world: a bioregionalization of coastal and shelf areas. Bioscience 57: 573–583.
- Spalding, M., Kainuma, M., and Collins, L. 2010. World Atlas of Mangroves. Washington DC: Earthscan. 336 pages.
- Spicer, J.I., Raffo, A. and Widdicombe, S. 2007. Influence of CO₂–related seawater acidification on extracellular acid–base balance in the velvet swimming crab *Necora puber*. Marine Biology 151: 1117–1125.
- Steyerberg, E.W., Eijkemans, M.J., Harrell Jr., F.E., and Habbema, J.D.F. 2000. Prognostic modelling with logistic regression analysis: a comparison of selection and estimation methods in small data sets. Statistics in Medicine 19: 1059–1079.
- Stralberg, D., Brennan, M., Callaway, J.C., Wood, J.K., Schile, L.M., Jongsomjit, D., Kelly, M., Parker, V.T., and Crooks, S. 2011. Evaluating tidal marsh sustainability in the face of sea–level rise: a hybrid modeling approach applied to San Francisco Bay. PLoS ONE 6(11): e27388. doi:10.1371/journal.pone.0027388.
- Streftaris, N., Zenetos, A., and Papathanassiou, E. 2005. Globalisation in marine ecosystems: the story of non– indigenous marine species across European seas. Oceanography and Marine Biology: An Annual Review 43: 419–453.
- Styf, H.K., Skold, H.N., and Eriksson, S.P. 2013. Embryonic response to long–term exposure of the marine crustacean *Nephrops norvegicus* to ocean acidification and elevated temperature. Ecology and Evolution 3: 5055–5065.
- Sumaila, U.R., Cheung, W., Lam, V.W.Y., Pauly, D., and Herrick, S. 2011. Climate change impacts on the biophysics and economics of world fisheries. Nature Climate Change 1: 449–456.
- Sunday, J.M., Bates, A.E., and Dulvy, N.K. 2012. Thermal tolerance and the global redistribution of animals. Nature Climate Change 2: 686–690.
- Sundby, S. 2000. Recruitment of Atlantic cod stocks in relation to temperature and advection of copepod populations. Sarsia 85: 277–298.
- Sutherland, W.J. 2006. Predicting the ecological consequences of environmental change: a review of the methods. Journal of Applied Ecology 43: 599–616.
- Swartz, R.C., Cole, F.A., and Deben, W.A. 1986. Ecological changes in the Southern California Bight near a large sewage outfall: benthic conditions in 1980 and 1983. Marine Ecology Progress Series 31: 1–13.
- Swiney, K.M., Long, W.C., and Foy, R.J. 2016. Effects of high pCO₂ on Tanner crab reproduction and early life history– part 1: long–term exposure reduces hatching success and female calcification, and alters embryonic development. ICES Journal of Marine Science 73: 825–835.

- Takasuka, A., Oozeki, Y., and Aoki, I. 2007. Optimal growth temperature hypothesis: why do anchovy flourish and sardine collapse or vice versa under the same ocean regime? Canadian Journal of Fisheries and Aquatic Sciences 64: 768–776.
- Taylor, J.R.A., Gilleard, J.M., Allen, M.C., and Deheyn, D.D. 2015. Effects of CO₂–induced pH reduction on the exoskeleton structure and biophotonic properties of the shrimp *Lysmata californica*. Scientific Reports 5: 1–12.
- Taylor, K.E., Stouffer, R.J., and Meehl, G.A. 2012. An Overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93: 485–498.
- Telford, M. 1982. Echinoderm spine structure, feeding and host relationships of four species of *Dissodactylus* (Brachyura: Pinnotheridae). Bulletin of Marine Science 32: 584–594.
- Thieler, E.R., and Hammar-Klose, E.S., 2000. National Assessment of Coastal Vulnerability to Sea-Level Rise: U.S. Pacific Coast. U.S. Geological Survey, Open-File Report 00-178. <u>https://pubs.usgs.gov/of/2000/of00-178/</u>.
- Thorne, K.M., Dugger, B.D., Buffington, K.J., Freeman, C.M., Janousek, C.N., Powelson, K.W., Gutenspergen, G.R., and Takekawa, J.Y. 2015. Marshes to mudflats—effects of sea–level rise on tidal marshes along a latitudinal gradient in the Pacific Northwest. U.S. Geological Survey Open–File Report 2015–1204. 54 pages plus appendices. <u>http://dx.doi.org/10.3133/ofr20151204</u>.
- Thorner, J., Kumar, L., and Smith, S.D. 2014. Impacts of climate–change–driven sea level rise on intertidal rocky reef habitats will be variable and site specific. PLoS ONE 9(1): e86130. doi:10.1371/journal.pone.0086130.
- Thresher, R.E., Koslow, J.A., Morison, A.K., and Smith, D.C. 2007. Depth–mediated reversal of the effects of climate change on long–term growth rates of exploited marine fish. Proceedings of the National Academy of Sciences of the United States of America 104: 7461–7465.
- Tomanek, L. 2010. Variation in the heat shock response and its implication for predicting the effect of global climate change on species' biogeographical distribution ranges and metabolic costs. Journal of Experimental Biology 213: 971–979.
- Toropova, C., Meliane, I., Laffoley, D., Matthews, E., and Spalding, M. (eds.) 2010. Global ocean protection: present status and future possibilities. Brest, France: Agence des aires 230 marines protégées, Gland, Switzerland, Washington, DC and New York, USA: IUCN WCPA, Cambridge, UK: UNEP–WCMC, Arlington, USA: TNC, Tokyo, Japan: UNU, New York, USA: WCS. 96 pages.
- Traill, L.W., Perhans, K., Lovelock, C.E., Prohaska, A., McFallan, S., Rhodes, J.R., and Wilson, K.A. 2011. Managing for change: wetland transitions under sea–level rise and outcomes for threatened species. Biodiversity and Distributions 17: 1225–1233.
- Triantis, K.A., Guilhaumon, F., and Whittaker, R.J. 2012. The island species–area relationship: biology and statistics. Journal of Biogeography 39: 215–231.

- Trowbridge, C.D. 1994. Defensive responses and palatability of specialist herbivores: predation on the NE Pacific ascoglossan gastropods. Marine Ecology Progress Series 105: 61–70.
- Tseng, Y.C., Hu, M.Y., Stumpp, M., Lin, L.Y., Melzner, F., and Hwang, P.P. 2013. CO₂-driven seawater acidification differentially affects development and molecular plasticity along life history of fish (*Oryzias latipes*).
 Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology 165: 119–130.
- U.S. Environmental Protection Agency (EPA). 1998. Guidelines for Ecological Risk Assessment. U.S. EPA Risk Assessment Forum. Washington D.C. EPA/630/R095/002F, 1998. 171 pages. https://www.epa.gov/risk/framework-ecological-risk-assessment.
- U.S. Environmental Protection Agency (EPA). 2003. Guidance for developing ecological soil screening levels. Office of Solid Waste and Emergency Response (US EPA), OSWER Directive 9285.7–55. 87 pages. https://rais.ornl.gov/documents/ecossl.pdf.
- U.S. Environmental Protection Agency (EPA). 2004. Overview of the ecological risk assessment process in the Office of Pesticide programs, U.S. Environmental Protection Agency endangered and threatened species effects determinations. Office of Prevention, Pesticides and Toxic Substances, Office of Pesticide Programs Washington, D.C. 92 pages. <u>https://www.epa.gov/sites/production/files/2014–11/documents/ecorisk-overview.pdf.</u>
- U.S. Environmental Protection Agency (EPA). 2008. Combined benthic database for development of Pacific Coast indicators. U.S. EPA Office of Research and Development, National Health and Environmental Effects Laboratory, Western Ecology Division, Pacific Coastal Ecology Branch. Newport, OR.
- U.S. Environmental Protection Agency (EPA). 2009. A framework for categorizing the relative vulnerability of threatened and endangered species to climate change. Washington D.C: National Center for Environmental Assessment, U.S. Environmental Protection Agency. EPA/600/R–9/011. <u>https://www.fws.gov/uploadedFiles/508_Climate%20change%20report%20-</u> %20GCWA%20example%5b1%5d.pdf.
- U.S. Environmental Protection Agency (EPA). 2012. Freshwater Traits Database. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R–11/038F. Available from the National Technical Information Service, Springfield, VA. <u>http://www.epa.gov/ncea.</u> <u>https://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=241813.</u>
- U.S. Environmental Protection Agency (EPA), 2015. Office of Water and Office of Research and Development. National Coastal Condition Assessment 2010. Washington, DC. December, 2015. EPA 841-R-15-006. <u>https://www.epa.gov/national-aquatic-resource-surveys/national-coastal-condition-assessment-2010-report</u>.
- U.S. Fish and Wildlife Service. 2004. National standards and quality components for wetlands, deepwater and related habitat mapping. Arlington, VA: U.S. Fish and Wildlife Service, Division of Habitat and Resource Conservation, Branch of Habitat Assessment. 18 pages. http://www.fws.gov/stand/standards/dl_wetlands_National%20Standards.doc.

- U.S. Fish and Wildlife Service. 2009. Data collection requirements and procedures for mapping wetland, deepwater and related habitats of the United States. Arlington, VA: U.S. Fish and Wildlife Service, Division of Habitat and Resource Conservation, Branch of Habitat Assessment. 96 pages. <u>http://www.fws.gov/wetlands/Documents/Data-Collection-Requirements-and-Procedures-for-Mapping-Wetland-Deepwater-and-Related-Habitats-of-the-United-States.pdf</u>.
- USGS/EPA RACE Data 1977–2006. 2013. USGS/EPA Consolidated RACE (Resource Assessment Conservation and Engineering) Data 1977–2006. Seattle, WA: National Oceanic and Atmospheric Administration (NOAA), Alaska Fisheries Science Center (AFSC), Resource Assessment Conservation and Engineering (RACE) Division.
- Uthicke, S., Schaffelke, B., and Byrne, M. 2009. A boom–bust phylum? Ecological and evolutionary consequences of density variations in echinoderms. Ecological Monographs 79: 3–24.
- Valentine, J.W. and Jablonski, D. 1986. Mass extinctions: sensitivity of marine larval types. Proceedings of the National Academy of Sciences 83: 6912–6914.
- Van Soest, R.W.M., Boury–Esnault, N., Vacelet, J., Dohrmann, M., Erpenbec, D., De Voogd, N.J., Santodomingo, N., Vanhoorne, B., Kelly, M., and Hooper, J.N.A. 2012. Global diversity of sponges (Porifera) PLoS ONE 7(4): e35105. doi: 10.1371/journal.pone.0035105.
- van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.–F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., and Rose, S.K. 2011. The representative concentration pathways: an overview. Climatic Change 109: 5–31.
- Vazquez, L.B. and Gaston, K.J. 2004. Rarity, commonness, and patterns of species richness: the mammals of Mexico. Global Ecology and Biogeography. 13: 535–542.
- Visser, M.E. 2008. Keeping up with a warming world; assessing the rate of adaptation to climate change. Proceedings of the Royal Society: Biological Sciences 275: 649–659.
- Waldbusser, G.G. and Salisbury, J.E. 2014. Ocean acidification in the coastal zone from an organism's perspective: multiple system parameters, frequency domains, and habitats. Annual Review of Marine Science 6: 221–247.
- Waldbusser, G.G., Brunner, E.L., Haley, B.A., Hales, B., Langdon, C.J., and Prahl, F.G. 2013. A developmental and energetic basis linking larval oyster shell formation to ocean acidification. Geophysical Research Letters 40: 2171–2176.
- Waldbusser, G.G., Gray, M.W., Hales, B., Langdon, C.J., Haley, B.A., Gimenez, I., Smith, S.R., Brunner, E.L., and Hutchinson, G. 2016. Slow shell building, a possible trait for resistance to the effects of acute ocean acidification. Limnology and Oceanography 61: 1969–1983.
- Waldbusser, G.G., Hales, B., Langdon, C.J., Haley, B.A., Schrader, P., Brunner, E.L., Gray, M.W., Miller, C.A., Gimenez, I., and Hutchinson, G. 2015. Ocean acidification has multiple modes of action on bivalve larvae. PLoS ONE 10(6): e0128376. doi:10.1371/journal.pone.0128376.

- Walther, G.R., Roques, A., Hulme, P.E., Sykes, M.T., Pyšek, P., Kühn, I., Zobel, M., Bacher, S., Botta-Dukát, Z., Bugmann, H, Czucz, B., Dauber, J., Hickler, T., Jarosík, V., Kenis, M., Klotz, S., Minchin, D., Moora, M., Nentwig, W., Ott, J., Panov, VE., Reineking, B., Robinet, C., Semenchenko, V., Solarz, W., Thuiller, W., Vilà, M., Vohland, K., and Settele, J. 2009a. Alien species in a warmer world: risks and opportunities. Trends in Ecology & Evolution 24: 686–693.
- Walther, K., Anger, K. and Pörtner, H.O. 2010. Effects of ocean acidification and warming on the larval development of the spider crab *Hyas araneus* from different latitudes (54° vs. 79°N). Marine Ecology Progress Series 417: 159–170.
- Walther, K., Sartoris, F.J., Bock, C., and Pörtner, H.O. 2009b. Impact of anthropogenic ocean acidification on thermal tolerance of the spider crab *Hyas araneus*. Biogeosciences 6: 2207–2215.
- Warren Pinnacle Consulting, Inc. 2011. SLAMM Analysis of the Oregon Coast for Ducks Unlimited, Vancouver, WA. 224 pages. <u>http://warrenpinnacle.com/prof/SLAMM/DU/SLAMM_Ducks_Oregon_Coast_1_13_2012.pdf</u>.
- Warren Pinnacle Consulting, Inc. 2014. Evaluation of Regional SLAMM Results to Establish a Consistent Framework of Data and Models. Gulf Coast Prairie Land Conservation Cooperative. Pages 1–46. <u>http://warrenpinnacle.com/prof/SLAMM/GCPLCC/WPC_GCPLCC_Final_Report.pdf</u>.
- Warren, M.S., Hill, J.K., Thomas, J.A., Asher, J., Fox, R., Huntley, B., Roy, D.B., Telfer, M.G., Jeffcoate, S., Harding, P., and Jeffcoate, G. 2001. Rapid responses of British butterflies to opposing forces of climate and habitat change. Nature 414: 65–69.
- Washington State Department of Natural Resources. No Date. The Washington State ShoreZone Inventory website: http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-inventory.
- Wayne, G.P. 2013. The Beginner's Guide to Representative Concentration Pathways. Skeptical Science. Version 1.0. 24 pages. <u>https://www.skepticalscience.com/docs/RCP_Guide.pdf</u>.
- Webber, M., Calumpong, H., Ferreira, B., Granek, E., Green, S., Ruwa, R., and Soares, M. 2016. Chapter 48. Mangroves. The First Global Integrated Marine Assessment World Ocean Assessment I (eds. Inniss, L. and Simcock, A.). United Nations. 18 pages.
 http://www.un.org/depts/los/global_reporting/WOA_RPROC/Chapter_48.pdf.
- Weinberg, J.R., Dahlgren, T.G., and Halanych, K.M. 2002. Influence of rising sea temperature on commercial bivalve species of the U.S. Atlantic coast. American Fisheries Society Symposium. Pages 131–140.
- Wernberg, T., Bennett, S., Babcock, R.C., de Bettignies, T., Cure, K., Depczynski, M., Dufois, F., Fromont, J.,
 Fulton, C.J., Hovey, R.K., Harvey, E.S., Holmes. T.H., Kendrick, G.A., Radford, B., Santana–Garcon, J.,
 Saunders, B.J., Smale, D.A., Thomsen, M.S., Tuckett, C.A., Tuya, F., Vanderklift, M.A., Wilson, S. 2016.
 Climate–driven regime shift of a temperate marine ecosystem. Science 353: 169–172.

- Wethey, D.S. and Woodin, S.A. 2010. Ecological hindcasting of biogeographic responses to climate change in the European intertidal zone. Hydrobiologia 606: 139–151.
- Wethey, D.S., Woodin, S.A., Hilbish, T.J., Jones, S.J., Lima, F.P., and Brannock, P.M. 2011. Response of intertidal populations to climate: effects of extreme events versus long term change. Journal of Experimental Marine Biology and Ecology 400: 132–144.
- Whiteley, N.M. 2011. Physiological and ecological responses of crustaceans to ocean acidification. Marine Ecology Progress Series 430: 257–271.
- Whittaker, R.J. and Fernandez–Palacios, J.M. 2007. Island Biogeography: Ecology, Evolution, and Conservation, Second Edition. Washington, DC: Smithsonian Institution Press. 416 pages.
- Wicks, L.C. and Roberts, J.M. 2012. Benthic invertebrates in a high CO₂ world. Oceanography and Marine
 Biology: An Annual Review (Eds. Gibson, R.N., Atkinson, R.J.A., Gordon, J.D.M., Hughes, R.N., Hughes,
 D.J., and Smith, I.P.) Vol. 50: 127–188.
- Wittmann, A.C. and Pörtner, H.O. 2013. Sensitivities of extant animal taxa to ocean acidification. Nature Climate Change 3: 995–1001.
- Wong, P.P., Losada, I.J., Gattuso, J.-P., Hinkel, J., Khattabi, A., McInnes, K.L., Saito, Y., Sallenger, A. 2014. Coastal systems and low-lying areas. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (Eds. Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., and White, L.L.). Cambridge University Press, Cambridge, UK, and New York, NY USA. pp. 361–409.
- Wood, H.L., Spicer, J.I., Lowe, D.M., and Widdicombe, S. 2010. Interaction of ocean acidification and temperature; the high cost of survival in the brittlestar *Ophiura ophiura*. Marine Biology 157, 2001– 2013.
- Woodroffe, C.D. 1990. The impact of sea-level rise on mangrove shorelines. Progress in Physical Geography 14: 483–520.
- Woodroffe, C.D. 1995. Response of tide–dominated mangrove shorelines in northern Australia to anticipated sea-level rise. Earth Surface Processes and Landforms 20: 65–85.
- Woodroffe, C.D. and Mulrennan, M.E. 1993. Geomorphology of the lower Mary River plains, Northern Territory. North Australia Research Unit and the Conservation Commission of the Northern Territory. 152 pages.
- Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I.A., and Saintilan, N. 2016. Mangrove sedimentation and response to relative sea-level rise. Annual Review of Marine Science 8: 243-246.

- World Register of Marine Species, 2013. (Eds. Boxshall, G., Mees, J., Costello, M.J., Hernandez, F., Vandepitte, L., Gofas, S., Hoeksema, B.W., Klatau, M., Kroh, A., Poore, G.C.B., Read, G., Stöhr, S., de Voogd, N.J., Walter, C.T., De Broyer, C., Horton, T., and Kennedy, M.). http://www.marinespecies.org/index.php.
- Wyllie-Echeverria, S. and Ackerman, J.D. 2003. Seagrasses of the Pacific Coast of North America. World Atlas of Seagrasses; Present status and Future Conservation (Eds. Green, E. and Short, F.). 217-225. University of California Press: Berkeley, CA. 260 pages.
- Yamane, L. and Gilman, S.E. 2009. Opposite responses by an intertidal predator to increasing aquatic and aerial temperatures. Marine Ecology Progress Series 393: 27–36.
- Yamano, H., Sugihara, K., and Nomura, K. 2011. Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures. Geophysical Research Letters 38: L0460.
- Zervas, C. 2009. Sea Level Variations of the United States 1854–2006. National Oceanic and Atmospheric Administration, US Department of Commerce, National Ocean Service, Center for Operational Oceanographic Products and Services. NOAA Technical Report NOS CO–OPS 053. 194 pages.
- Zhang, H., Shin, P.K., and Cheung, S.G. 2016. Physiological responses and scope for growth in a marine scavenging gastropod, *Nassarius festivus* (Powys, 1835), are affected by salinity and temperature but not by ocean acidification. ICES Journal of Marine Science 73: 814–824.
- Zippay, MK.L. and Hofmann, G.E. 2010. Effect of pH on gene expression and thermal tolerance of early life history stages of red abalone (*Haliotis rufescens*). Journal of Shellfish Research 29: 429–439.









Office of Research and Development (8101R) Washington, DC 20460

Official Business Penalty for Private Use \$300



PRESORTED STANDARD POSTAGE & FEES PAID EPA PERMIT NO. G-35