FROM MARINE SNAILS TO MARINE SPATIAL PLANNING: THE SCIENCE OF HUMAN IMPACTS AND RELATIONSHIPS WITH MARINE ECOSYSTEMS

by

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Abstract

Extractive human systems are driving unprecedented biodiversity loss and exacerbating social inequity. The magnitude of the intertwined climate, biodiversity, and social inequity crises has prompted the development of interdisciplinary research approaches to address these complex problems. One such approach, social-ecological systems (SES), aims to understand the relationships between coupled human and ecological systems. This thesis applies an SES lens to understand the science of human impacts on and relationships with marine ecosystems and inform characterizations of system vulnerability. First, I examined the sensitivity of marine ectothermic animals to climate change by conducting a meta-analysis of the effects of ocean acidification and warming. My synthesis of nearly five hundred factorial studies demonstrates the negative effects of these two drivers, identifies specific taxonomic groups (molluscs), life-history traits (adults, sessile), and latitudes (tropical and temperate) that are more sensitive, and refutes two common assumptions about the drivers' interactive effects. Next, I tested whether populations of a marine snail vary in their vulnerability to ocean warming based on thermal sensitivity and local rates of ocean warming. Using coupled lab and field experiments with snails from two regions in the middle of their range that differ in thermal characteristics, I found that snails from the warmer Salish Sea, an urban sea, showed greater vulnerability to ocean warming than those from the cooler central coast of British Columbia, Canada. Finally, to inform how humans can mitigate our impacts while sustaining complex relationships with the ocean, I partnered with the Sḵwx̱wú7mesh Úxwumixw (Squamish Nation) and regional stewardship organizations on a marine spatial planning project in the Salish Sea. I employed a mixed-methods community-based participatory mapping approach to characterize place-based values and outline opportunities to decolonize research and mapping processes. The results contribute important social data about place-based values, reveal value interactions, reflect knowledge system plurality, and identify avenues to advance reconciliation. Overall, this thesis highlights the vulnerability of marine life, particularly life within urban seas, to climate change and provides a roadmap for researchers and decision-makers to meaningfully steward the health and well-being of coastal social-ecological systems.

Lay Summary

Humans are driving unprecedented rates of change to the world around us, culminating in the climate, biodiversity, and social inequity crises. Here, I examine human impacts and relationships with the ocean to inform how we can respond to these intersecting crises. I use research approaches that span spatial scales and disciplines. By combining global synthesis with laboratory and field experiments, I reveal widespread negative effects of climate change on marine animals and clarify species characteristics and environmental contexts that increase vulnerability to ocean warming and acidification. Through a collaborative mapping project with local and Indigenous partners, I identify important places and values to protect within an urban sea and highlight opportunities to advance reconciliation in marine spatial planning and research processes. Collectively, my dissertation contributes new information to inform research and planning agendas and strengthens our ability to care for sensitive places and creatures.

Preface

This dissertation comprises original research that I designed and implemented with support and guidance from my supervisor, Dr. Christopher DG Harley. I wrote all five chapters with revisions provided by CDG Harley and my supervisory committee, Dr. Amanda Vincent, Dr. Michelle Tseng, and Dr. Dolph Schluter.

I conceptualized Chapter 2 with CDG Harley and independently led the meta-analytical design, data collection, analysis, and writing. My co-authors supported data collection and extraction (Lara Calvo), advised on data analysis (Dr. Devin Lyons), contributed mathematic equations to enhance the accuracy of factorial mean effect size estimates (Appendix A, Dr. Marc Lajeunesse), and contributed toward the editing and improvement of the writing (all). I have prepared a formatted version of this chapter for submission to a peer-reviewed journal with myself as lead author.

Chapter 3 was conceptualized with CDG Harley, who also contributed substantially to the structuring and editing process. I led the experimental design, data analysis and writing. My co-authors, Graham Brownlee and Dr. Alyssa-Lois Gehman, supported data collection in the field and lab experiments. Field technicians from the Hakai Institute also assisted the data collection at their Calvert Island field station. The reciprocal transplant of Nucella lamellosa was permitted by DFO ITC license number 119163. All co-authors reviewed and edited a manuscript version of this chapter that has been submitted for publication as: F. Beaty, AM Gehman, G Brownlee, CDG Harley, Not just range limits: warming rate and thermal sensitivity shape climate change vulnerability in a species range centre. It is currently undergoing revisions for resubmission.

I led the co-creation of Chapter 4 with research and community advisory team members associated with the Átl'ka7tsem/Howe Sound Marine Stewardship Initiative. The study's design, data collection, and analysis involved collaboration with co-authors and community members. I led and conducted majority work through all phases and independently wrote up the chapter. My co-authors supported the data collection and analysis process as follows: Myia Antone and Jonathan Williams led the interviews with Skwxú7mesh Úxwumixw (Squamish Nation) members, Bridget John transcribed all interview data, Bridget John and Nikita Wallia led the GIS spatial data analysis, Dr. Nathan Bennet advised on the design, data analysis, and structuring

and editing process, and CDG Harley supported the editing process. The following members of my community advisory team contributed substantially toward the design and dissemination phases: Ruth Simons, Sarah McJannet, Jay Ritchlin, Randall Lewis, Courtney Smaha, Charlene Williams, Joyce Williams, Chris Lewis, Jessica Schultz, Aroha Miller, and Kathleen Edwards. The research protocol was approved by UBC's Behavioural Research Ethics Board review (H20-01674) and by the Sk̲wx̲ú7mesh Úxwumixw council under a collaborative research agreement. Dr. Amanda Vincent also provided significant guidance toward the design and writing of this chapter. A formatted version of this chapter is being prepared for submission to a peer-reviewed journal, with myself as lead author, and I have created and shared accessible versions of the data (i.e., narrative reports, story maps, shapefiles) with the Átl'k̲a7tsem/Howe Sound Marine Stewardship Initiative for inclusion in their marine spatial planning decision-support tools.

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List of Abbreviations

B.C. = British Columbia

CI = confidence interval

CO_2 = carbon dioxide

CT_{max} = critical thermal maximum

GIS = geographic information system

HSD = honestly significant difference

lnRR = log response ratio

MSI = Marine Stewardship Initiative

MSP = marine spatial planning

NA = not applicable

NBS = National Bureau of Standards

OA = ocean acidification

OCLTT = oxygen- and capacity-limited thermal tolerance

PGIS = participatory geographic information system

pH = potential hydrogen

PPGIS = public participatory geographic information system

PRISMA = preferred reporting items for systematic reviews and meta-analyses

RCP = representative concentration pathway

RMR = resting metabolic rate

SE = standard error

SES = social-ecological system

SST = sea surface temperature

UBC = University of British Columbia

USA = United States of America

USD = United States dollars

YSI = Yellow Springs instrument

Glossary

Átl'ka7tsem: one of three Skwxwú7mesh place names for Howe Sound, meaning to paddle out of the Sound

Ectotherm: an organism that is dependent upon external sources of body heat (as opposed to endotherm). Their body temperatures reflect their environments to varying degrees

Indigenous knowledge: the understandings, skills, and philosophies developed by societies with long histories of interactions with their surroundings

Intraspecific: occurring or existing within a species or between individuals of the same species

Local knowledge: the understandings and skills developed by people specific to the place they live

Ocean acidification: the collective changes of marine CO_2 systems, including reduced carbonate ion content and pH and increased total hydrogen ion content and CO_2 partial pressure

Phenotypic plasticity: a single genotype's adjustment of phenotypic expression based on environmental conditions

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I am extremely grateful to the Sk̲wx̲wú7mesh, Haíłzaqv, Wuikinuxv, Snuneymuxw, xʷməθkʷəy̓əm, selílwitulh, and shíshálh First Nations, in whose ancestral lands and waters I have lived and worked while creating this dissertation. Thank you for your past and ongoing stewardship of the life around us, and a special thanks to the Sk̲wx̲wú7mesh Úxwumixw (Squamish Nation) for all you have taught me through our collaboration.

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Thank you to my dear family and friends outside of school and work. You give my life meaning and continue to shape me in a way that I am incredibly grateful for. To my parents, Ross and Trisha, thank you for nurturing in me a deep love of biodiversity, the Salish Sea, writing ("death to acronyms!"), collaboration, and leadership. Thank you to my siblings, Care, John, Shan, Heath, Eamonn, Britta, Ross, and Keenan for your eternal support and love. Thank you to my niblings (Aiden, Sebi, Sloan, Josie, Lucas, Sam, Molly, and Celeste) for bringing joy and goofiness to my life and to Lynn, Glenn, Laurie, Curt, and Sarah for welcoming me into your family and allowing me to share my love of snails and the sea with you! Thank you, friends, especially Cali, Claire, Devyn, Aubree, Ellie, Hannah, and Izzy, for celebrating, exploring, and building community together these past many years – I learn so much from you! Thanks to my fur-babies Floof and Maurice for being the purrfect cuddle companions (and distractions!). And thank you to my life-partner Greg for your grounding love, thoughtful care, and derpy humour that have nurtured me throughout this epic journey.

Finally, thank you ocean. Being near you is my therapy, learning about you is my inspiration, and growing my sense of stewardship with you is my compass.

Dedication

To the leading ladies all around me and to the memory of my Grandma, Patience (Pat) Fockler (1924-2021), who taught me the value of simplicity, smiles, hard work, family, and grammar

Excerpt from 'A letter from the ocean' by Caridad Svich

A letter came from the ocean
It was addressed to "the person that went away to the hut in the woods"
The letter was enclosed in a small envelope that smelled of lilac
I opened the seal carefully
It's not every day, after all, that the ocean writes you a letter
The paper was gossamer thin
The letter began

Dear person that went away to the hut in the woods while the world was on fire,
I don't imagine that you know what you sound like.
But from where I live, it sounds as if every word is dandelion.
I hadn't heard that word in a long time.
Just like I hadn't heard the words "nectar," "willow,"
since you were seven years of age.

I missed those words. I like them better than "blog" and "cut and paste."
But then again, you know that, because you are here. In the woods.
In the hut where a poet once lived and others too.
And soon, you will go back to your city and try to live your life again. And perhaps let go of some of your rage,
And perhaps start to look at others with kindness.

It's not easy. I know.
I am used to my rage, too.
It can be useful. It is a part of us, after all.
Sometimes I rage so much that my waves destroy everything.
And I think, they will learn now.
These humans will learn, because they have brains.
They have logic and reason. And they have this thing too called imagination,
And with it, they can do so much, so much good, and so much beauty,
And so much music.

And sometimes when I hear their songs, I can't help but get emotional.
I'm a softie that way. I hope you can forgive me.
I know being soft is not in fashion these days.
But sometimes I can't help myself.

Because sometimes – on certain days, when the light hits the sky a certain way,
Or I see someone walking along the beach, their eyes full of possibility,
Or some child is rescued in a peacekeeper's arms
While bombs carry their city away
I think: I'm in love.
I really am.
I love you all so much.

Chapter 1: Introduction

1.1 Social-ecological systems and vulnerability

What does it mean to be a scientist in the twenty-first century, when humans are causing unprecedented rates of change to the world around us? Anthropogenic climate change, exploitation (e.g., fishing, hunting), and habitat conversion are driving biodiversity loss and social inequity crises throughout the world (Friel et al., 2022; Jaureguiberry et al., 2022). Since the turn of the millennium, language has evolved to capture these crisis-induced transformations to ecological and social systems. 'The Anthropocene' references the proposed geological epoch and events defined by humanity's imprint on global geochemical, climatological, and biological systems (Otto, 2018; Waters et al., 2016). 'Solastalgia', a term coined in 2003 that describes the emotional distress caused by environmental change, is strongly associated with mental health responses to climate change's transformational effects on people's homes via extreme wildfires, flooding, droughts, and melting sea ice (Albrecht, 2016; Watts et al., 2015). Finally, 'reconciliation' refers to the process of healing relationships between Indigenous and non-Indigenous peoples that were fractured and eroded by centuries of colonialism (TRC, 2015; Wong et al., 2020). Collectively, these words describe some of the planetary, emotional, and ethical consequences of extractive human behaviours and evoke a desire to do better, to heal. The million-dollar question is *how* do we heal our society and the ecosystems upon which we depend? This thesis focuses on answering that question by understanding the science of human interactions with life in the sea.

Alongside language, science has also evolved in response to the intertwined climate, biodiversity, and social equity crises, as demonstrated by the development of theories that attempt to explain, address, and even solve these complex problems (Weber, 2019). For example, social-ecological systems (SES) research applies an interdisciplinary lens to understand the relationships between people and nature and embraces the complex and coupled interactions across social and ecological systems (Levin et al., 2013; Ostrom, 2009). Social systems are defined by human economic, political, social, and cultural processes while ecological systems include ecological processes and organisms that interact with one another and their environment (Weber, 2019). SES research situates humans within nature, rather than apart from it, and thus provides an avenue for aligning western scientific and Indigenous ways

of knowing (Burt, 2019; Grenz, 2020; Reid et al., 2021). By enabling the synthesis of diverse theories and epistemologies across disciplines, SES research can enhance scientific characterization of complex transformations and system vulnerability to crises (Whitney et al., 2017).

Vulnerability is a measure of a system's susceptibility to negative impacts (Adger, 2006; Williams et al., 2008). The study of vulnerability originated in socio-political and disaster-risk communities, yet the past two decades have brought a surge in the number of vulnerability assessments across natural and social sciences and inspired complementary and integrated theoretical development (Miller et al., 2010; Petersen et al., 2018). Key parameters of vulnerability include a focal system's exposure, sensitivity, and adaptive capacity to drivers of change (Fig 1.1, Adger, 2006). Exposure refers to the magnitude and type of drivers of change experienced by the system, sensitivity is the magnitude of change in a system caused by the exposure, and adaptive capacity is the ability to respond positively to the exposure through time (Bennett et al., 2016; Pacifici et al., 2015). Exposure tends to be an extrinsic factor, sensitivity is intrinsic to the social-ecological system (e.g., species traits, socio-political and economic conditions), and adaptive capacity is a latent property activated in response to exposure (e.g., the potential to evolve, learn, plan, Whitney et al., 2017; Williams et al., 2008). A related, yet distinct, term to describe system responses to change is resilience, defined as the ability for a system to absorb and adjust to changes while retaining its functions, structures, and feedbacks (Folke et al., 2004; Holling, 1973).

In this thesis, I characterize the exposure and sensitivity of marine animals to climate change (Chapters 2 and 3) and explore spatial planning strategies employed by coastal communities to protect vulnerable places (i.e., respond positively) to anthropogenic drivers of change (Chapter 4, Fig 1.1).

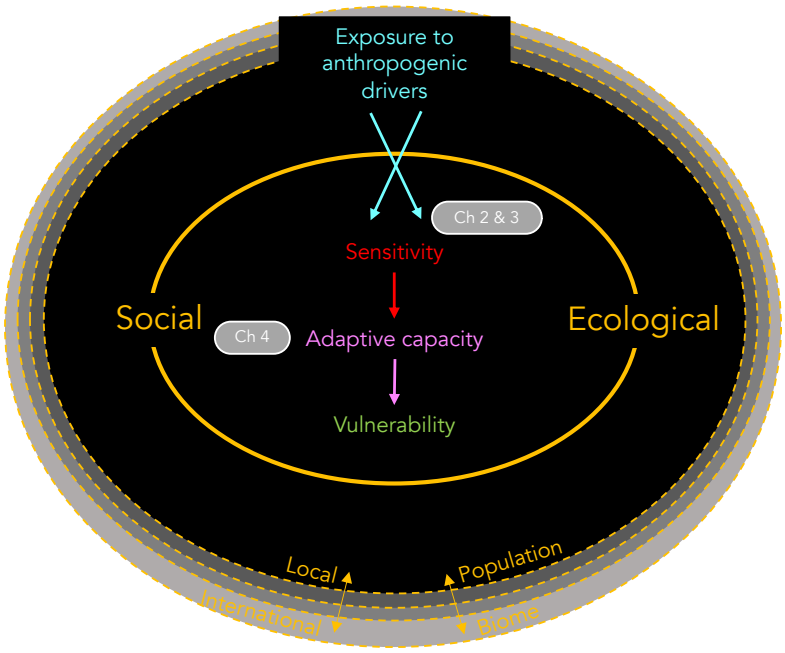

Figure 1.1. Conceptual schematic illustrating the three components of vulnerability (exposure, sensitivity, and adaptive capacity) analyzed in this thesis through a social-ecological systems (SES) lens. Chapters 2 and 3 explore exposure and ecological sensitivity to interacting climate change drivers and Chapter 4 explores a dimension of social adaptive capacity (development of management and spatial planning resources). Vulnerability components within the solid yellow line are largely intrinsic to the SES, which can be defined across spatial scales (dashed concentric circles). The crossed blue arrows indicate drivers that can interact across scales (global, local, distal).

1.2 Anthropogenic drivers of change in the sea

Vulnerability analyses begin with identifying and isolating the effects of high-magnitude drivers of social-ecological change (hereafter referred to as 'drivers'). This is a complex process since systems are often simultaneously exposed to global (e.g., climate change), local (e.g., development, exploitation), and distal drivers (e.g., histories of colonialism, Cannon, 2022; Crain et al., 2008; Forster et al., 2017). Distal drivers are physically removed processes that underlie and interact with global and local driver impacts (Forster et al., 2017). The cumulative effects of drivers across scales have prompted social-ecological transformations as ecosystems shift or tip from one state to another (Gunderson and Holling, 2002; Harley et al., 2017). For example, overfishing, nutrient loading, and climate change drivers have flipped many reefs from coral dominated to macroalgal dominated states, and the combination of ocean warming, storms, and apex predator removal via hunting have transformed many coastal kelp forests into urchin barrens (Burt et al., 2018; Cannon, 2022; Hughes et al., 2003; Stewart and Konar, 2012). The often severe ecological and social ramifications of these transformations (e.g., reduced biodiversity, food security, and cultural continuity) motivate research on the cumulative effects of multiple drivers.

Predicting the cumulative effects of multiple drivers is complex even within driver categories. For example, global climate change comprises myriad sub-drivers, such as ocean acidification and warming, that manifest unevenly across space and time. Ocean acidification is the chemical process where atmospheric carbon dioxide molecules interact with water to increase the concentration of hydrogen ions and reduce the availability of carbonate ions in the sea (Feely, 2004). The ongoing oceanic absorption of atmospheric CO_2 and heat has led seawater acidity to increase by 20-35% since 1980 and global sea surface temperatures to increase by 0.35-0.77°C since 1950 (Bates et al., 2014; IPCC, 2021). By the end of the twenty-first century, global ocean pH levels are projected to drop by a further 0.3-0.4 units and sea surface temperatures to increase by 3.6-4.4°C (IPCC, 2021). Collectively, these two global change drivers have generated substantial shifts in marine organismal performance and abundance, with cascading direct and indirect effects across linked ecological and social systems (Harley et al., 2006; Harvey et al., 2013; Pecl et al., 2017). Ocean warming is driving shifts in commercially and culturally important fish species distributions, with complex ramifications for local food security and fisheries management across governance scales (Palacios-Abrantes et al., 2022). Similarly, ocean acidification impairs the performance and survival of many marine organisms and is anticipated to cause annual losses of more than one trillion USD to the world economy by 2100 (Aze et al., 2014; Kroeker et al., 2013a). Regional context and the ability of humans to mitigate anthropogenic greenhouse gas emissions will determine the exact magnitude of social-ecological effects of ongoing ocean acidification and warming.

One approach to disentangle the local effects of multiple drivers is understanding how they interact with one another to anticipate phase shifts and tipping points (Côté et al., 2016; Harley et al., 2017). Driver interactions can be classified into the following three categories: 1) null effects, where the combined effect of multiple drivers does not involve interactions (i.e., equals the sum of individual stressors or the sum minus the product in the case of multiplicative effects); 2) synergistic interactions, when the combined effect of multiple drivers is greater than expected based on the null combined effects; and 3) antagonistic interactions, when the combined effect is less than expected (Dey and Koops, 2021; Orr et al., 2020). Synergies are particularly concerning as they can produce ecological surprises that accelerate biodiversity loss (Crain et al., 2008; Paine et al., 1998). Despite the surge in research effort toward understanding patterns of driver interactions, uncertainty remains regarding the overall prevalence of interaction types and their implications for conservation and management (Côté et

al., 2016). Resolving some of this uncertainty is the focus of Chapter 2, which investigates the vulnerability of ectothermic marine animals to climate change by synthesizing the individual and interactive effects of ocean acidification and warming.

1.3 Vulnerability and urban seas

Management decisions to protect vulnerable places and species are informed by the distribution and overlap of drivers in space. Research and conservation resources (e.g., time, capacity) are limited; thus, management entities often prioritize protecting places where biodiversity gains are maximized and invested resources and human conflict are minimized. Historically, this prioritization has led to an emphasis on protecting remote regions with low human density, as fewer overlapping anthropogenic drivers are associated with lower conflict potential. Urban and near-urban environments, on the other hand, have been largely avoided by conservation and management entities due to the higher number of overlapping drivers and greater magnitude of ecological degradation (Kehoe et al., 2021). However, many urban centres have flourished because of their proximity to and dependence upon highly biodiverse regions (e.g., floodplains, estuaries, coastlines), and majority of the world's land (73.4%) and ocean (66%) are moderately to intensively used by humans (Bennett et al., 2022; Halpern et al., 2015). In addition, fostering positive interactions between people and nature around urban centres can improve human well-being and benefit wider attitudes toward biodiversity conservation (Shwartz et al., 2014). Thus, protecting environments and managing human activities around high-impact areas is essential to minimize further biodiversity loss and degradation of human well-being (Locke et al., 2019).

Coastal urban environments are particularly important places to focus management and stewardship attention, since 40% of the world's population live within 100 kilometres of the coast and most marine organisms live within the shallowest 100 metres of the sea (Costello and Chaudhary, 2017; Sumaila et al., 2020). Urban seas, defined as semi-enclosed coastal seas bordering urban centres, are hotspots for cumulative impacts of anthropogenic drivers and have been identified as focal regions for research and management within the United Nations Decade of Ocean Science (Ocean Studies Board, 2022). They are among the most heavily impacted regions of the ocean due to high concentrations of human activities, yet they also represent strategic regions to nurture diverse relationships between people and the sea and generate support for marine conservation (Halpern et al., 2015; Vincent, 2011).

Along the northeast Pacific coast, the Salish Sea is an excellent example of an urban sea. Extending across the international border between Canada and the United States, this semi-estuarine inland sea is home to nearly nine million people and supports biologically diverse ecosystems emblematic of the Pacific northwest (Fig 1.2, Sobocinski, 2021). It comprises three bodies of water: the Strait of Juan de Fuca (the main outlet to the open ocean), Strait of Georgia (Canadian side of the border), and Puget Sound (American side of the border, Greene et al., 2022). Indigenous communities throughout the Salish Sea bioregion have lived in relationship with the lands and waters for upwards of 10,000 years, while settlers arrived in the late 1700s and established communities, now major urban centres, from the 1870s onwards (Lindo et al., 2017). Over the past 150 years, social systems within the Salish Sea have undergone rapid transformations, including the designation of colonial borders that bisect land, water, and Indigenous governance systems, large-scale industrialization (e.g., Vancouver and Seattle ports), and rapid urbanization (i.e., coastal development). These regional drivers have degraded the Salish Sea's social-ecological health by disrupting Indigenous ways of life, unsustainably extracting marine life, and fragmenting, contaminating, and converting habitat (Sobocinski, 2021). In turn, declines in regional ecosystem and community health increase the vulnerability of social systems, including ocean-based livelihoods and cultural continuity. Accordingly, many regional institutions and governing bodies have identified the need to collaboratively identify strategies to restore social-ecological health and well-being in the Salish Sea.

Figure 1.2. Map of the Salish Sea watershed (solid blue line). Map created by Willem van Riet, courtesy of the David Suzuki Foundation.

Climate change exacerbates the social-ecological effects of regional anthropogenic drivers. Local impacts of this global driver include altered precipitation and salinity regimes, rises in sea level, increased frequency and severity extreme weather events (e.g., 2021 heat dome), and rapid rates of ocean acidification and warming (Evans et al., 2022; Ianson et al., 2016; Jarnıkova, 2022; Raymond et al., 2022; Sobocinski, 2021). The effects of ocean warming are particularly concerning for marine life in the Salish Sea because it is already a hotspot in terms of climatic conditions. As well, local increases in seawater temperature, particularly in the Strait of Georgia, are occurring at twice the global mean rate of change (Amos et al., 2015; British Columbia and Ministry of Environment, 2016; Helmuth et al., 2006). These rapid local rates of warming from an already warm baseline could surpass tolerance thresholds and rates of evolutionary adaption for certain marine species and increase ecological vulnerability of life in the Salish Sea.

Species sensitivity to climate change is predominantly determined by organismal traits, habitats, and distributions (Willis et al., 2015). Species with restricted dispersal, slow reproductive rates, and narrow physiological tolerances can be highly sensitive and have low evolutionary adaptive capacity to rapid and extreme environmental change (Harvey et al., 2021; Pacifici et al., 2015). Organisms that live in habitats where maximum environmental temperatures approach their upper thermal limits, such as along rocky intertidal shorelines and in the warmest parts of species ranges, are also predicted to be most vulnerable to environmental warming (Marshall et al., 2015; Somero, 2010). Accordingly, intertidal organisms with sensitive life-history traits could be especially vulnerable to climate change if environmental temperatures exceed upper thermal tolerance thresholds and the local rates of warming surpass rates of evolutionary adaptation. Chapter 3 investigates this topic by characterizing the vulnerability of an intertidal snail, *Nucella lamellosa*, to ocean warming in the Salish Sea.

1.4 Marine spatial planning

Alongside the need to focus on urban seas to mitigate global biodiversity loss, urban seas are excellent regions to examine how marine management and conservation approaches can perpetuate status-quo extractive patterns or transform toward reciprocal and regenerative systems. The next decade is projected to herald an era of rapid development of the ocean's economic potential as the 'blue economy' grows from 1.5 trillion USD in 2010 to three trillion

USD by 2030 (OECD, 2016). Given that urban seas are already hotspots of ocean-based economic development, the “unbridled” intensification of the blue economy could substantially increase their vulnerability, especially if social equity and sustainability principles are sidelined in favour of extraction and exclusivity (Bennett et al., 2019a). However, if management systems critically examine power-dynamics and center inclusivity across governments, civil society, and the private sector, urban seas could serve as a model regions for developing transformative governance and stewardship strategies to protect marine social-ecological health.

Marine spatial planning (MSP) is one approach to proactively manage human activities and protect vulnerable places, species, and relationships with the ocean. MSP involves integrated, ecosystem-based, and participatory decision-making about human use and access to marine spaces (Douvere, 2008). It emerged from the widespread realization toward the end of the twentieth century that single-sectoral and top-down marine management approaches were leading to unsustainable and inequitable outcomes, such as the decimation of fish stocks and violation of community and Indigenous rights (Bennett et al., 2023; Foley et al., 2010). While original conceptualizations of MSP centered inclusive governance and participatory processes, the past decade has seen the implementation of exclusive and inequitable power dynamics in some MSP processes (Flannery et al., 2018). Managing human impacts using MSP approaches that transform rather than perpetuate status-quo patterns is essential to reduce social-ecological vulnerability in complex regions such as urban seas.

Two contributions toward the transformation of marine spatial planning involve centering co-governance across Indigenous and non-Indigenous communities and elevating the role of social sciences throughout MSP knowledge-gathering and interpretation processes. For example, co-creating research and mapping processes can enhance cultural inclusivity and equitable dynamics associated with the development of spatial plans (Ban and Frid, 2018). Gathering data about place-based values and relationships between people and the ocean (i.e., the human dimensions of the sea) can also strengthen the ability for MSP to reflect multiple ways of knowing (e.g., Indigenous, local, and western scientific knowledge systems, Strickland-Munro et al., 2016), build social acceptance of planning decisions (St. Martin and Hall-Arber, 2008), and enable a paradigm shift from people as ‘impacts’ to people as an integral part of a healthy ocean (Frazão Santos et al., 2019). Chapter 4 describes the co-creation of a community and

Indigenous-led approach to characterize human dimensions of the Salish Sea in support of transformative and adaptive marine spatial planning.

1.5 Positionality and context

My underlying motivation for this thesis stems from growing up on the shores of the Salish Sea and caring deeply about protecting the marine and human life connected with my home waters. My connection to place drew me to work with non-profit organizations on marine projects in Átl'ka7tsem/Howe Sound prior to and during my degree. Átl'ka7tsem is one of three Skwxwú7mesh (Squamish) place names for Howe Sound, a fjord in the Salish Sea. Projects I led and supported include the Átl'ka7tsem/Howe Sound Marine Conservation Assessment, Ocean Watch Howe Sound editions, Salish Sea Nearshore Habitat Recovery Project, and most relevant to this dissertation, the Átl'ka7tsem/Howe Sound Marine Stewardship Initiative (Bodtker, 2017; MCA, 2019; Miller, 2020; MSI, 2021; SeaChange, 2022). This work experience immersed me in Átl'ka7tsem/Howe Sound's social, political, cultural, and ecological systems and enabled me to nurture relationships and absorb abundant place-based knowledge that were central to my co-creation of Chapter 4. My identity as an 'insider' to the regional Átl'ka7tsem and Salish Sea communities granted me access to spaces and conversations that would have taken an 'outside' researcher a long time to access. It also motivated my implementation of a community-based participatory approach, despite this being a previously unexplored research method in my lab at the University of British Columbia.

That said, while my roots grant me the identity of an 'insider' to the regional Átl'ka7tsem and Salish Sea community, I am an outsider to many communities within these regions, specifically Indigenous ones. I am a white, upper-class woman of European settler decent, and I recognize that I have benefitted from the extractive human systems that have generated the climate, biodiversity, and social inequity crises. As such, I am still (un)learning the extent to which my worldview perpetuates colonial and privileged assumptions and harm. I have tried actively to practice reflexivity about my identity, be critically aware of my worldview throughout my research process, and take responsibility for crafting my research in a way that minimizes the perpetuation of extractive harm. Collectively, these emotional and positional components of my identity shape the lens through which I create knowledge and cannot be separated from my research questions, methods, interpretations, or desired outcomes.

1.6 Navigating the thesis

This thesis examines the vulnerability of coastal social-ecological systems to anthropogenic drivers of change using approaches that span spatial scales, disciplines, and knowledge systems. My first research objective was to characterize the vulnerability of marine animals to climate change, specifically ocean acidification and warming. I quantify the sensitivity of marine ectothermic animals across the globe to these two drivers using a meta-analysis (Chapter 2) and investigate the population-specific sensitivities of a marine snail to ocean warming using manipulative field and laboratory experiments (Chapter 3). My second research objective was to understand how life in and around urban seas responds to anthropogenic drivers of change, both in terms of ecological vulnerability to climate change (Chapter 3) and approaches to manage and protect vulnerable places and strengthen adaptation (Chapter 4). My three data chapters are written for submission to peer-reviewed publications. Chapter 3 is undergoing revisions for resubmission to *Ecology* and Chapters 2 and 4 are in preparation for submission to *Global Change Biology* and *Ecosystems and People.* Data from Chapter 4 have also been shared with organizations (e.g., Marine Stewardship Initiative) and governments (e.g., Sk̲wx̲wú7mesh Úxwumixw, Squamish Nation) in the format of spatial data layers and narrative reports to inform regional marine spatial planning.

My thesis begins by examining marine organismal vulnerability to climate change using a meta-analytical approach (Chapter 2). I synthesize the individual and interactive effects of ocean acidification and warming across marine taxa and quantify support toward hypotheses that predict organismal sensitivity based on species traits and environmental factors. I also compare the relative sublethal and lethal effects of these two drivers and test eco-physiological predictions regarding driver interactions.

In Chapter 3, I examine intraspecific variability in climate change vulnerability using manipulative field and laboratory experiments with a marine snail, *Nucella lamellosa* (Gmelin, 1791). I test whether populations in the centre of this species' range vary in their vulnerability to ocean warming based on thermal sensitivity and local rates of ocean warming. I conducted a reciprocal transplant and mesocosm experiment using snail populations from two regions in British Columbia that differ in thermal characteristics: the Central Coast, a cool region, and the Strait of Georgia, one of the warmest regions of this species' range that is warming faster than the Central Coast. I examine how snail growth, survival, and feeding rates vary when

populations are outplanted in each region and exposed in the lab to seawater temperatures that reflect current and projected future temperatures for each region.

In Chapter 4, I explore how local and Indigenous-led mapping can advance the equitable documentation of places that are vulnerable to anthropogenic drivers to inform marine spatial planning. In partnership with the Sk̲wx̲wú7mesh Úxwumiwx and regional stewardship organizations, I employed a community-based participatory mapping approach to characterize and spatialize place-based values within Átl'k̲a7tsem/Howe Sound. I conducted surveys and semi-structured interviews to understand: 1) how do different community groups value the ocean; 2) how do place-based aquatic values interact with each other and in space; and 3) what are the challenges and opportunities associated with decolonizing participatory mapping and marine spatial planning processes. I illustrate ways that community-led and top-down marine spatial planning processes can weave together to advance equitable and inclusive management processes in coastal and urban seas.

My concluding chapter describes my overarching contributions toward the scientific assessment of ecological vulnerability to climate change drivers and the spatial characterization of human relationships with the sea in support of MSP. I discuss implications of my multi-scalar and interdisciplinary approach to understand social-ecological vulnerability. I also identify opportunities to transform both research and planning approaches by centering equity, relationality, and reciprocity. Overall, my desire is that this dissertation provides knowledge that strengthens society's ability to care for ecosystems and communities negatively impacted by anthropogenic drivers of change.

Chapter 2: A comprehensive meta-analysis of the interactive effects of ocean acidification and warming across marine ectothermic animals reveals widespread negative effects and challenges assumptions

2.1 Synopsis

Ecological theory predicts organismal sensitivity to climate change based on who you are (i.e., organismal traits) and where you live (i.e., environmental context). The past decade has contributed a surge of empirical studies that test theoretical predictions about the effects of ocean acidification (OA) and warming across traits and environmental contexts; yet a comprehensive synthesis of these studies has not been performed since 2013. Updating our understanding of the effects of these two drivers across marine ecosystems is needed to inform ongoing research and policy agendas. Here, I synthesize results from nearly 500 factorial experiments to evaluate support toward nine hypotheses about the individual and interactive effects of OA and warming across marine taxonomic groups. My results provide robust evidence that OA and warming have largely negative direct effects across marine taxa and indicate a few taxonomic groups (molluscs), organismal traits (adults, sessile), and latitudes (tropic, temperate) that are generally more sensitive to both drivers. I also refute two common assumptions about the combined effects of OA and warming: there was no evidence that OA reduces upper thermal tolerance thresholds and there was no general tendency toward synergistic interactive effects. These results inform future research agendas by refining the predictive power of the nine tested predictions and advancing generalized understanding of the negative effects of ocean acidification and warming on marine ectotherms.

2.2 Introduction

Climate change is causing the earth's physio-chemical properties to rapidly shift, altering the health and structure of ecosystems worldwide (Burrows et al., 2011; Pinsky et al., 2019; Poloczanska et al., 2013). Since the 1850s, the rise in atmospheric carbon dioxide has led to an increase in air and ocean temperatures and a reduction in seawater pH (ocean acidification, OA, Fabry et al., 2008; IPCC, 2021, 2019). The ecological effects of these oceanographic changes have motivated the formulation of myriad hypotheses to predict which species and regions are most vulnerable to climate change, with the overall goal of informing research

agendas, conservation and climate change policy. However, numerous uncertainties, inconsistent results, and untested assumptions challenge the predictive confidence of these hypotheses. Given the increased availability of empirical tests published over the past decade, a comprehensive review can strengthen confidence about the effects of ocean acidification and warming across marine ectothermic animals.

Synthesis research quantifies evidence toward theoretical hypotheses and can bridge the gap between empirical data and research and policy agendas by identifying general trends associated with ecological responses to climate change (Koricheva et al., 2013). One category of theoretical hypotheses to predict the effects of OA and warming is based on organismal traits. Here we outline assumptions and data gaps across four categories of trait-based hypotheses: taxonomy, life stage, developmental strategy, and mobility. Calcifying taxa are expected to be more sensitive to OA than non-calcifying taxa due to the energetic requirements associated with building shells and metabolizing under hypercapnic (high CO_2/low pH) conditions (Harvey et al., 2013; Kroeker et al., 2013b; Przeslawski et al., 2015). Knowledge gaps exist regarding the consistency of this trend across response variables (e.g., reproduction, survival) and upon exposure to warming (Figuerola et al., 2021; Leung et al., 2022). Younger life stages, especially planktonic larvae, are presumed to be more sensitive to stressful environmental conditions due to the high energetic costs of developmental transitions (e.g., metamorphosis) and the lower availability of embryonic protections during this life stage (Przeslawski et al., 2015). However, the relative sensitivity of larvae compared to adults has varied across driver combinations, taxonomic groups, and response variables (Harvey et al., 2013; Kroeker et al., 2013b; Pandori and Sorte, 2019). Developmental strategy is a third lens through which to investigate organismal vulnerability to OA and warming. Since indirect developers, often broadcast spawners, need to tolerate varied environmental conditions across their dispersal range, they tend to have more quantitative genetic variance and phenotypic plasticity than direct developers, and thus higher adaptive potential to rapid environmental change (Sunday et al., 2011b). Fourth, mobility can influence organismal vulnerability to environmental change, where sessile species could be more vulnerable than mobile organisms to rapid environmental change (e.g., heat waves) as they are unable to seek microrefugia or use movement as a response strategy (Sunday et al., 2014). Yet, over generations, the inability to move away from stressful conditions could result in the evolution of greater tolerance in sessile species (Huey, 2002). The extent to which sessile animals show greater tolerance than mobile species to OA and warming, and the responses of

sublethal response variables across mobility categories remains untested. While these four categories (taxonomy, life stage, developmental strategy, mobility) of organismal traits show strong predictive value in certain contexts, the above listed knowledge gaps, varying results, and small sample sizes in previous studies justify re-evaluating empirical support toward the predictions.

Environmental context, such as latitude and habitat type, is another important predictor of organismal vulnerability to climate change and can explain trends alongside trait-based hypotheses. For example, species that experience high environmental fluctuations within generations (e.g., in temperate latitudes, dynamic coastal habitats) can have higher phenotypic plasticity and could be pre-adapted to cope with rapid environmental change (Munday et al., 2013; Padilla-Gamiño et al., 2016). In contrast, species that inhabit thermally stable conditions (e.g., tropical or polar latitudes, pelagic habitats) tend to be thermal specialists, where performance is maximized over a narrow thermal range (Angilletta, 2009; Morley et al., 2019; Sunday et al., 2012). Tropical species also tend to inhabit environments where maximum temperatures are close to their upper thermal limits, while polar species experience some of the fastest rates of environmental warming and acidification (Fabry et al., 2008; Figuerola et al., 2021; Lenoir et al., 2020; Sunday et al., 2014). Accordingly, organisms from these latitudes may be challenged to adapt at the same rate as ocean acidification and warming. Latitudinal patterns of thermal tolerance are well documented; however, their persistence under scenarios that include OA (either alone or in combination with warming) is inconsistent (Cattano et al., 2018; Pandori and Sorte, 2019).

Many analyses assume that organismal responses to climate change are dominated by lethal effects; however, this assumption has inconsistent empirical support (Przeslawski et al., 2015). Focusing exclusively on lethal effects can overlook the importance of sublethal responses for organismal fitness and population structure (Harley et al., 2017). Organisms that survive extreme events, such as heatwaves, can experience energetic trade-offs that compromise growth and reproduction (Brownlee, 2022). Population growth can also be constrained by the temperature-dependence of non-lethal performance metrics (e.g., male fertility thermal limits, van Heerwaarden and Sgrò, 2021). Over time and across generations, altered sublethal performance could prompt cascading effects across interacting species and communities (Kroeker et al., 2020a, 2017). Understanding the relative sensitivity across lethal and sublethal

response variables under OA and warming can improve understanding of the multi-generational effects of climate change.

Predicting the ecological consequences of simultaneous ocean acidification and warming can be challenging because environmental drivers of change can interact and produce unexpected outcomes (Kroeker et al., 2017). Driver interactions are often classified into the following three categories: synergistic, antagonistic, and null (e.g., additive, multiplicative, for further discussion of null models see Dey and Koops, 2021; Thompson et al., 2018). Synergistic interactive effects occur when the combined effect of multiple drivers is greater than what is expected based on the combined effects of individual drivers (Crain et al., 2008). Synergies often imply more dire ecological outcomes than null expectations (e.g., ecological surprises, Dey and Koops, 2021). In contrast, antagonistic effects occur when the combined effect is less than the expected null effect. Synergies are perceived to be the most common interaction type across many driver combinations; however, the true extent to which they outnumber antagonistic or null interactions is unclear (Darling and Côté, 2008). In prior meta-analyses of interactive effects of OA and warming, synergistic interactions were the most common interaction type across taxa (Harvey et al., 2013) and in early life stages (Przeslawski et al., 2015). However, the small sample size of factorial studies in these studies, varying analytical methods, and inconsistent outcomes with other meta-analyses of these two drivers (Lefevre, 2016) reduce confidence in the conclusion that synergies dominate interactive effects and call for a re-evaluation of driver interactions.

Understanding mechanisms that underscore interaction types is an area of growth within the multiple-drivers literature, and the oxygen- and capacity-limited thermal tolerance (OCLTT) hypothesis attempts to do so applying physiological theory. The OCLTT predicts that thermal tolerance windows will shrink upon exposure to hypercapnic (and anoxic) conditions because of both an increased demand for oxygen and a reduced capacity to transport oxygen to cells under warmer conditions (Pörtner, 2021, 2010; Pörtner and Farrell, 2008). Empirical support toward this prediction is mixed and, to my knowledge, the effect of OA on upper thermal tolerance limits (e.g., CT_{max}) has not been quantified, warranting a synthetic analysis.

Recent meta-analyses have focused on the effects of ocean acidification and/or warming on specific taxonomic groups (Cattano et al., 2018; Leung et al., 2022), regions (Figuerola et al., 2021), and response variables (Lefevre, 2016; Pandori and Sorte, 2019); however, there has

not been a comprehensive synthesis of interactive effects of these two drivers across marine ectotherms since 2013 (Harvey et al., 2013). Given the abundance of factorial experiments with these two drivers published since 2013, I replicated Harvey et al. (2013)'s analyses using exclusively factorial experiments, which provides a more accurate comparison of overall and interactive effects of OA and warming. Additionally, I addressed the above listed knowledge gaps and inconsistencies by comparing sensitivity across trait-based and environmental predictors, measuring the effect of OA on upper thermal tolerance, and estimating the relative sensitivity of sublethal versus lethal performance metrics.

This mixed-effects factorial meta-analysis estimates the overall and interactive effects of ocean acidification and warming on marine ectothermic animals. Since I expect driver effects to vary across trait-based and environmental predictors, I tested the following predictions: 1) calcifying taxa are more sensitive to ocean warming and acidification than non-calcifying taxa; 2) younger life stages, specifically planktonic larvae, are more sensitive than older life stages; 3) direct developers are more sensitive than indirect developers; 4) sessile organisms show greater lethal tolerance (i.e., greater survival) than mobile organisms; 5) organisms from polar and tropical regions are more sensitive than organisms from temperate regions; 6) organisms from stable habitats (e.g., pelagic and deep ocean habitats) are more sensitive than those from variable coastal habitats (e.g., intertidal, kelp forest); 7) sublethal and lethal effects of ocean acidification and warming are similar in magnitude; 8) ocean acidification reduces upper thermal tolerance; and 9) synergistic interactions dominate interaction types between ocean warming and acidification.

2.3 Methods

2.3.1 Database formation

I searched for papers in the ISI Web of Science [v5.35] using the keywords "ocean acidification" and "temperature", which yielded 2132 papers. This limited keyword search effectively targeted marine ecological papers that manipulated CO_2 and temperature. To be included, each paper needed to align with the following three inclusion criteria: 1) factorially manipulate seawater acidity and temperature in a laboratory; 2) test the response of a marine ectothermic animal; and 3) measure a lethal or sublethal performance trait variable that is directly related to fitness (e.g., growth, development, metabolism – genetic and cellular metrics were excluded, Kawecki and Ebert, 2004; Monaco and Helmuth, 2011; Sinclair et al., 2016). I created a second database

of papers that measured a thermal tolerance metric (CT_{max}) of marine ectotherms that were acclimated to normocapnic and hypercapnic conditions. Both datasets were limited to studies published between January 1st 2012 and Dec 31st 2019, allowing for a comparison with previous meta-analyses that reviewed the individual and interactive effects of ocean acidification and warming prior to 2012 (Harvey et al., 2013; Kroeker et al., 2013b).

The factorial manipulation criterion required that experiments include at least four environmental treatments: a control with environmental driver levels that was representative of the ambient environmental conditions for the study region (Harvey et al., 2013; Pandori and Sorte, 2019); acidification alone; elevated temperature alone; and acidification and elevated temperature combined. If studies included more than four treatments, I extracted data from the acidification, temperature, and combined treatments that aligned closest with the IPCC RCP 8.5 projections for 2100 (i.e., seawater acidity decrease of 0.3-0.5 pH and temperature increase of +3-4°C, IPCC, 2019). The maximum threshold for seawater acidity manipulation was a change of 0.5 pH (IPCC, 2019; Kroeker et al., 2013b). I exclusively selected papers that manipulated seawater carbonate chemistry through bubbling CO_2 (as opposed to via acid addition, which is an inaccurate way of simulating ocean acidification) and selected papers that measured either pH or pCO_2. When studies manipulated additional drivers (e.g., salinity, food availability), I only extracted data from the four treatments outlined above when the other drivers were held at ambient/control levels.

I classified response variables into the following categories: calcification, development and reproduction, calcification, feeding rate, growth, metabolism (respiration and resting metabolic rate, RMR), aerobic scope (maximum metabolic rate – RMR), survival (mortality data was transformed to survival using 1 – mortality), and CT_{max}. This is the first multi-taxa meta-analysis to quantify the factorial effects of OA and warming on feeding rate and metabolism. A list of specific measurements that fall into each response variable category can be found in Appendix A: Table A.1. If studies measured more than one trait within these categories, I selected the more comprehensive trait (e.g., wet tissue weight rather than body length, Kroeker et al., 2013). When studies included more than one species or population, I extracted data for each species or population. While the results are not truly independent, I considered them as separate comparisons and included study number as a random effect in the models (see 'Data analysis' for more details, Koricheva et al., 2013; Kroeker et al., 2013; Pandori and Sorte, 2019). When

studies measured multiple time-points or multiple life stages of the same individuals, I only extracted data from the final timepoint or life stage to avoid pseudoreplication and to gather data on the longest exposure to treatments. For transgenerational studies, I extracted data from offspring whose parents were held at control conditions. Finally, I recorded modifying factors associated with my hypotheses that can influence the experimental outcomes, including taxonomic group, life stage, development strategy, mobility class and category, latitude, and habitat type.

I conducted data transformations to ensure directional alignment and consistency within and across response variables, where positive values indicate increases that are beneficial to organismal fitness and negative values indicate reductions that are deleterious to fitness. For example, when studies reported weight loss, where a larger number indicated more weight lost rather than gained, I multiplied the effect sizes by -1 to align the direction with studies that reported weight gain. I assumed that shorter development times are more beneficial to organismal performance, since they can reduce the duration of vulnerable egg and larval life stages, overall development costs, and be associated with increased survival and fecundity (Kingsolver and Huey, 2008; Marshall et al., 2020; Przeslawski et al., 2015). Accordingly, when papers reported development or hatching time, I multiplied the effect size by -1. I acknowledge, however, that if development time is too short, important metamorphoses or larval transport distances may not be reached (O'Connor et al., 2007). I did not transform the directionality of metabolism data points. Metabolic reactions occur faster with warming due to thermodynamics; thus, increases in RMR can be beneficial to organismal performance when they increase the supply of energy. However, beyond a certain point, further increases in RMR may be associated with a stress response. Since I do not have information about this inflection point for each experiment, I retained the directionality of driver responses for metabolism (where increases in RMR are associated with a positive direction) and interpret the fitness implications in the discussion.

The final inclusion filter was that experiments needed to report a mean response value, a form of variance (e.g., standard error of the mean, standard deviation, or confidence intervals), and the unit of replication. When papers met the inclusion criteria but failed to report these statistics, I contacted authors to request these data. An exception to this requirement was CT_{max} measurements, since these data are often unaccompanied by variance metrics (CT_{max} is often a

categorical explanatory variable without variance). I report exclusion rationale for all excluded studies following PRISMA best practices (Appendix A: Table A.2) and extracted data from included studies using the *metadigitize* package in R (v. 4.0.3, O'Dea et al., 2021; Pick et al., 2019).

2.3.2 Database analysis

To understand how ocean acidification and warming affect marine ectotherms when acting in isolation and combination, I conducted three analyses: 1) an unpaired analysis of the overall and interactive effects of OA and warming; 2) a tolerance analysis of the effects of OA on upper thermal tolerance thresholds; and 3) a paired analysis of the relative lethal and sublethal responses to OA and warming. For all analyses, I used the log response ratio (lnRR), which calculates the log-proportional change between the means of a treatment and control group (Hedges et al., 1999). I selected this effect size metric because it is visually intuitive to interpret, assumes multiplicative effects of multiple drivers, and is consistent with previous meta-analyses on multiple drivers, facilitating comparison across studies (Brown et al., 2018; Harvey et al., 2013; Lefevre, 2016; Morris et al., 2007; Pandori and Sorte, 2019). A multiplicative null assumes that drivers are additive based on their probabilistic sum (i.e., interactive effect = $effect_{DriverA}$ + $effect_{DriverB}$ – $effect_{DriverA}$*$effect_{DriverB}$) and that driver effects are uncorrelated. It is an appropriate null for this study given I compare lethal and sublethal response variables, and lethal effects of multiple drivers must follow probabilistic sums (i.e., you cannot die twice, Brown et al., 2018; Dey and Koops, 2021). That said, lnRR does not deal well with datasets that include bidirectional data (i.e., treatment and control responses go in both positive and negative directions) and can be biased when studies have small sample sizes, variance is unequal across treatments, and when means are close to zero in one or more treatments (Lajeunesse, 2015). I addressed these limitations by excluding experiments with bidirectional data (n = 22) and with 0 in one or more treatment (n = 10), and by calculating bias-corrected mean effect size estimators to correct for small-sample bias (see Appendix A).

I used equations A.4, A.6, A.9 and A.10 to calculate the overall and interactive effect sizes with the small-sample size correction term added (Appendix A: A.1). To estimate the overall and interactive effects of ocean acidification and warming, I employed a factorial meta-analysis (Brown et al., 2018; Gurevitch et al., 2000; Morris et al., 2007; Viechtbauer, 2010). I calculated the weighted mean effect size for each response variable and taxonomic category (except for

CT_{max} experiments that did not report variance) using the *rma.mv* function in the *metafor* package in R (v. 4.1.2), which weights each lnRR by the inverse of its variance (random effects meta-analysis; Hedges and Olkin, 1985; Viechtbauer, 2010). To calculate average effect sizes across response variables and categorical moderators I excluded metabolism data because the directionality interpretation was inconsistent with the remaining response variables.

In addition to calculating overall effect sizes across response variables, I partitioned the effect sizes into *a priori* defined categories based on the following categorical moderators: taxonomic group, life stage (adult, juvenile, larvae, embryo), dispersal strategy (broadcast spawner, direct developer), mobility class (0 = sessile; 1 = very low mobility, planktonic and larval; 2 = medium to high mobility, small ranges; 3 = high mobility, large ranges), mobility category (mobile or sessile), latitude (polar > 66.5°, temperate, tropical <30°), and habitat type (dynamic, stable). I assumed that residual between-studies variance was heteroscedastic across levels of the categorical models due to underlying physiological and evolutionary mechanisms that differ across levels of the categorical moderators (e.g., taxonomic group, life stage etc.). Accordingly, I applied Cochran's *Q*-test to estimate the pooled residual between-study variance of categorical moderators and allowed the residual heterogeneity to vary across levels (Rubio-Aparicio et al., 2020). I included study identity as a random effect in the models to control for the impacts of any one study on individual and interactive driver effects (Cornwall et al., 2022). Finally, the minimum number of experiments required to report effect sizes was five for overall effects across response variables and taxonomic groups and three for categorical moderators, as this is the minimum threshold for Cochran's *Q*-test (Harvey et al., 2013). When there were more than three studies within a taxon, response variable, and multiple levels of a categorical moderator (e.g., larval and adult coral survival), I applied Cochran's *Q*-test to test difference across the categorical moderator effect sizes.

Statistical significance was attributed by assessing whether the summary effect's confidence intervals (CIs) overlapped with zero. If they did not, the mean effects were considered statistically significant. I also used CIs to interpret the certainty of effect size magnitudes. In the unpaired analysis, a positive lnRR with CIs that did not overlap with zero signified that the driver had a positive impact on organismal performance (i.e., greater growth, survival, calcification), whereas a negative lnRR signified a negative impact. The exception to this interpretation was metabolism, as described above. For the interactive effects, the interaction was considered

multiplicative if the interaction effect size overlapped with zero (i.e., lnRR = 0.00). If the directionality of both drivers was positive, the interactive effect was synergistic when greater than zero and antagonistic when less than zero. If the individual drivers had negative or opposite sign effects, the interactive effect was considered synergistic when less than zero and antagonistic when greater than zero (Harvey et al., 2013). To facilitate interpretation of the overall effects of acidification and warming in the unpaired analyses, I back transformed the mean lnRR to percent changes using the antilog (Kroeker et al., 2013b). The statistical significance of categorical moderators was determined using heterogeneity tests, which identify the total heterogeneity explained by each level within the categorical moderator (Hedges and Pigott, 2004). A significant Q_M indicates that the effects of each driver was different across levels within that categorical moderator.

For the tolerance analysis, since several estimates of CT_{max} did not report variance, I manually calculated an unweighted mean effect size across the *k* studies and CIs using a t-distribution with df = *k* – 1 (Hamman et al., 2018). Manual calculation is the best option for these studies because *metafor* requires within study variance to calculate confidence intervals, even when running an unweighted mean effect size analysis. A positive lnRR with non-overlapping CIs signified that acclimation to hypercapnic seawater increased thermal tolerance, whereas a negative lnRR signified a reduction in thermal tolerance (as hypothesized by the OCLTT).

In the paired analysis, I quantified differences between sublethal and lethal response variables using the following equation, based on Pandori and Sorte (2019): $lnRR_{paired} = lnRR_{sublethal} – lnRR_{lethal}$. This paired analysis was only run for the overall effects of acidification and warming across all taxonomic groups, since the directionality of the interactive effects was dependent upon those of the individual drivers and thus interpreting the difference between effect size magnitudes is not feasible. Since the $lnRR_{paired}$ did not have its own variance, I manually calculated mean effect sizes and CIs using methods outlined in the tolerance analysis (Hamman et al., 2018). Positive effect sizes with CIs that do not overlap zero indicated that lethal response variables were more sensitive to the driver(s) (i.e., the magnitude of their adverse effect was larger), and negative effect sizes indicated that sublethal response variables were more sensitive. For example, if the effect size for sublethal was -2 and for lethal was -5, the $lnRR_{paired}$ would be +3, meaning that the lethal response was more sensitive. Since this analysis is targeting the relative effect of the two drivers on lethal versus sublethal responses, I only

included studies that measured both a sublethal and lethal response on the same individuals. That is, I restricted this analysis to a subset of the full dataset used in the unpaired analysis. This enabled directly answering whether the effect magnitudes of OA and warming were different across sublethal and lethal response variables when organisms were exposed to the same experimental conditions (Pandori and Sorte, 2019). When studies measured more than one sublethal response variable, I calculated the $\ln RR_{paired}$ for all possible combinations of sublethal and lethal response variables. Again, I excluded metabolism from this dataset given its inconsistent directionality with other sublethal response variables.

Finally, I ran sensitivity tests (funnel plots and Rosenthal's fail-safe number) to determine publication bias (Koricheva et al., 2013; O'Dea et al., 2021; Rosenthal, 1979). The latter estimates the number of non-significant results needed to change the statistical significance of the meta-analysis and considers results to be robust when the calculated number exceeds 5N+10.

2.4 Results

2.4.1 Database formation

This database comprised 489 factorial comparisons from 200 peer-reviewed papers published between 2012-2019 that aligned with the inclusion criteria and reported the necessary statistical parameters (see Appendix A: Table A.2 for a bibliography of included and excluded papers). The most frequently measured sublethal response variable was growth (n = 128) and the most common taxonomic group experimented upon was molluscs (n = 162, Appendix A: Table A.3). The database comprised eight taxonomic groups: annelids, cnidarians (separated into corals and non-calcifying cnidarians), crustaceans, echinoderms, fish, molluscs, sponges, and trematodes. Trematodes and non-calcifying cnidarians were the only taxonomic groups with fewer than five experiments (n = 1 and 4, Appendix A: Table A.3, Table A.4). Therefore, I included these two taxonomic groups in the overall and mean effects across response variables but did not calculate effect sizes across categorical moderators.

2.4.2 Unpaired analysis

2.4.2.1 Overall and interactive effects across response variables

Acidification and warming negatively affected marine ectotherms, significantly reducing average performance by six and five percent respectively ($p < 0001$; Fig 2.1, Appendix A: Table A.5).

The overall effects of each driver differed significantly across response variables, with warming driving a greater range in effect magnitudes than acidification ($p < 0.02$; Fig 1.1, Appendix A: Table A.5). Acidification significantly reduced calcification by 12%, feeding rates by 10%, growth by 5%, development by 12%, and survival by 11% (Fig 2.1). OA had no net effect on metabolism and the effects of both drivers on aerobic scope were positive but non-significant (Fig 2.1). With warming, metabolism increased by 22%, whereas calcification and survival reduced by 13-29% respectively (Fig 2.1). Non-significant effects of warming included growth and development reductions (3-7%) and feeding rate increases (3%). The interactive effect of ocean acidification and warming was synergistic for feeding rate (lnRR = -0.14, lower = -0.25, upper = -0.02) and multiplicative for development and growth (Fig 2.1). Confidence intervals (CIs) overlapped zero for all other interactive effects, but the negative effect on aerobic scope is associated with antagonistic outcomes and the small negative effects on metabolism, calcification, survival, and the average effect across response variables indicate synergistic outcomes (Fig 2.1).

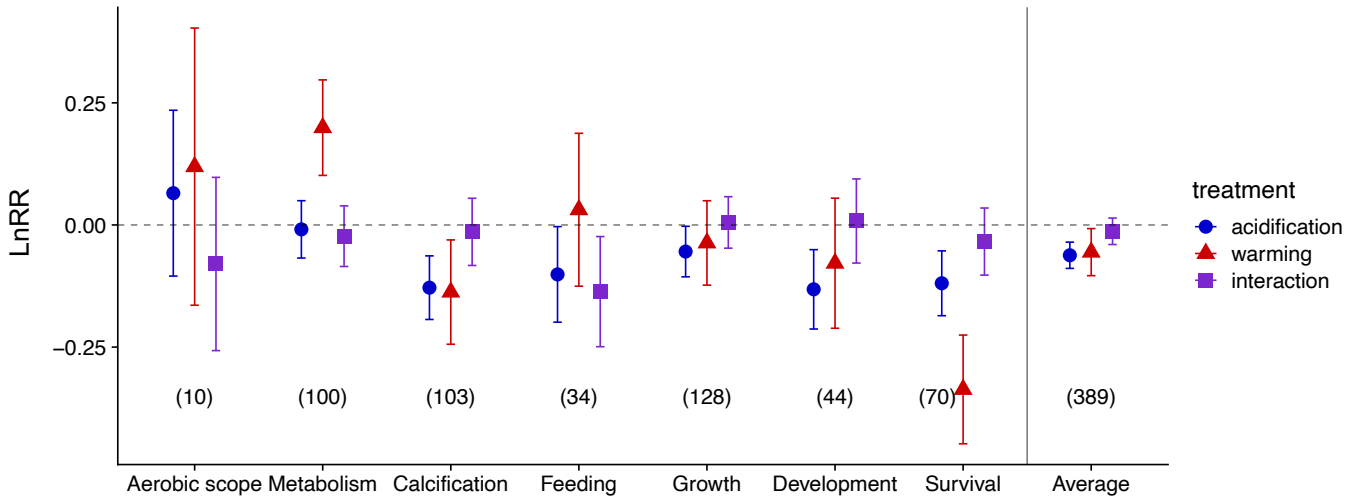

Figure 2.1. The pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) across response variables based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The average effect size reflects the pooled effect of each driver across response variables, excluding metabolism. The number of effect sizes within the three driver groups are provided in parentheses for each response variable (e.g., there are n = 10 acidification, n = 10 warming, and n = 10 interaction effect sizes for aerobic scope).

2.4.2.2 Overall and interactive effects across life stage, development strategy, mobility, latitude, and habitat

The negative effects of acidification increased in magnitude with life stage (from 1% reduction in embryos to 10% in adults), while the negative effects of warming were largest in embryos and adults (8-12%) and smallest in larvae and juveniles (1-3%, Fig 2.2a). For both drivers, performance reductions were only statistically significant in adults and there was no statistical difference across life stages (Fig 2.2a, Appendix A: Table A.6). The interactive effects were multiplicative in larvae and juveniles, synergistic in adults, and antagonistic (but non-significant) in embryos (Fig 2.2a). Across development strategies, negative effects were similar in magnitude for acidification (3-6% reduction) and warming (5-10%), yet the reductions were only statistically significant for indirect developers (Fig 2.2b, Appendix A: Table A.6). The interactive effects were non-significant across both developmental strategies but in opposite directions: antagonistic for direct developers and synergistic for indirect developers (Fig 2.2b).

Across mobility categories, sessile and lower mobility class organisms experienced significantly greater performance reductions than mobile organisms under both acidification and warming ($p < 0.05$; Fig 2.2cd, Appendix A: Table A.6). Acidification reduced performance by 10% in sessile organisms and 5% in mobile ones, while warming reduced performance by 15% in sessile organisms and 1% in mobile ones (Fig 2.2d). Warming increased performance by 8% for Class 3 (high mobility) organisms, although the CIs crossed zero (Fig 2.2c). The interactive effects were multiplicative in mobile and Class 1 and 3, synergistic in Class 2, and synergistic but not significant in Class 0 and sessile organisms.

The effects of acidification differed significantly across latitudes, with those from temperate latitudes showing the largest negative magnitudes (12% reduction), followed by tropical (4%) and polar (2%, Fig 2.2e, Appendix A: Table A.6). There was no statistical difference among the effect of warming across latitude and organisms from tropic and temperate latitudes showed similar magnitude mean reductions (5-7%, Fig 2.2e, Appendix A: Table A.6). None of the interactive effects across latitude were significant, but they did differ in direction with tropic and polar latitudes averaging around antagonistic and temperate latitudes synergistic (Fig 2.2e). Last, the mean reduction with warming was the same across dynamic and stable habitat types (5%) with different certainty (CIs did not overlap zero for dynamic and did for stable, Fig 2.2f). Acidification reduced performance by 6% in dynamic habitats (significant effect) and 3% in

stable habitats (Fig 2.2f). The interactive effects were multiplicative for stable and synergistic but non-significant in dynamic habitat types (Fig 2.2f).

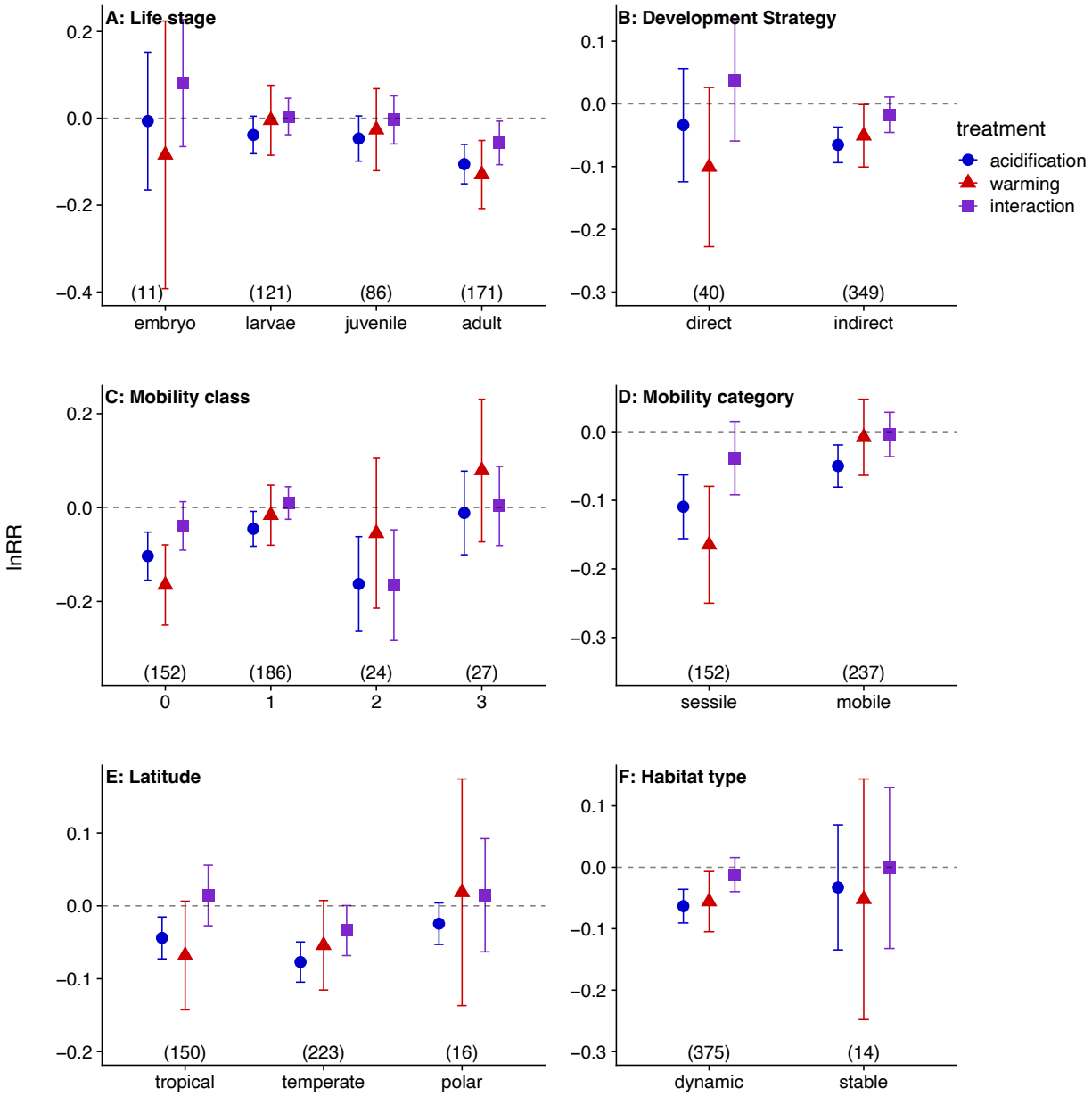

Figure 2.2. The pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) across six categorical moderators based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals: A) life stage, B) development strategy, C) Mobility class (0 = sessile, 1 = low mobility/planktonic, 2 = medium mobility, 3 = high mobility); D) mobility category; E) latitude; F) and habitat type. Experiments that measured metabolism are excluded from these pooled effect sizes. The total number of effect sizes within the three driver groups are provided in parentheses for each

categorical moderator (e.g., there are n = 11 acidification, n = 11 warming, and n = 11 interaction effect sizes for embryo).

2.4.2.3 Aerobic scope and metabolism

Across taxonomic groups, acidification reduced metabolism from 2-20%, although no effects were statistically significant and there was no difference among taxonomic groups (Fig 2.3a, Appendix A: Table A.7). Warming increased metabolic rates from 1-49% across taxa, with fish and sponges the most affected in terms of magnitude (41 and 49% increase respectively) and fish and molluscs the only groups with statistically significant increases (Fig 2.3a). The interactive effect of acidification and warming was non-significant across all taxa except molluscs where it was antagonistic (Fig 2.3a). The directionality of the non-significant interactive effects was synergistic in corals and crustaceans, and antagonistic in echinoderms, fish, and sponges (Fig 2.3a). Both acidification and warming increased aerobic scope by 12-15% (non-significant) and the interactive effect was multiplicative (Appendix A: Fig A.1).

Fish and molluscs were the only taxonomic groups where the effects of acidification and warming on metabolism differed significantly across categorical moderators (e.g., life stage, development strategy etc., Appendix A: Fig A.2). Acidification increased metabolic rates by 10-17% in Class 3 and direct developing fish, significantly higher than Class 1 (planktonic) and indirect developers ($p < 0.018$; Appendix A: Table A.8, Fig A.2). Warming increased metabolic rates by 35-53% in mobile and Class 1 molluscs relative to 5% reductions in sessile and Class 0 organisms ($p < 0.05$; Appendix A: Table A.8, Fig A.2). Finally, mobile molluscs and adult and polar fish experienced large antagonistic interactive effects relative to sessile molluscs, younger fish, and tropical and temperate fish ($p < 0.04$; Appendix A: Table A.8, Fig A.2).

2.4.2.4 Calcification

Acidification reduced calcification by 8-17% across corals, crustaceans, echinoderms, and molluscs, although the reduction was only statistically significant in corals (17%, Fig 2.3b). The effect of warming differed significantly across taxonomic groups, with coral calcification significantly reduced by 27% and echinoderm calcification increased (non-significant) by 25% ($p = 0.004$; Fig 2.3b, Appendix A: Table A.7). CIs for all interactive effects crossed zero; however, the directional effect was antagonistic for crustaceans, synergistic for corals, echinoderms, and

molluscs (Fig 2.3b). There were no significant differences in the overall or interactive effects of OA and warming on calcification across categorical modifiers (Appendix A: Fig A.3).

2.4.2.5 Feeding rate

Acidification reduced feeding rates by 11-29% in crustaceans, fish, and molluscs, where crustaceans were the only group with statistically significant reductions (29%, Fig 2.3c). In contrast, warming increased feeding rate by 0-23%, although no effects were significant (Fig 2.3c). The interactive effects were not significant but the directionality was antagonistic for crustaceans and fish, and synergistic for molluscs (Fig 2.3c). Acidification reduced Class 2 crustacean feeding rates by 22%, significantly more than Class 1 crustaceans ($p = 0.006$; Appendix A: Table A.9, Fig A.4).

2.4.2.6 Growth

Acidification reduced growth by 2-10% across most taxa, with molluscs the only group where reductions were statistically significant and sponges the only taxa where acidification increased growth by 3% (non-significant, Fig 2.3d). Warming reduced growth by 14-17% in molluscs and sponges, where molluscs were again the only taxa with significant reductions, and had small negative and positive effects across the remaining taxa (-1-3%, Fig 2.3d). The interactive effect on growth was multiplicative in fish and non-significant for all other taxa with the following directionality: antagonisms in crustaceans, molluscs, and sponges and synergies in corals and echinoderms (Fig 2.3d).

The effect of both drivers on growth across categorical modifiers differed in echinoderms, fish, and molluscs. Adult echinoderm growth was reduced by 37% under acidification, significantly more than juveniles and larvae (3-4% reduction, $p = 0.03$; Appendix A: Table A.10, Fig A.5). Under warming, sessile molluscs grew 14% less than mobile organisms, which only experienced a 3% reduction ($p = 0.02$; Appendix A: Table A.10, Fig A.5). Warming also reduced growth more in fish from stable habitats relative to dynamic ones (14% growth reduction compared to 6% growth increase, $p = 0.04$; Appendix A: Table A.10, Fig A.5). The effects of both drivers in isolation and combination on echinoderm growth differed significantly across latitudes (Appendix A: Table A.10, Fig A.5). Finally, adult fish and Class 2 echinoderms experienced large synergistic interactive effects relative to younger fish life stages and Class 1 echinoderms ($p < 0.001$; Appendix A: Table A.10, Fig A.5).

2.4.2.7 Development and reproduction

Acidification reduced echinoderm and molluscan development by 13-25%, respectively, had small negative effects on crustaceans and fish (8% reduction) and a small positive effect on coral development (4%). The magnitude of effects of warming on development ranged from 13% increases in molluscs to 26% reductions in echinoderms, with no significant effects (Fig 2.3e). The interactive effect was multiplicative in crustaceans, synergistic but non-significant in corals, and antagonistic but non-significant in echinoderms, fish, and molluscs (Fig 2.3e). There were no differences in the overall or interactive effects of drivers across categorical modifiers and taxonomic groups (Appendix A: Fig A.6).

2.4.2.8 Survival

Acidification negatively affected crustacean, echinoderm, fish, and mollusc survival (8-29% reductions), although the only statistically significant reduction was in fish (Fig 2.3f). Acidification had no net effect on coral survival (0% change) and led to a 5% increase in sponge survival (Fig 2.3f). Warming, on the other hand, exclusively reduced survival with significant reductions in crustaceans (49%), fish (39%), and molluscs (28% reduction, Fig 2.3f). Interactive effects were all small and non-significant with the following directionality: antagonisms in corals, crustaceans, echinoderms, and sponges, and synergies in fish and molluscs (Fig 2.3f).

The magnitude of negative effects of acidification on survival decreased with life stage in molluscs from 22% reduction in larvae to 0% difference in adults ($p = 0.003$; Appendix A: Table A.11, Fig A.7). Acidification reduced survival in sessile corals and mobile molluscs compared to the alternative categories ($p < 0.04$; Appendix A: Table A.11, Fig A.7). Warming reduced survival by 70% in direct developing molluscs, significantly more than in indirect developers (17%, $p = 0.001$; Appendix A: Table A.11, Fig A.7). Finally, the interactive effects on survival differed significantly across mollusc mobility classes and categories, with sessile molluscs experiencing more antagonisms and mobile molluscs more synergisms, although neither effect was statistically significant (Appendix A: Fig A.7).

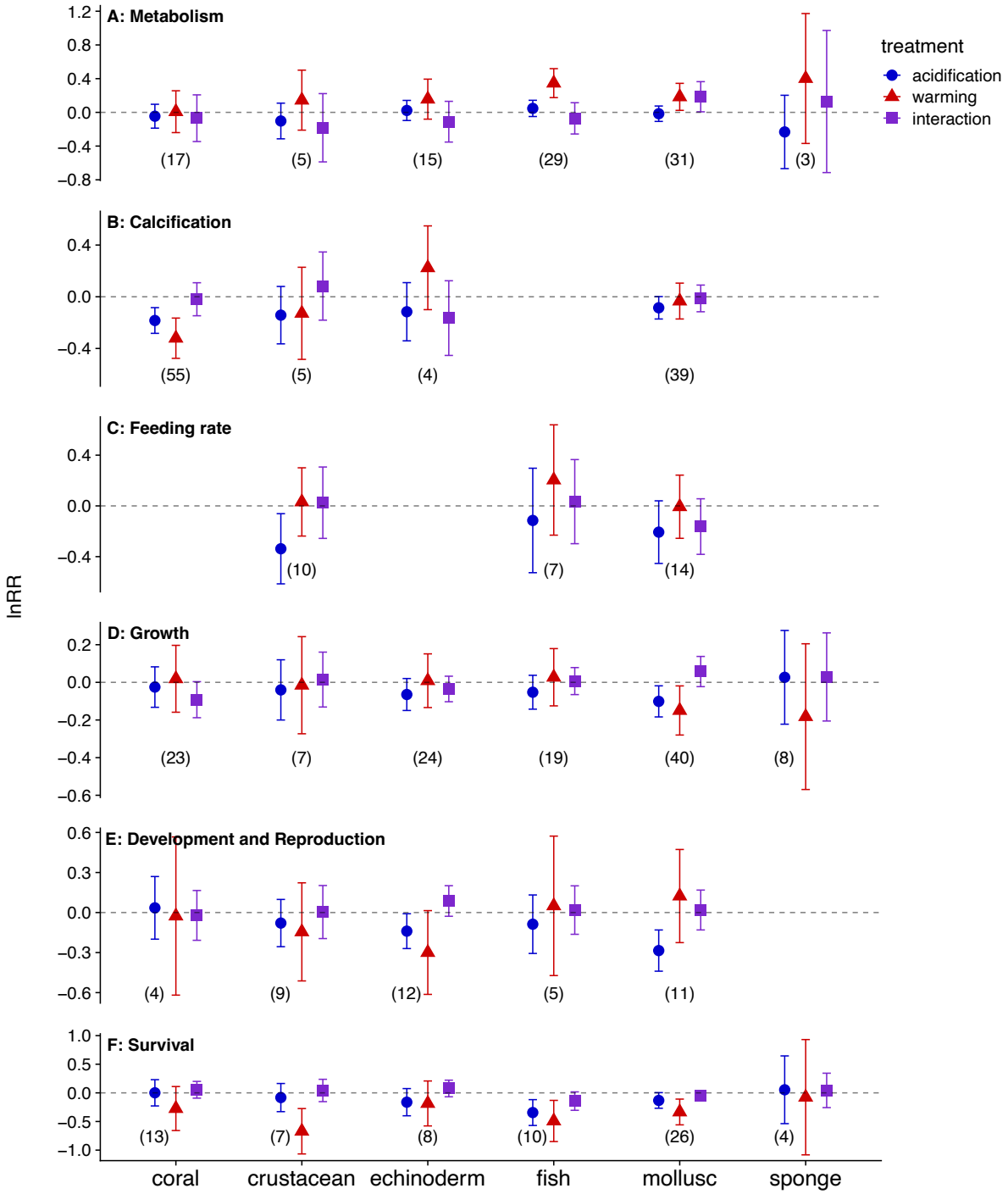

Figure 2.3. The pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) across six response variables and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each taxonomic group and response variable (e.g., there are n = 17 acidification, n = 17 warming, and n = 17 interaction effect sizes for coral metabolism).

2.4.3 Thermal tolerance under ocean acidification:

Ten experiments from 10 selected papers measured the effect of acidification on upper thermal tolerances and found no significant effect (LnRR = 0.0112, lower CI = -0.0365, upper CI = 0.0590). That is, I am unable to reject the null hypothesis that ocean acidification has no effect on upper thermal tolerance.

2.4.4 Paired analysis:

I identified 55 experiments in 48 papers that measured both a lethal and sublethal response variable on the same population under factorial conditions. Since I calculated separate paired mean effects for each sublethal variable measured in an experiment, the total database comprised 76 data points. Sublethal response variables were more adversely affected by acidification than lethal responses for corals, crustaceans, and molluscs, although the effect was only significant in corals. Warming had greater lethal effects than sublethal across all taxa except for corals, with significantly greater effects in fish ($lnRR_{paired}$ = 0.70, lower = 0.65, upper = 1.03) and when $lnRR_{paired}$ was averaged across taxa ($lnRR_{paired}$ = 0.24, lower = 0.07, upper = 0.40, Fig 2.4).

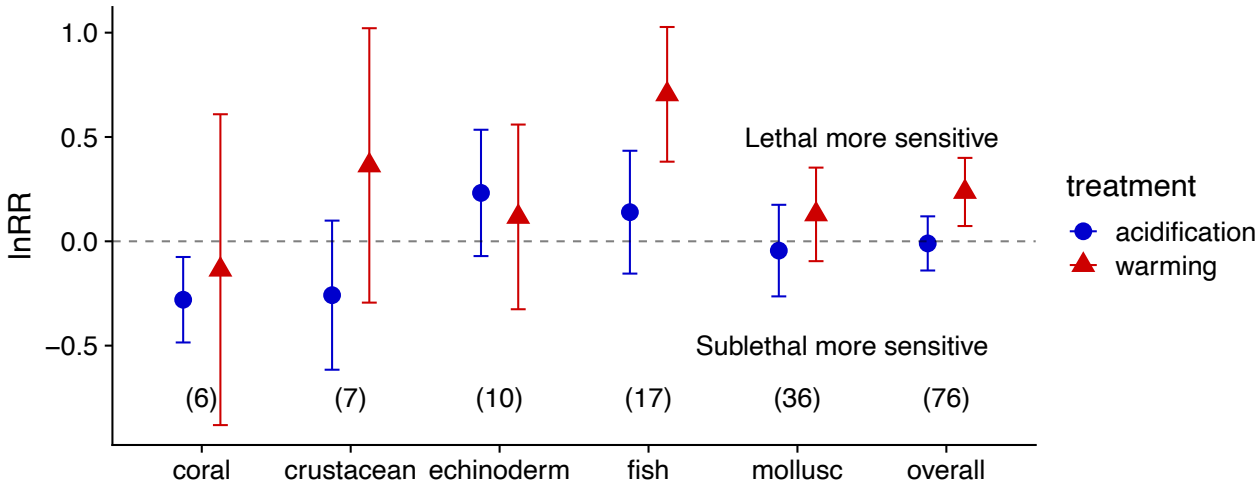

Figure 2.4. The relative pooled overall effects of ocean acidification (blue circles) and warming (red triangles) on sublethal and lethal response metrics across taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the two driver groups are provided in parentheses for each taxonomic group (e.g., there are n = 6 acidification and n = 6 warming effect sizes for corals).

2.4.5 Sensitivity analyses:

Funnel plots show some evidence for asymmetry in the overall and interactive effects of acidification and warming across the full dataset, where studies with low sample sizes and positive non-significant effects of each driver are missing (i.e., bottom right corners of funnels, Appendix A: Fig A.8). This absence could be due to a publication bias against studies with low power and non-significant effects in the positive direction or due to a lack of true effects in this direction. The Rosenthal (1979) analysis indicates that the results are relatively robust to publication bias (Appendix A: Table A.12). There were only five instances where the calculated fail-safe number was below the 5N + 10 threshold: the effects of acidification and interactive effects on feeding rate and on Class 2 organisms and the interactive effects on mollusc metabolism (Appendix A: Table A.12). The relatively small sample sizes and moderate CI ranges of these categories may explain this susceptibility to bias (n = 34 feeding rate, n = 24 Class 2, and n = 31 mollusc metabolism).

2.5 Discussion

This synthesis of nearly 500 factorial experiments reveals that ocean acidification (OA) and warming have net negative effects on marine life, elucidates the high magnitude lethal effects of warming but not acidification relative to sublethal responses, and refines predictions about driver effects across calcifying taxa, life stages, development strategies, mobility types, latitudes, and habitats. The results refute two assumptions about the combined effects of OA and warming: 1) the tolerance analysis did not support the OCLTT's predictions that OA reduces upper thermal tolerance; and 2) there was no general tendency toward synergistic interactive effects across response variables or taxonomic groups. Overall, these results refine the predictive power of the tested hypotheses (see Table 2.1 for conceptual summary) and advance scientific understanding of how ocean acidification and warming affect marine ectotherms.

Table 2.1. Predictions, results, and research agenda generated by this meta-analysis to further understand marine ectotherm responses to climate change.

Prediction	Results and new findings	Emergent questions
Calcifying taxa are more sensitive to ocean acidification (OA) and	*Mixed support* ▪ Molluscs are highly sensitive to OA across both sublethal and lethal response variables ▪ Coral, crustacean, echinoderm, and fish sensitivity to OA and warming is greatest	To what extent do effects of OA and warming on facilitating or foundation species (especially molluscs) create cascade/indirect effects through their associated communities?

warming (Harvey et al., 2013; Kroeker et al., 2013b; Przeslawski et al., 2015)	in specific response variables (coral calcification, crustacean feeding rate for OA, echinoderm development, fish survival) ▪ Warming significantly impairs calcification and the interactive effect is synergistic but uncertain	To what extent do effects of OA and warming on coral calcification, crustacean feeding, echinoderm development, and fish survival confer deleterious intergenerational and cascade effects? What physiological mechanisms underscore calcification reductions under warming?
Younger life stages are more sensitive to OA and warming (Pandori and Sorte, 2019; Przeslawski et al., 2015)	*Low support* ▪ Adults show the greatest magnitude reductions in performance under OA and warming and experienced significant synergistic interactive effects ▪ Sensitivity to OA increases with life stage ▪ Under warming, embryos (mostly fish) show similar magnitude performance reductions as adults but greater uncertainty ▪ Adult echinoderm growth is reduced under OA significantly more than younger life stages ▪ Younger mollusc mortality is higher under OA than adults. Their survival is also significantly reduced under warming	To what extent are older life stages more vulnerable within taxonomic groups and variables?
Direct developers are more sensitive to OA and warming (Sunday et al., 2011b)	*Mixed support* ▪ Both direct and indirect developers are sensitive to OA and warming, but the effects are only significant in indirect developers ▪ The magnitude of reduction is greater for indirect developers under OA and direct developers under warming. Sample sizes are unbalanced ▪ Within taxa, warming reduces survival by 4-fold in direct developing molluscs compared to indirect developers	To what extent is direct development selected upon as an adaptive development strategy in response to rapid and sustained environmental change? Direct developers are underrepresented in estimates of OA and warming's effects.
Sessile organisms show greater lethal tolerance (i.e., greater survival) than mobile organisms (Huey, 2002)	*Lack of support* ▪ Sessile organisms are more sensitive to OA and warming than mobile ones ▪ Performance reductions are greatest in Class 2 under OA and in Class 0 under warming, ▪ Drivers interact synergistically in Class 2 ▪ Mobile molluscs grew 5-fold more than sessile molluscs under warming, but died slightly more than mobile molluscs under OA ▪ Sessile corals died more than planktonic ones under OA	To what extent is sessile vulnerability even greater under field conditions due to more restricted access to microrefugia/ thermoregulation than mobile organisms? The effect of mobility on OA and warming tolerance thresholds should be tested on taxa that have both mobile and sessile adult species to disentangle the effects of mobility and life stage

Tropical and polar species are more sensitive to OA and warming (Lenoir et al., 2020; Sunday et al., 2014)	*Mixed support* ▪ Temperate species are the most sensitive to OA followed by tropic and polar ▪ Warming reduced performance in both tropic and temperate species but not polar ▪ Temperate latitude interactive effects are synergistic with some uncertainty ▪ Polar species showed the greatest uncertainty in warming, but sample size is much smaller relative to temperate and tropical categories	To what extent does exposure to variable pH in temperate or dynamic habitats increase organismal vulnerability to OA and to multiple drivers? What are the evolutionary effects of environmental variability? How does exposure to OA and OW vary across latitudes (i.e., exposure to mean versus extreme stress, mosaic patterns of environmental change)?
Organisms from stable habitats are more sensitive (Pinsky et al., 2019; Sunday et al., 2014)	*Low support* ▪ Organisms from both stable and dynamic habitats show similar magnitude reductions under warming while those from dynamic show slightly greater magnitude reductions under OA ▪ Only dynamic habitats show significant effects; however, sample sizes are very unbalanced	Polar species and species from stable habitats are relatively underrepresented in dataset, thus more experiments may improve estimates of sensitivity.
OA and warming effects are similar in magnitude across sublethal and lethal responses	*Mixed support* ▪ On average, the magnitude effects of OA are similar across sublethal and lethal response variables. Corals, crustacean, and mollusc sublethal responses are more sensitive than lethal whereas echinoderm and fish lethal are slightly more sensitive (only corals are significant). ▪ Warming affects lethal responses more than sublethal on average, with fish and crustaceans showing the greatest magnitude difference. Corals are the only group where warming affected sublethal responses slightly more than lethal, although there is great uncertainty.	To what extent do lethal effects of ocean warming dominate the sublethal effects of OA and warming, especially in fishes and crustaceans? To what extent are sublethal performance reductions under OA selected upon in corals, crustaceans, and molluscs, and what changes prompt indirect effects across dependent communities and alter ecosystem function and services? Replicating the paired analysis with a database of single-stressor studies could strengthen confidence in results interpretations.
Exposure to hypercapnic conditions reduces upper thermal tolerance (Pörtner, 2012; Pörtner and Farrell, 2008)	*Lack of support* ▪ Exposure to low pH (high pCO_2) seawater had no consistent effect on upper thermal tolerance	The OCLTT predictions of OA's effects on upper thermal limits were not supported by empirical studies, warranting an adjustment of this theory's assumptions and generality.
Synergies are the most	*Lack of support*	Further meta-analyses of overall and interactive effects should investigate

common interaction type between OA and warming (Harvey et al., 2013)	▪ Multiplicative interactions were the most common significant interaction type across response variables and categorical moderators (Figures 1-3, n = 11), followed by synergies (n =3) and antagonisms (n = 1). Non-significant interactive effects included 19 synergies and 21 antagonisms.	variability across categorical moderators within taxonomic groups. Attempting to generalize interaction types of OA and warming across and within taxonomic groups may be a highly challenging research endeavour due to biological complexity and not necessary to resolve before implementing climate change mitigations actions.

The results contribute four insights into the overall effects of ocean warming and acidification across response variables. First, I detected a negative overall effect of warming on calcification, with corals being particularly sensitive. This differs from smaller meta-analyses that found no net effect of warming on calcification and could be due to this study's higher statistical power and broader taxonomic coverage (n = 103 comparisons of warming and calcification versus n = 13 and 18 in Harvey et al., 2013 and Kroeker et al., 2013 respectively). Higher seawater temperatures increase the solubility of magnesium ions, which many calcifying species use to build shells and skeletons; thus, ocean warming may accelerate the skeletal solubility of these species (Figuerola et al., 2021). An alternative hypothesis is that warming induces stress responses that decrease energy available for calcifying mechanisms (Leung et al., 2022; Rodolfo-Metalpa et al., 2010; Wolfe et al., 2013).

Second, while some calcifying taxa (e.g., molluscs) showed consistent negative sensitivity to OA across response variables, coral, crustacean, and echinoderm sensitivity was linked with specific response variables and in some cases was lower than the sensitivity of non-calcifying taxa sensitivity (e.g., fish). This result supports the growing consensus that non-calcifying taxa are vulnerable to OA and some calcifying species can implement compensatory mechanisms to buffer OA (Cattano et al., 2018; Heuer and Grosell, 2014; Leung et al., 2022). Rather than expecting calcifying capacity to drive taxonomic sensitivity to OA, we highlight that molluscs are generally sensitive across response variables while other taxonomic groups show specific response variable sensitivity (e.g., coral calcification, crustacean feeding, echinoderm development, fish survival). These taxa-response variable pairings indicate areas to investigate potential cascade and intergenerational effects of climate change. Over time, reductions in calcification and growth may compromise other sublethal performance metrics that are body-size dependent (e.g., feeding rate, reproduction) or due to energy re-allocations associated with shell and skeleton maintenance (Leung et al., 2022; Sokolova, 2013). Since corals and molluscs

comprise many habitat forming and facilitating species, sublethal performance reductions in these taxa could compromise their ability to support dependent species and confer indirect negative effects of OA across marine communities (Harvey et al., 2021, Sunday et al., 2012). Ongoing research into taxonomic responses to OA should investigate why organisms persist alongside why they perish to capture both negative and non-negative impacts of climate change.

Third, while both drivers reduce organismal performance by similar magnitudes (5-6%), ocean acidification led to predominantly negative effects across response variables and taxa whereas warming conferred greater variability in effect directions, magnitudes, and uncertainties. The positive, yet non-significant, effects of warming align with some previous results for certain taxa-response variable pairings (e.g., echinoderm growth) but not others (crustacean development, Harvey et al. 2013). The only significant positive effects of temperature were on metabolism, where warming drove an overall increase in resting metabolic rates (RMR), especially in fishes and molluscs. Since elevated temperatures increase RMR up to a certain point due to thermodynamics, I am unable to conclude whether these RMR increases reflect simple thermodynamic effects or physiological upregulation in response to organismal stress (O'Connor et al., 2007). The higher positive magnitude and tighter certainty around fish and mollusc metabolic responses to temperature could suggest that these taxa are more sensitive to warming if metabolic increases surpass stressful inflection points. However, the reductions observed in corals, crustaceans, and echinoderms could also suggest that these taxa are under high stress and shutting down their metabolism (Bahr et al., 2018). Incorporating knowledge about metabolic thresholds for organismal performance is an important avenue for improving the interpretation of biologically significant effects of temperature on metabolism.

Finally, the largest effect-size magnitude across response variables was the reduction of survival with warming, which was two-fold greater than the reduction in calcification, development, and survival caused by acidification. The paired analysis supports this trend and the growing notion that temperature causes greater lethal effect magnitudes compared to sublethal effects (Przeslawski et al., 2015). The effects of OA do not follow this pattern and underscore the importance of incorporating both sublethal and lethal effects of acidification into research and management practices. The greater negative sublethal effects of OA on corals is particularly notable and can scale-up to substantially negatively affect coral-population and

community performance metrics (e.g., abundance, species richness, Hill and Hoogenboom, 2022). One limitation of the paired analysis is that the underlying database exclusively comprised factorial studies; however, the paired analysis does not require fully factorial studies. Thus, sample sizes could be increased by replicating this analysis with single driver studies, so long as both categories of response variables are measured.

The effect of ocean acidification and warming across life stages contradicts predictions and previous results that younger life stages are more sensitive to climate change (Cattano et al., 2018; Harvey et al., 2013; Kroeker et al., 2013b; Pandori and Sorte, 2019). Rather, performance reduction magnitudes increased with age under both OA and warming, except in embryos under warming. This trend could be driven by the dominant response variables and taxa measured within each life stage: coral and mollusc calcification and growth comprise 58% of adult measurements whereas crustaceans, echinoderms, fish, and molluscs comprise more balanced portions of the juvenile and larval measurements. Within taxa-response variable comparisons (e.g., mollusc survival), there is evidence that younger life stages are more vulnerable, alluding to a potentially important demographic bottleneck for this vulnerable taxon (Kroeker et al., 2013b). The variability between my findings and prior studies could be due to different analytical methods (e.g., effect size estimates, categorical moderators), underlying databases and sample sizes (e.g., single driver versus factorial experiments), or due to true biological variability in life-history stage traits both across and within taxa (Przeslawski et al., 2015). As the quantity of factorial studies across varying life stages increases, meta-analyses should quantify within taxa comparisons to enhance the precision and accuracy of life stage vulnerability comparisons under OA and warming.

The negative effect of acidification on indirect developers contrasted predictions based on development strategy. One explanation for the smaller magnitude effects in direct developers to hypercapnia is that brooding eggs within the maternal environment can protect early life stages and confer increased resilience throughout subsequent life stages. This fitness advantage of brooding has been demonstrated in numerous marine invertebrate species that inhabit regions of rapid environmental change and hypercapnic environments and that evolved direct development from broadcasting ancestors (Lucey et al., 2015). That said, the substantially different sample sizes between the direct and indirect developing cohorts (n = 40, 349 respectively) challenges the conclusion that direct developers are less sensitive to OA or more

sensitive to warming and reveals an important research gap. Highly dispersive indirect developers could still have fitness advantages if their larvae disperse away from the stressful conditions and track optimal environmental conditions (e.g., isotherms); however, in the face of multigenerational, widescale environmental change, parental care and direct development could become more adaptive developmental strategies.

Acidification and warming caused greater performance reductions in sessile compared to mobile species, contrasting expectations that sessile organisms have greater tolerance to drivers and previous findings of comparable extirpation risk across mobile and sessile marine taxa (Pinsky et al., 2019). Corals and molluscs dominate the sessile category and thus drive this finding. The high vulnerability of sessile taxa could be even greater in the field because they are less able to seek microrefugia than mobile taxa (e.g., rock crevices, different regions of the water column, Gilman et al., 2015) and because intertidal and coastal sessile species are exposed to coastal acidification (large pH fluctuations driven by interactions with freshwater, anthropogenic, and coastal biological activities, Leung et al., 2022). That said, the predicted effects were observed in mollusc survival, where mobile molluscs experienced slightly higher mortality than sessile ones, perhaps because molluscs were the only taxon with adult species in both mobility categories (e.g., mobile snails and clams, sessile oysters and mussels). This could suggest that even slight mobility can enable behavioural adjustments that reduce the need to evolve high tolerance thresholds (Huey, 2002).

This comparison of marine ectotherm responses to OA and warming across latitudes indicate that both tropic and temperate species are sensitive to warming and that temperate species are the most sensitive to acidification. Tropic species could be sensitive to warming because they already live at temperatures close to their upper thermal limits (i.e., they have small thermal safety margins, Pinsky et al., 2019). Rapid environmental warming could surpass their thermal tolerance thresholds and compromise performance and survival, especially for species with restricted mobility (e.g., corals, molluscs) or dispersal (e.g., direct developers) that are less able to employ behavioural thermoregulation (Sunday et al., 2014). The negative effects of OA and warming on species from temperate latitudes suggests that additional mechanisms underscore vulnerability to climate change across latitudes. Since both temperate and dynamic habitats experience greater environmental variability than tropical, polar, and stable habitats, shifts in extreme exposure to hot and hypercapnic conditions (e.g., during heat waves and upwelling)

could play a larger role in vulnerability than mean incremental changes (Burger et al., 2022; Vasseur et al., 2014). This hypothesis of greater vulnerability in environmental variable regions is relatively unexplored for pH variability compared to thermal variability. For both drivers a strong determinant of organismal vulnerability to environmental variability is the relationship between the predictability and timescale of variability relative to genetic adaptation (Kroeker et al., 2020a). While these results contravene expectations that polar species are more sensitive to hypercapnia than their temperate and tropical counterparts, polar ecosystems may still be at greater vulnerability due to the faster rates of acidification and warming occurring in those regions and the inability for polar species to escape either driver through migration. As with development strategy, the substantially lower sample size of polar comparisons (n = 16) relative to temperate and tropical (n = 223, 150) warrants a call for more polar studies before concluding that low magnitude effects of acidification and warming dominate this system.

Quantifying empirical support toward theoretical assumptions is a critical function of meta-analyses. I found a lack of general support for the oxygen- and capacity-limited thermal tolerance (OCLTT) hypothesis' prediction that ocean acidification reduces the upper thermal tolerance of marine ectotherms. Rather, hypercapnia had no directional effect on upper thermal tolerance. This finding contributes to the growing call to redefine the OCLTT's predictive assumptions and applications and potentially reject its universality in predicting the mechanisms and outcomes of climate change for marine ectotherms (Gräns et al., 2014; Jutfelt et al., 2018; Lefevre, 2016). Rather, the OCLTT may provide predictive value for the interactive effect of OA and warming for specific species (e.g., polar fishes where I did find a synergistic interactive effect on metabolism) or for explaining mechanisms that underscore the interaction between anoxia and thermal stress. This study only measured the effect of OA on upper thermal tolerance and did not measure changes to lower thermal tolerance thresholds; therefore, I cannot definitively conclude that hypercapnia failed to reduce thermal tolerance windows. However, the results still challenge the OCLTT's predictions that acidification will reduce upper thermal tolerance thresholds.

This study's exclusive selection of factorial manipulations yields the largest quantitative synthesis of the factorial effects of OA and warming to date and a robust conclusion that there is no general prevalence of synergistic interactions for these two drivers. Rather, effect size directions were balanced in frequency across synergistic and antagonistic interaction types and

the most common significant effect classification was multiplicative. In general, interactive effect size magnitudes were small, indicating that even when interactive effects (i.e., synergies and antagonisms) were detected, the magnitudes did not diverge substantially from the null. Significant interactive effects were more common in the analyses of categorical moderators across taxonomic groups, perhaps driven by the higher eco-physiological specificity within these sub-categories. As more factorial studies of OA and warming are conducted, further syntheses should focus on variability in effect sizes within taxonomic and categorical moderator groups.

The general lack of one dominant interaction type supports the emergent notion that driver interactions are challenging, if not impossible, to predict based on current theory and that the search for general predominance of one type over another could be an impractical research endeavour with vague applicability to management entities (Côté et al., 2016). Developing mechanistic models based on eco-physiological theory (e.g., non-linear effects) is one approach to improve the predictability of interactive effects (Kroeker et al., 2017). Meanwhile, the generalized unpredictability of ocean acidification and warming interactions should not be viewed as an impediment to climate change action, rather as an inherent property of complex biological systems. That is, these results showed a net negative effect of both drivers on marine life; thus, climate change mitigation actions (i.e., emissions reductions) will largely benefit marine life regardless of the interaction type.

Meta-analyses quantify empirical support for theoretical hypotheses, and, as is the nature of ecological research, frequently generate more questions than they answer. Pursuing the emergent questions outlined in Table 2.1 will invariably advance our scientific understanding of climate change's effects on marine life; however, these questions do not need to be completely resolved before advocating for and implementing climate change mitigation and adaptation actions. This synthesis of nearly five hundred factorial comparisons provides a robust confirmation that ocean acidification and warming have largely negative direct effects on marine organisms, regardless of the interaction type. Beyond that, I indicate a few taxonomic groups (molluscs), organismal traits (adults, sessile), and latitudes (tropics and temperate) that are generally more sensitive to climate change than others. While this study is limited in its ability to predict the local effects of climate change, these results can motivate government and corporate agencies to implement climate change mitigation policies that drastically reduce greenhouse gas emissions for the global betterment of marine ecosystem health.

Chapter 3: Not just range limits: warming rate and thermal sensitivity shape climate change vulnerability in a species range centre

3.1 Synopsis

Climate change manifests unevenly across space and time and produces complex patterns of stress for ecological systems. Species can also show substantial among-population variability in response to environmental change across their geographic range due to evolutionary processes. Explanatory factors or their proxies, such as temperature and latitude, help parse apart these sources of environmental and intraspecific variability; however, overemphasizing latitudinal trends can obscure the role of local environmental conditions in shaping population vulnerability to climate change. Focusing on the geographic centre of a species range to disentangle latitude, I test the hypothesis that populations from warmer regions of a species range are more vulnerable to ocean warming. I conducted a mesocosm experiment and reciprocal transplant with four populations of a marine snail, *Nucella lamellosa,* from two regions in British Columbia, Canada, that differ in thermal characteristics: the Central Coast, a cool region, and the Strait of Georgia, one of the warmest regions of this species' range that is warming faster than the Central Coast. Populations from the Strait of Georgia experienced growth reductions at contemporary summertime seawater temperatures in the lab and showed stark reductions in survival and growth in future seawater conditions and when outplanted at their native transplant sites. This indicates high vulnerability to environmental warming, especially given the faster rate of ocean warming in this region. In contrast, populations from the cooler Central Coast demonstrated high performance at contemporary seawater temperatures and high growth and survival in projected future seawater temperatures and at their native outplant sites. Given their position within the geographic centre of *N. lamellosa*'s range, extirpation events in the vulnerable Strait of Georgia populations could compromise connectivity within the meta-population and lead to gaps in this species' range. Overall, this study supports predictions that populations from warm regions of species ranges are more vulnerable to environmental warming, suggests that the Strait of Georgia and other inland or coastal seas could be focal points for climate change effects and ecological transformation, and emphasizes the importance of analyzing climate change vulnerability in the context of regional environmental data and throughout a species range.

3.2 Introduction

Species persistence in the face of climate change is shaped by the interplay of three fundamental response strategies: dispersal and migration, genetic adaptation, and acclimatization via phenotypic plasticity (Schiffers et al., 2013). Predicting which strategy, if any, a species can employ in response to environmental change is complex and often informed by laboratory experiments that assume, but do not test, alignment between lab results and ecological outcomes in the field (De Boeck et al., 2015). This assumption can over- or underestimate organismal vulnerability to environmental drivers of change (e.g., warming) and is particularly concerning when experiments extrapolate laboratory responses of a single population across an entire species' range (Barley et al., 2021). Populations can demonstrate distinct sensitivities and adaptations to environmental drivers (e.g., expressions of phenotypic plasticity, different thermal tolerances) based on their local environmental conditions and organismal traits (Angilletta, 2009; Kawecki and Ebert, 2004; Valladares et al., 2014). In addition, the complex nature of how climate change manifests in space and time (e.g., local variation in the rate, magnitude, direction and/or frequency of change), can produce mosaics of climate risk across a species' range (Gilman et al., 2006; Helmuth et al., 2006, 2002; Kroeker et al., 2020a). Despite recent progress, it remains unclear to what extent intraspecific variation in thermal sensitivity intersects with climate risk mosaics to produce hot spots of vulnerability to ongoing warming across a species range.

Latitude is often used to predict organismal vulnerability to climate change, with populations at warmer and lower-latitude edges of species ranges predicted to be especially vulnerable to environmental warming (Deutsch et al., 2008; Kingsolver, 2009; Lenoir et al., 2020). Vulnerability is determined as a function of exposure (the magnitude of experienced environmental change), sensitivity (magnitude of change caused by exposure to environmental variability), and adaptive capacity (the ability for populations to respond positively to changes over time, Pacifici et al., 2015). While there exist myriad hypotheses to explain the greater vulnerability of lower-latitude populations (e.g., climate-variability hypothesis and tolerance-plasticity trade-off hypothesis, Compton et al., 2007; Somero, 2010; van Heerwaarden and Kellermann, 2020), here I focus on one in particular: narrow thermal safety margins. Thermal safety margins, defined as the difference between an organism's upper thermal tolerance limit and the maximum environmental temperatures it experiences, are generally smaller for lower-latitude populations within a species range (Rohr et al., 2018; Sunday et al., 2014). When

maximum environmental temperatures exceed upper thermal limits and when species have long generation times (and thus slow rates of evolutionary adaptation), low dispersal or restricted mobility, thermal safety margins can shrink such that populations are extirpated (Morley et al., 2019). Extirpation events in lower-latitude populations are more common in marine than terrestrial ectothermic species due to having smaller thermal safety margins, fewer means of behavioural thermoregulation and stronger isotherm tracking (Lenoir et al., 2020; Pinsky et al., 2019; Sunday et al., 2011a).

While latitudinal predictions of organismal vulnerability to climate change offer strong predictive power within certain contexts (e.g., comparisons of marine versus terrestrial vulnerability), the assumption that thermal gradients shift linearly with latitude is not always accurate. For instance, varying tidal cycles along continuous coastlines can result in populations experiencing warmer environments in the middle of their range that drive the evolution of higher thermal tolerance in mid-latitude than lower-latitude populations (Kuo and Sanford, 2009). Elevated thermal tolerance in response to heat stress can be adaptive. However, molecular, physiological, and demographic constraints can hamper the evolution of thermal tolerance in response to ongoing warming and evolution of high tolerance can be costly and lead to performance trade-offs (e.g., reduced growth, reproduction, Marshall et al., 2015; Meester et al., 2018; Tangwancharoen et al., 2020). That is, genetic adaptation to previous environmental change does not guarantee that populations can continue responding via genetic adaptation to ongoing climate change. Accordingly, populations that live in the warmest regions of their species range, be it the trailing, low-latitude edge or the geographic centre near mid-latitudes, can be at risk of extirpation if they cannot continue evolving higher thermal tolerance thresholds or acclimatize faster than the rate of local warming (Schiffers et al., 2013). Relying solely upon latitude as a predictor of population vulnerability to climate change can obscure these instances of mid-range thermal vulnerability.

On the northeast Pacific coast between central California and Alaska, some of the warmest summertime sea surface temperatures occur in the geographic centre, along Washington (USA) and British Columbia's (B.C., Canada) coastlines, rather than near the low-latitude edge (JPL MUR MEaSUREs Project., 2015). The Strait of Georgia is a large body of water within the Salish Sea, an inland estuarine sea along B.C.'s south coast, and has warmer mean annual seawater temperatures than the exposed coastlines to the north, west, and south (Amos et al.,

2015; Chandler et al., 2018; Johannessen and Macdonald, 2009). This region's sea surface temperature (SST) is also warming faster than anywhere else along B.C.'s coast and at double the global average rate of ocean warming (Amos et al., 2015; British Columbia and Ministry of Environment, 2016). Finally, the Strait of Georgia experiences summertime low tides that coincide with solar noon (as opposed to in the morning to the north and south), exposing intertidal organisms to stressful aerial temperatures (Helmuth et al., 2006; Ianson et al., 2016; Raymond et al., 2022). Together, the high ocean and air temperatures and the rapid relative rate of environmental warming make the Strait of Georgia a potential hot spot of climate risk for species whose ranges extend along the northeast Pacific coast.

One such species is the intertidal dogwhelk, *Nucella lamellosa* (Gmelin 1791), a common predatory snail whose range extends from Santa Cruz (California, USA) to the Aleutian Islands (Alaska, USA, Sorte and Hofmann, 2005). This species is an ideal candidate in which to examine the vulnerability of mid-range populations to climate change. Several lines of evidence suggest that *N. lamellosa* has likely evolved population-specific relationships between temperature and performance. For example, this species has restricted gene flow (crawl-away juveniles) and low adult mobility, and well as genetic, phenotypic and phenological variation among populations throughout B.C. and Alaska (Marko, 2004; Spight, 1974).

Here I employ field and laboratory experiments to test two central research questions: to what extent do populations in the geographic centre of a species' range show intraspecific variation in upper thermal sensitivity, and how does this variability align with climate change risk mosaics to impact vulnerability to climate change? I answered these questions using a mesocosm experiment and a reciprocal transplant study with populations of *Nucella lamellosa* from two regions within the geographic centre of its range: the Central Coast of B.C., characterized by cooler seawater temperatures and slower rates of ocean warming; and the central Strait of Georgia, characterized by higher annual temperatures and faster rates of ocean warming. I hypothesized that populations from warm regions are more vulnerable to ocean warming than those from cool regions because maximum environmental temperatures approach upper thermal performance thresholds. Accordingly, I predicted that populations from the warmer Strait of Georgia will have higher survival and growth rates at warm temperatures than those from the cooler Central Coast, but that they will be more vulnerable to predicted future conditions due to their greater risk of exposure to stressful temperatures. I also hypothesized

that the Strait of Georgia is a hot spot of climate risk for *N. lamellosa* because the rapid rate of environmental warming may surpass this species' ability to adjust its upper thermal tolerance limits. Thus, I predict populations from both regions will perform better (i.e., experience higher growth and survival) on the Central Coast.

3.3 Methods

3.3.1 Site and population characteristics

I selected two regions where *N. lamellosa* are abundant along B.C.'s central and southern coastlines: the Central Coast and the central Strait of Georgia (Fig 3.1). In each region I identified two wave-sheltered sites: Pruth lagoon ('Pruth') and Kwakshua channel ('Kwakshua') on the Central Coast, and Cedar boat ramp ('Cedar') and Blue Heron Park ('Heron') in the central Strait of Georgia. The Wuikinuxv and Haíłzaqv (Heiltsuk) First Nations hold Indigenous rights to their territories where the field data were collected on the Central Coast, and the Strait of Georgia sites are located within the unceded and ancestral territory of the Snuneymuxw First Nation.

I selected these regions to test the hypothesis of intraspecific variability in thermal vulnerability because the distinct thermal conditions across these two regions could drive spatially varying selection and phenotypic divergence in *N. lamellosa*. Summer SST recorded from May – Sept 2012-2020 was 3.7 ± 0.86°C SE higher on average in the Strait of Georgia than on the Central Coast (the 90th percentile was 4.1 ± 1.00°C SE higher in the Strait of Georgia, Fig 3.1, Government of Canada, 2019). The average annual temperatures were also higher and more variable in the Strait of Georgia (11.86 ± 4.2°C SE) than on the Central Coast (10.48 ± 2.6°C SE, Chandler et al., 2018; Government of Canada, 2019). In addition, between 2016-2021, satellite data indicate that summertime SST for *N. lamellosa*'s entire range were consistently the highest in the central Strait of Georgia (Appendix B: Video B.1, JPL MUR MEaSUREs Project. 2015). Snails from each region demonstrate phenotypic and phenological divergence that may be in response to the varying thermal environments: Central Coast snails have frillier shells with greater colour variance than Strait of Georgia snails, which tend to have smooth and predominantly white shells (Appendix B: Fig B.1). Central Coast snails lay egg capsules in the early spring (March – April), whereas Strait of Georgia snails lay egg capsules in winter months (Dec – Jan, pers. obvs., Beaty).

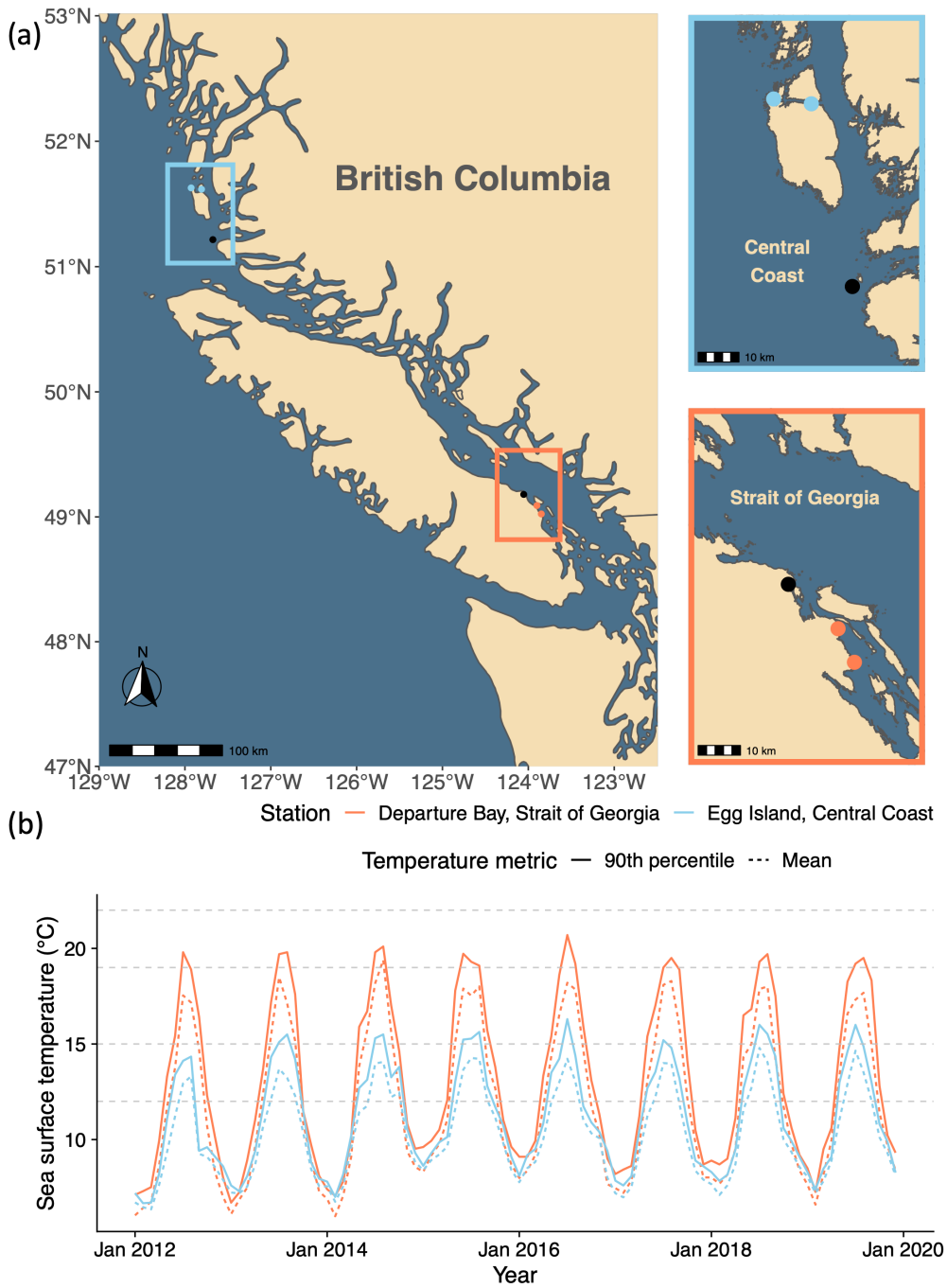

Figure 3.1. Sites for the four populations of *N. lamellosa* used in the reciprocal transplant and mesocosm experiments. Blue dots are the two Central Coast sites (Pruth is west of Kwakshua) and orange dots are the Strait of Georgia sites (Cedar is north of Heron). Black dots are lighthouses where long-term sea surface temperature (SST) data were sourced for each region (Egg Island on the Central Coast and Departure Bay in the Strait of Georgia). (b) The monthly 90th percentile (solid line) and mean (dashed line) SST based on lighthouse data between 2012-2020 (Government of Canada, 2019). The horizontal dashed grey lines show the four seawater temperature treatments in the mesocosm experiments (12, 15, 19, and 22°C).

3.3.2 Experimental design: mesocosm

To test intraspecific variability in sublethal and lethal responses to temperature, I conducted a six-week mesocosm experiment where I exposed snails from all four source populations to seawater conditions that span current and future ocean temperatures for each region (July 23rd – Sept 3rd, n = 42 days). In June 2018, I collected approximately 200 snails (sized 15-30mm, approx. one year old) from each site and brought them to the laboratory at the University of British Columbia, within the unceded territory of the xʷməθkʷəy̓əm (Musqueam) First Nation. Snail growth rate is relatively rapid in this size class and thus suitable for short-term experiments (Sanford and Worth, 2010; Spight, 1973). Snails were acclimated to laboratory conditions (approx. 13°C) in a sea table without food for three weeks prior to beginning the experiment (as per Barclay et al., 2019).

I exposed snails to four temperature treatments: 12, 15, 19, and 22°C, with two to five replicate recirculating tanks (260 litres) per temperature treatment (Appendix B: Table B.1). The 12-15°C and 15-19°C treatments reflected contemporary summertime seawater temperatures for the Central Coast and the Strait of Georgia respectively based on SST data from each region (Fig 3.1) and on temperature dataloggers installed at each site (see reciprocal transplant section). The 19°C and 22°C temperatures reflect potential future seawater temperatures for each region according to the IPCC RCP 8.5 scenario (i.e., +3-4°C, DFO, 2022; IPCC, 2019). Seawater was sourced locally from the Burrard Inlet, B.C. I maintained constant pH and salinity levels across all treatments (Appendix B: Table B.1). All tanks were bubbled with ambient air drawn from outside the building.

For each source population, I placed seven individually labelled snails into a plastic container (15*15*10cm) with mesh sides to permit water flow. I kept source populations separate from one another to control for competition among the populations. I then placed one container of snails from each source population into each tank (two sites for each of the two regions, four containers per tank, Appendix B: Fig B.2). Tank seawater started at 12°C and was increased at a rate of 2°C/day until the final treatment temperatures were reached. Each tank also contained mussels (13 *Mytilus trossulus* and 13 *M. californianus*) outside the containers that were part of a separate experiment; *Mytilus* spp. mussels commonly co-occur with *N. lamellosa*.

Each tank had a chiller/heater to regulate seawater temperature and a four-step filtration system to maintain nutrient balance and water quality (including sock filters, bioballs, a protein skimmer, and UV sterilizer). On Day 2, equipment failures led to 100% mortality in three tanks, which were excluded from further analyses (Appendix B: Table B.1). Within the first week of the experiment (July 23 – 29th), an atmospheric heatwave impacted the room where the experiment was housed. While temperatures rose above target levels during the heatwave (peak daily temp = 23.65°C, Appendix B: Fig B.3), all animals survived with no visible sublethal effects during and directly afterward. Since the heatwave affected all tanks, I still consider July 23rd as Day 1. Finally, I re-assigned one of the 12°C replicates to the 15°C treatment because the chiller was unable to maintain the lower seawater temperature. For final sample sizes, see Appendix B: Table B.1.

I monitored nutrient levels of ammonium, nitrate, and nitrite weekly using API Marine Master Test Kit and conducted twenty percent water changes when necessary (as per Stevenson et al., 2020). I monitored seawater temperature using temperature dataloggers (DS1922L-F5# Thermochron iButtons) that recorded temperature every 15 minutes. Finally, I recorded daily temperature, salinity, and pH measurements (YSI Pro 30, Professional Series, YSI, Yellow Springs, USA; Oakton pH probe 150 calibrated with NBS buffers; Appendix B: Table B.1).

3.3.3 Experimental design: reciprocal transplant

To test the response of populations to each region within this species' range, I conducted a fully crossed reciprocal transplant experiment where snails from each site were outplanted across all four sites. At each outplant site, I installed 16 stainless steel mesh cages (30*30*5 cm) with 5mm mesh size to prevent escapement (Sanford et al., 2003) that were arranged into four blocks of four cages. Each block comprised the unit of replication (n = 8 per outplant region), and contained one cage per source population, with six snails from a single source population in each cage (Appendix B: Fig B.2). The block positions were haphazardly distributed based on substrate availability in the mid intertidal (+0.9-1.6m above Mean Low Low Water). Prior to installation, I standardised food availability by scraping the substrate. All cages were supplied with food-rocks with 200-250 *Balanus glandula* on them. Halfway through the experiment the barnacle rocks were removed and replenished. Next to each block of cages, I secured two iButtons with epoxy (z-spar, n = 8 per site), set to record temperature every 30 minutes. I also

measured temperature, salinity and pH during site visits at the beginning, middle, and end using the same YSI and pH meter as the mesocosm experiment.

In early spring 2019, I collected 96 snails at each site that measured between 15-35 mm in length (six snails for each of four cages at each of four sites). I measured and labelled each snail with bee tags in the lab, and then outplanted half on the Central Coast in March 2019 and the other half in the Strait of Georgia in early April. The snails remained in the field until August 2019 (21 and 20 weeks for the Central Coast and the Strait of Georgia, respectively). I chose this experimental duration because when I conducted the same reciprocal transplant in 2018, an atmospheric heatwave in August caused significant mortality at both Strait of Georgia sites. To avoid a similar mass mortality event in 2019 and ensure sufficient survival for measuring sublethal response variables, I ended the 2019 experiment in August before the hottest air and ocean temperatures.

3.3.4 Response variable measurement

In both experiments, I measured the following snail response variables at the beginning, middle and end: shell length, shell lip thickness, linear shell growth, total weight, and submerged weight. Total and submerged weights were measured to facilitate non-destructive differentiation between shell and tissue growth, where shell weight is calculated based on a regression between submerged and dry shell weight (Appendix B: Fig B.4), and tissue weight equals total weight – shell weight (Palmer, 1982). Linear shell growth was measured by painting the peripheral edge of each shell with nail polish and measuring linear growth beyond this mark.

In the mesocosm experiment, I also quantified feeding rates on a weekly basis. I supplied each container of snails with an excess of prey, 12 *M. trossulus* per week as determined by a pilot experiment, and quantified per capita feeding rate as the number of mussels consumed per live individual per week. This approach accounted for uneven mortality across treatments over time. Survival was monitored on an ongoing basis in the mesocosm experiment and at the middle and end of the reciprocal transplant. Dead snails were removed from cages and tanks.

3.3.5 Data analysis

I conducted all analyses in R, version 4.1.2. Growth metrics were calculated as the difference between final and initial size. I excluded linear shell growth from analyses as it was highly

correlated with change in shell length. In the mesocosm experiment, I analyzed survival, feeding rate, and growth response metrics by fitting linear mixed-effects models from the *lme4* package (Bates et al., 2022) that included source region (Central Coast or Strait of Georgia), temperature treatment and their interactions as fixed effects, and tank and source population as random effects. Initial size metrics (e.g., initial length, initial shell weight) were included in the growth models as fixed covariates. The reciprocal transplant linear mixed-effects models were very similar. I included source region, outplant region and their interactions as fixed effects, and block nested within outplant site, and source population as separate random effects. Again, initial size metrics were included as covariates in the growth models. To analyze iButton temperature data from the field, I calculated daily mean and 90th percentiles across sites.

To analyze survival, feeding rate, and growth models, I ran Type III sums of squares ANOVAs using the *car* package (Fox et al., 2021). Tukey's honestly significant difference multiple comparisons were run to identify significant differences across pairs when likelihood ratio tests found significant fixed effects or interactions.

3.4 Results

3.4.1 Mesocosm experiment

3.4.1.1 Survival and feeding rate

Survival was comparably high at 12, 15, and 19 °C, but snails from both regions experienced high mortality in the 22°C treatment, with survival reduced to approximately 10% for Central Coast snails and 50% for Strait of Georgia snails in this treatment (Temp*Source region $p < 0.001$; Fig 3.2a, Table 3.1). Snails ate the least at 22°C, and snails from the Central Coast ate more than snails from the Strait of Georgia across all temperatures (Temp $p < 0.001$; Source region $p < 0.001$; Fig 3.2b, Table 3.1). The effect of temperature on feeding rate was similar across source regions (Temp*Source region $p = 0.276$, Table 3.1).

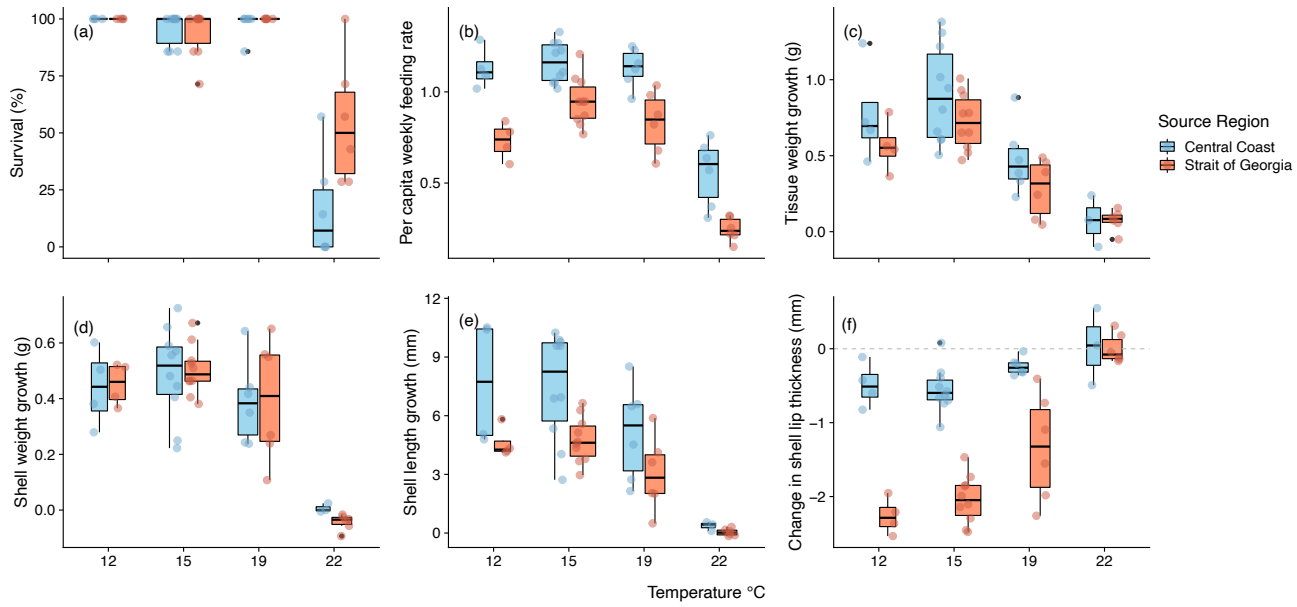

Figure 3.2. Survival, feeding rate, and growth from the 49-day mesocosm experiment. The dots are averaged response metric (survival, feeding rate, growth) for each source population within a given tank and the boxplots visualize the growth within source regions across the temperature treatments (i.e., two source populations are pooled within their corresponding source region). The dashed horizontal line at 0 in panel (f) facilitates interpretation of growth reductions.

Table 3.1. Effects of source region, temperature treatment, and their interaction on the growth, feeding rate, and survival of *N. lamellosa* during the 2018 mesocosm experiment.

Parameter	Source	X^2	*df*	*p*
Survival	Source region	0.000	1	1.00
	Temperature	170.5	3	**<0.001**
	Source region * Temperature	19.22	3	**<0.001**
Feeding rate	**Source region**	16.32	1	**<0.001**
	Temperature	101.5	3	**<0.001**
	Source region * Temperature	3.867	3	0.276
Tissue weight growth	Source region	1.223	1	0.269
	Temperature	42.06	3	**<0.001**
	Source region * Temperature	2.504	3	0.475
	Initial tissue weight	7.629	1	**0.006**
Shell weight growth	Source region	0.011	1	0.975
	Temperature	21.98	3	**<0.001**
	Source region * Temperature	0.012	3	0.999
	Initial shell weight	1.138	1	0.286
Shell length growth	Source region	2.646	1	0.104

	Temperature	60.49	3	**<0.001**
	Source region * Temperature	9.309	3	**0.025**
	Initial length	37.71	1	**<0.001**
Change in shell lip thickness	**Source region**	7.139	1	**0.008**
	Temperature	2.693	3	0.441
	Source region * Temperature	51.09	3	**<0.001**
	Initial thickness	80.71	1	**<0.001**

3.4.1.2 Growth

Snails from both regions showed similar temperature-growth relationships for tissue and shell weight that peaked at 15°C before declining to negligible growth at 22°C (Temp $p < 0.001$; Fig 3.2cd, Table 3.1). In contrast, the effect of temperature on shell length and thickness varied across source regions (Temp*Source region $p < 0.025$ for shell length; $p < 0.001$ for lip thickness, Fig 3.2ef, Table 3.1). For shell length, snails from the Central Coast grew less at 19°C than in the 12 and 15°C treatments (Tukey's HSD t-test, $p = 0.035$ between 12°C and 19°C and $p = 0.022$ between 15°C and 19°C; Fig 3.2e), whereas Strait of Georgia snails retained similar - albeit lower - growth rates until 22°C when they dropped to negligible levels (Tukey's HSD t-tests, $p < 0.006$ between 22°C and all other temperatures; Fig 3.2e). For shell lip thickness, Central Coast snails retained similar thickness across temperatures, whereas the Strait of Georgia snail shells became thinner in the 12°C, 15°C, and 19°C treatments compared to 22°C (Tukey's HSD t-test, $p < 0.001$ between 22°C and all other temperatures; Fig 3.2f, Table 3.1). This trend is likely because snails from the Strait of Georgia started with thicker shells than those from the Central Coast and because snails grew in the absence of predator cue (and the associated stimulus to grow thicker shells, Appendix B: Fig B.5). Initial size was significant for every growth metric except shell weight, with smaller snails growing at faster rates (Table 3.1).

3.4.2 Reciprocal transplant

3.4.2.1 Environmental characteristics

Between April 12th – August 2nd 2019, the mean daily temperatures recorded by iButtons in the Strait of Georgia was 2.67°C warmer than on the Central Coast, and daily 90th percentile temperatures were 3.57°C warmer than on the Central Coast (Fig 3.3). Temperatures were also more variable, with larger temperature swings between spring and neap tide in the Strait of Georgia (mean ± 3.06°C SE; 90th percentile ± 4.51°C SE) than on the Central Coast (mean ±

2.06°C SE; 90th percentile ±2.15°C SE; Fig 3.3). The average pH at the Strait of Georgia sites was higher with greater variability than pH on the Central Coast (mean ± SE: 8.14 ± 0.26 and 7.89 ± 0.07 respectively), and salinity levels were similar across regions (mean ± SE: 27.44 ppt ± 2.00 and 28.09 ppt ± 2.36 respectively; Appendix B: Table B.2).

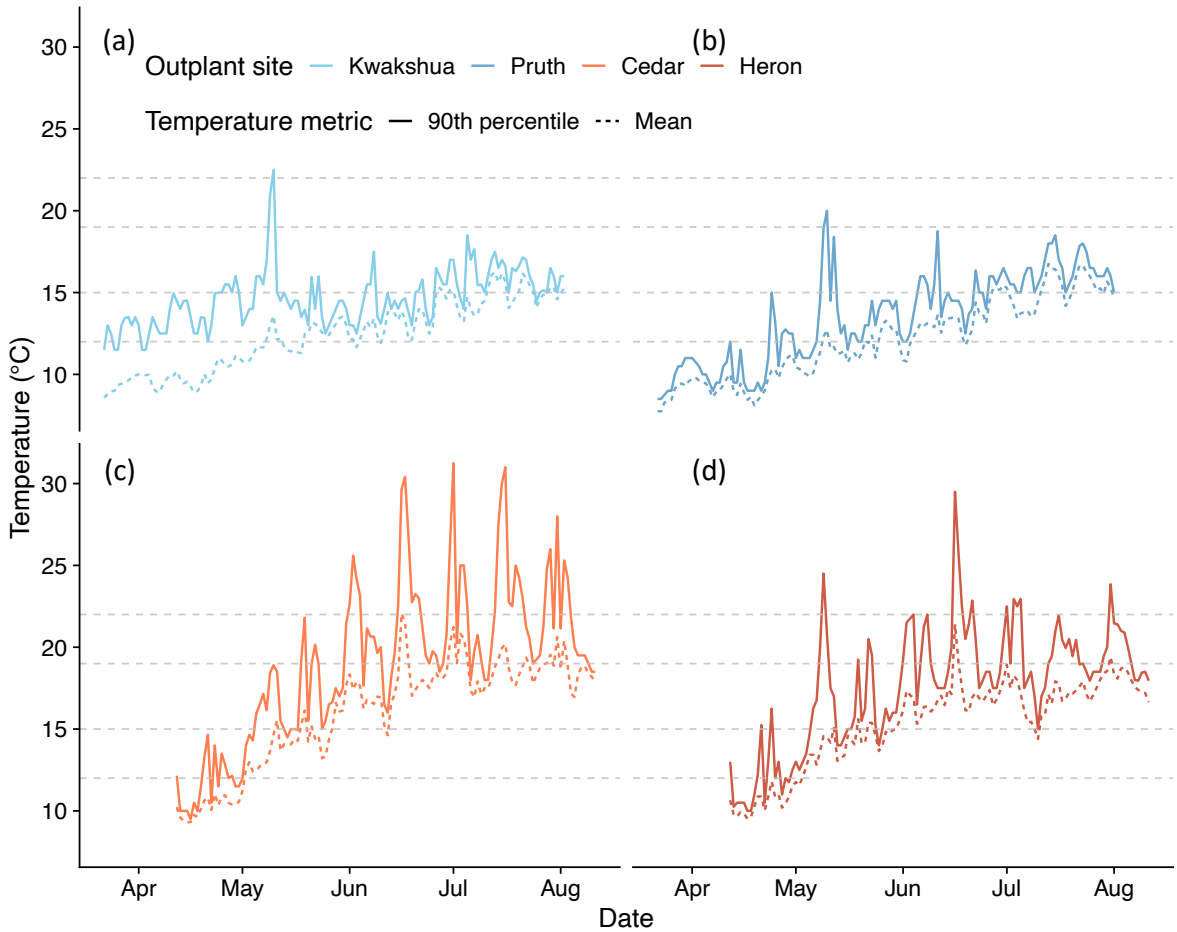

Figure 3.3. The 90th percentile (solid line) and mean (dashed line) daily substratum air and seawater temperatures experienced during the 2019 reciprocal transplant, collected by eight iButton temperature loggers installed at each site: a) and b) are Central Coast outplant sites (blue, Kwakshua and Pruth), while c) and d) are Strait of Georgia outplants sites (orange, Cedar and Heron). The highest temperatures reflect aerial exposure during low tide, while the low temperatures are likely reflective of sea surface temperatures during immersion of the dataloggers at high tide. The horizontal dashed grey lines show the four seawater temperature treatments in the mesocosm experiments (12, 15, 19, and 22°C).

3.4.2.2 Survival and growth

Survival was 21-34% lower in Strait of Georgia than Central Coast for both populations (outplant region p=0.015), with snails from the Central Coast experiencing marginally lower survival in the Strait of Georgia than the native snails (Tukey's HSD t-test, p = 0.052; Fig 3.4a, Table 3.2). The directional effect of transplanting to a foreign region was different for each source region across all growth metrics (i.e., all interactions between source and outplant region were significant; Fig 3.4b-e, Table 3.2). For tissue weight, shell weight, and shell length, snails from the Central Coast grew at comparable rates when outplanted in the Strait of Georgia relative to their home sites, whereas snails from the Strait of Georgia grew consistently more tissue and shell when outplanted on the Central Coast than in their native sites (Fig 3.4bcd, Table 3.2). Snails from both regions grew thicker shells in their foreign region relative to their native region (Fig 3.4e, Table 3.2). Again, initial size covariates had a significant effect on all growth metrics, with smaller snails growing faster than larger ones (Table 3.2, Appendix B: Fig B.6, B.7).

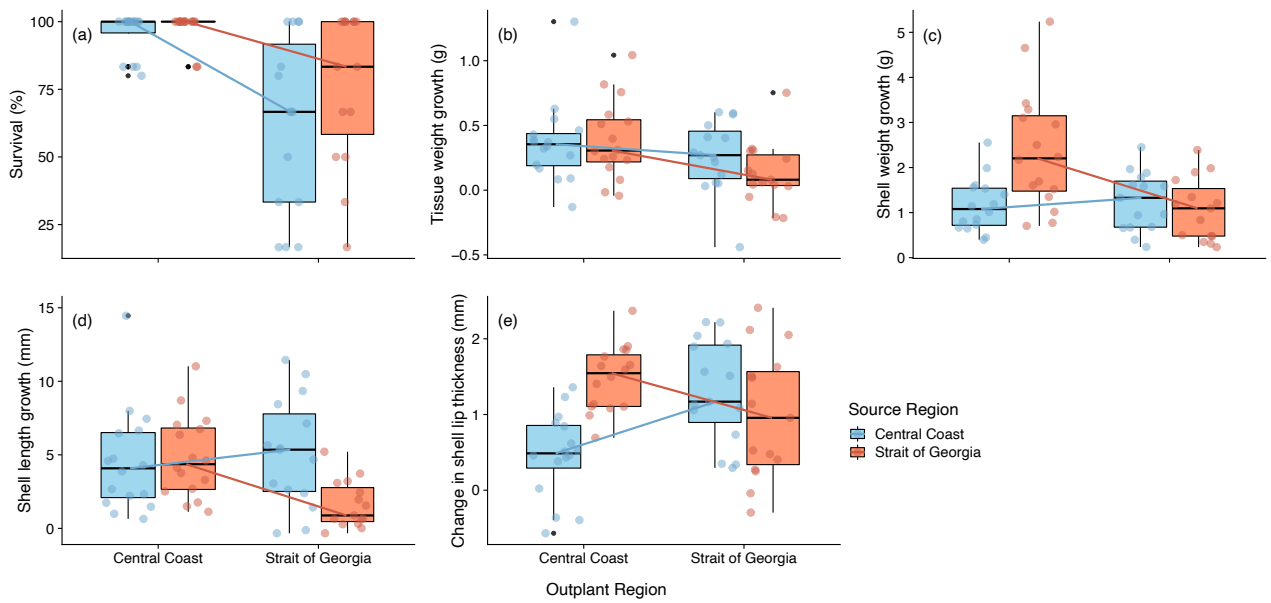

Figure 3.4. Survival and growth data from the reciprocal transplant (March – August 2019). Lines track the change in median survival and growth of source regions between outplant regions to visualize interactions. The dots are average survival and growth for each source population within a given cage and the boxplots visualize the survival and growth within source regions across outplant regions (i.e., boxplots pool populations that correspond with each source region).

Table 3.2. Effects of outplant region, source region, and their interaction on the growth and survival of *N. lamellosa* during the 2019 reciprocal transplant experiment.

Parameter	Source	X^2	*df*	*p*
Survival	**Outplant region**	7.318	1	**0.006**
	Source region	0.103	1	0.749
	Outplant region * Source region	1.447	1	0.229
Tissue weight growth	Outplant region	1.237	1	0.266
	Source region	0.177	1	0.674
	Outplant region * Source region	4.317	1	**0.038**
	Initial tissue weight	93.16	1	**<0.001**
Shell weight growth	Outplant region	0.082	1	0.092
	Source region	26.87	1	<0.001
	Outplant region * Source region	35.07	1	**<0.001**
	Initial shell weight	2.285	1	0.131
Shell length growth	Outplant region	0.054	1	0.817
	Source region	0.086	1	0.769
	Outplant region * Source region	26.97	1	**<0.001**
	Initial length	78.12	1	**<0.001**
Change in shell lip thickness	Outplant region	0.801	1	0.371
	Source region	12.30	1	**<0.001**
	Outplant region * Source region	9.955	1	**0.002**
	Initial thickness	186.1	1	**<0.001**

3.5 Discussion

This study provides support for predictions that populations from a warm region in the centre of *N. lamellosa*'s range are vulnerable to environmental warming and that the Strait of Georgia is an area of high climate risk. Despite showing evidence for higher thermal tolerance (i.e., survival) than Central Coast snails in the lab and field experiments, Strait of Georgia snails grew and ate at negligible levels and experienced stark survival reductions in their potential future seawater temperature and their native outplant region. This alignment between laboratory and field results suggests that Strait of Georgia snails are stressed in their current environment and vulnerable to future warming. In contrast, populations from the cooler Central Coast grew and survived at high rates across both contemporary and potential future seawater temperatures predicted for their native region. Combined, these results indicate that populations in the middle of a species' range can show both high and low vulnerability to climate change, even across

small changes in latitude. This emphasizes the importance of examining climate change vulnerability throughout a species' range rather than just at the range limits to better understand the risk of extirpation.

Populations from the warmer region (Strait of Georgia) experienced higher survival than populations from the cooler region (Central Coast) in the hottest conditions in both the lab and field experiments, suggesting the evolution of higher thermal tolerance. The marginally higher survival in the Strait of Georgia populations when transplanted in their native sites is also a signal for local adaptation (i.e., home-field advantage, Hereford et al., 2009; Kawecki and Ebert, 2004). Intraspecific variability in acute thermal tolerance has also been demonstrated in populations of *N. lamellosa* from the east (Strait of Georgia) and west coasts of Vancouver Island, with those from the warmer east coast showing higher aerial thermal tolerance (i.e., emersion during low tide) but comparable aquatic thermal tolerance (i.e., immersion during high tide, Iwabuchi and Gosselin, 2020). In combination with my results, this suggests that populations of *N. lamellosa* may evolve distinct thermal performances when long term seawater temperatures and acute aerial temperatures differ. Whether it is possible for Strait of Georgia populations of *N. lamellosa* to evolve even higher upper tolerances in response to ongoing warming is uncertain and depends on their current proximity to key physiological thresholds and alignment between rates of genetic adaptation and environmental warming.

The mismatch between growth and feeding performance across temperatures in the lab suggests that a thermal optimum could be surpassed between 15-19°C. Snails from both regions grew significantly less tissue in the 19°C treatment despite eating similar amounts across the 12, 15 and 19°C treatments. Consumed energy could be directed toward mounting a thermal stress response (e.g., production of heat-shock proteins) or repairing existing tissue rather than growing new tissue. Over time, if periods of thermal stress are frequent and long, energetic trade-offs associated with thermal stress-responses may compromise organismal growth, reproductive capacity, and survival, with consequences for population fitness (Kroeker et al., 2020b; Sokolova, 2013). *N. lamellosa* in the Strait of Georgia already experience stressful sea surface temperatures (SST) more frequently than on the Central Coast: during summer months (May – August) between 2012-2020, daily SST exceeded 15°C 75% of days in the Strait of Georgia versus 10% on the Central Coast, and exceeded 19°C 15% of days in the Strait of Georgia but never on the Central Coast (Government of Canada, 2019). Accordingly, while

populations from both regions show similar relationships between sublethal performance and temperature in the lab, contextualizing these finding in contemporary oceanographic data suggests that Strait of Georgia populations experience stressful seawater temperatures that frequently exceed their thermal optima and either impair function, induce energetic trade-offs, or both.

The reduction in performance for Strait of Georgia snails but not Central Coast snails upon exposure to their respective future seawater temperatures in the lab indicates varying abilities for populations in the middle of *N. lamellosa's* range to adjust to ongoing ocean warming. Strait of Georgia populations may be further challenged in tracking local environmental changes as the rate of ocean warming is faster in this region than both the Central Coast and global average (0.42°C/decade as opposed to 0.12°C/decade on the Central Coast and 0.19°C/decade global average, Amos et al., 2015; Chandler et al., 2018). Since this region is likely one of the warmest parts of this species' range already (JPL MUR MEaSUREs Project., 2015), the rapid rate of ocean warming could mean summer seawater temperatures soon shrink or even exceed their thermal safety margins. Importantly, populations from the cooler Central Coast showed low vulnerability to future ocean warming as they grew and survived well at both current and future seawater temperatures and their seawater temperatures are unlikely to surpass sublethal or lethal thresholds within the next century. While the generalizability of our findings is restricted due to only examining two regions of this species' range, Strait of Georgia populations could have a higher risk of extirpation than populations outside this inland sea as they have less time to track ocean warming through plasticity and genetic adaptation before important physiological thresholds are surpassed (Kroeker et al., 2020a).

In addition to driving steady increases in ocean temperature, climate change exposes intertidal organisms to increased aerial temperatures and frequency of extreme temperature events (i.e., heatwaves, Harvey et al., 2021). Maximum rock (i.e., substratum) temperatures already surpass acute aerial (emersed) thermal tolerances for populations of *N. lamellosa* in the Strait of Georgia, suggesting that stressful conditions may persist throughout the tidal cycle and increase in intensity with climate change (Iwabuchi and Gosselin, 2020). Strait of Georgia intertidal invertebrates also demonstrated higher relative thermal sensitivity than elsewhere along B.C.'s coastline during the 2021 heat dome, an unprecedented extreme weather event that caused significant human and ecological mortality (Raymond et al., 2022). Intertidal invertebrate

mortality was much higher in the Salish Sea relative to the Central Coast and west coast of Vancouver Island, largely due to the coincidence of low tide with solar noon, low cloud cover, and low wave exposure within this inland sea (Raymond et al., 2022). *N. lamellosa* populations in the Strait of Georgia experienced among the highest rates of mortality among species surveyed along B.C.'s coast during and after the heat dome (Harley et al., 2023, in prep). These results underscore the potentially greater relative vulnerability of intertidal invertebrates in the Strait of Georgia, particularly *N. lamellosa*, to multiple thermal dimensions of climate change (i.e., marine and aerial warming, heatwaves). Further investigation into variable thermal exposure in the Pacific northwest could investigate projected changes in cloud and fog cover, which can reduce aerial thermal stress during low tide, and the intergenerational effects of mass mortality events in populations with restricted dispersal.

The geographic position of the Strait of Georgia in the centre of this species' range enhances the extirpation risk for these populations, since snails to the north, west, and south inhabit cooler environmental conditions and thus could be less able to colonize this region. The ecological consequences of extirpation patches in the middle of a species' range are uncertain, and the implications for meta-population connectivity and range shifts are complex and understudied in marine systems compared to terrestrial and aquatic ones (Yeager et al., 2020). Extirpation patches could create discontinuous patches of presence and absence along a species' range, with extirpation holes where environmental mosaics (e.g., tidal cycles) and varying rates of climate change (e.g., ocean warming) collide to produce regions of high stress. That said, Strait of Georgia populations could provide a source of warm-adapted genotypes to speed adaptation in surrounding cooler areas, provided they persist and can disperse to these regions.

Small thermal safety margins and areas of high stress are important predictors of population vulnerability; however, they are not always directly correlated with extirpation, as many species can behaviourally thermoregulate or move in response to high thermal stress. In fact, behavioural thermoregulation is a likely explanation for why terrestrial ectotherms often inhabit regions where environmental temperatures frequently exceed their upper thermal tolerance (Sunday et al., 2014). The demonstration of behavioural regulation is comparatively understudied in the marine realm (Pinsky et al., 2019); however, coastal and pelagic marine species, especially mobile ones, can behaviourally thermoregulate through aestivation (Marshall et al., 2015), microhabitat use (Gilman et al., 2015), and vertical migration patterns (Nay et al.,

2015). *N. ostrina,* a congener species that inhabits higher intertidal regions than *N. lamellosa*, alters its foraging behaviour to avoid high aerial thermal stress and thus reduces its overall vulnerability to aerial warming due to climate change (Hayford et al., 2015, 2021, 2018).

Despite its silver bullet appeal in alleviating thermal stress, behavioural regulation can come with trade-offs (Kroeker et al., 2020b). For example, species that seek thermal refugia or go into states of dormancy may increase their vulnerability to predation. *N. lamellosa* inhabit the mid to low intertidal range; however, during periods of high aerial thermal stress in summer months they can retreat to the upper subtidal (pers. obvs., Beaty and Harley). While this behaviour may reduce their exposure to high aerial temperatures, it increases their exposure to predatory sea stars and large crabs (e.g., *Pisaster ochraceus*, *Cancer productus*) and reduces co-occurrence with prey (intertidal barnacles and mussels) which are depleted in subtidal habitats by those same sea stars and crabs. Since the reciprocal transplant experimental design restricted mobility (i.e., cages were fixed in place), snails were unable to move to the subtidal or access microhabitats. Accordingly, concluding that the Strait of Georgia is a high thermally stressful region may be accurate; however, without incorporating the role of behavioural thermoregulation and microhabitat refugia, I may overestimate the precise vulnerability of species with limited mobility, such as *N. lamellosa*.

Focusing on chronic thermal stress can also obscure the influence of additional biotic and abiotic drivers of survival and performance. *N. lamellosa* and congeneric species can show high phenotypic plasticity in response to predator cues, with snails growing thicker shells in the presence of crab cue and higher degrees of ornamentation (frills) in response to sea star predation (Appleton and Palmer, 1988; Mavson et al., 2018). While I did not survey predator abundance during the reciprocal transplant, I qualitatively observed more crabs at the Strait of Georgia field sites than on the Central Coast. The different types of predator cues in the nearby seawater may explain some of the variation and interactions in shell growth patterns across the outplant sites and source populations, particularly shell thickness. In addition to shell growth plasticity, I observed shell colour polymorphisms across populations that aligns with polymorphism in a congener, *N. lapillus.* This species' colour polymorphism likely evolved in response to solar heating, where white morphs from warm sites heat up slower during low tide emersion, reach lower temperatures, and retain more moisture than darker morphs from cooler sites (Etter, 1988).

I found patterns of different thermal tolerances across the populations, as inferred by the survival results. However; since I tested the response of juvenile snails caught in the field for both the reciprocal transplant and mesocosm experiments, their responses to environmental change could be influenced by their thermal history from previous seasons, as well as maternal effects and transgenerational plasticity from their parent's generation (Burford MO et al., 2014; Hendry and Gonzalez, 2008; Kawecki and Ebert, 2004; Sanford and Kelly, 2010; Sanford and Worth, 2010). Thus, while these results signal local adaptation of thermal tolerance, the experimental design prevents concluding this to be an evolved genetic trait.

Thermal history and variability can also influence the shape and limits of thermal performance curves as organisms acclimatize and build tolerance to environmental stressors, such as temperature, over the course of a season (Brownlee, 2022; Sinclair et al., 2016). Because I used snails caught at the beginning of summer that had not shifted their thermal tolerance over time via acclimatization, they may have been more stressed than if I had run a similar experiment using snails caught at the end of the summer. In addition, I acknowledge that exposing organisms to stable conditions in the lab can inaccurately reflect variable field conditions and produce different results than when organisms are exposed to more realistic fluctuating temperatures in the lab (Kroeker et al., 2020b; Marshall et al., 2021). Accounting for seasonal acclimatization and exposing organisms to conditions in the lab that more accurately track environmental variability and seasonality can improve the precision of population vulnerability estimations.

Overall, *N. lamellosa* populations in the Strait of Georgia are vulnerable to ocean warming due to proximity between environmental temperatures and upper thermal performance limits (both sublethal and lethal), the higher rate of local environmental warming, and low likelihood of colonization by surrounding populations. In contrast, populations elsewhere in the middle of *N. lamellosa*'s range could persist and adapt with environmental warming. If extirpations occur within hot spots like the Strait of Georgia, a patchwork mosaic of presence and absence could form in the middle of this species' range. Predicting regions where multiple anthropogenic drivers of change concentrate (e.g., coastal or inland seas, Halpern et al., 2015) and drive overlapping extirpation mosaics for multiple species could be an important approach to identify regions where novel ecosystems may emerge. In sum, considering both environmental

conditions and phenotypic variation across a species' range can enhance understanding of geographic mosaics of climate risk.

Chapter 4: A local and Indigenous-led approach to knowledge creation transforms marine spatial planning tools and processes: a case study in the Salish Sea

4.1 Synopsis

The climate, biodiversity, and social inequity crises are driving negative changes across social-ecological systems. Centering reciprocity and equity in social processes, such as planning, can reduce further harm as people strive to manage and mitigate these crises. Marine spatial planning (MSP) is an integrated management approach to sustain and balance relationships between people and the ocean. It has evolved substantially since the early 2000s, yet emergent issues associated with MSP include: (i) being biased toward biophysical data and western scientific knowledge systems; and (ii) perpetuating inequitable and status-quo power dynamics. This chapter contributes a community-led approach to create knowledge in support of MSP that works to address both these issues. Through a partnership between Indigenous, academic, and non-profit organizations, we co-created a participatory mapping approach to characterize place-based values within a fjord in the Salish Sea (Canada and USA). I interviewed 30 knowledge holders and surveyed over 300 residents with the following research objectives: (i) map places that support social, ecological, cultural, and economic values; (ii) characterize community perceptions of value-interactions (i.e., conflict, compatibility); (iii) identify challenges and opportunities associated with decolonizing mapping and MSP processes. Communities showed strong support toward ecological values and identified places where spatial conservation opportunities can be explored that protect ecological, social, and cultural values with minimal perceived conflict. We also identified four ways that our research process advanced reconciliation (strengthen relationships among Indigenous and non-Indigenous communities and center Indigenous youth, language, and cultural values) and two outstanding challenges associated with decolonizing MSP. Finally, I outline how this community-driven approach to understand where and why people value the ocean can be replicated in other coastal communities to enhance the harmonization of MSP across governance and ecological scales and in complex urban seas. Overall, this case study contributes a local and Indigenous-led approach that centers reciprocity and equity in early MSP stages so that both ocean and community health are meaningfully protected.

4.2 Introduction

Ecosystems and human communities throughout the world are undergoing drastic shifts due to the intersecting climate, biodiversity, and social equity crises (Friel et al., 2022; IPBES, 2019). The wicked problems generated by these crises require transformative changes across social-ecological systems to protect ecological health and social equity (Buxton et al., 2021; Ostrom, 2009; Salomon et al., 2019). In the ocean, marine spatial planning (MSP) is an ecosystem-based, integrated management approach that aims to proactively reduce anthropogenic threats, protect marine ecological resilience, and sustain relationships between people and the ocean for present and future generations (Douvere, 2008; Frazão Santos et al., 2019). MSP comprises three phases that repeat: knowledge creation (i.e., pre-planning, gathering, and analyzing knowledge); knowledge interpretation (i.e., developing plans and zones to protect social, cultural, economic, and ecological objectives); and knowledge mobilization (i.e., implementing, enforcing, monitoring the plan, Ban et al., 2013a; Frazão Santos et al., 2019). While MSP has evolved substantially since the early 2000s, there is growing awareness of issues associated with the knowledge creation phase, such as a bias toward biophysical and quantitative data, perpetuation of non-participatory power dynamics, and exclusion of diverse ways of knowing (e.g., Indigenous and local knowledge systems, Buscher et al., 2021; Flannery et al., 2018; Frazão Santos et al., 2019). If not addressed, these three issues can generate conflict within communities affected by planning outcomes and hamper achieving overall MSP objectives.

Gathering social data alongside biophysical information is critical to develop holistic characterizations of social-ecological systems, understand complex and place-based relationships between people and nature, and achieve planning and conservation goals, notably successful compliance and enforcement (Ban et al., 2013b; Voyer et al., 2012). Within an MSP context, social data about the human dimensions of the ocean can include place-based values and perceptions, human relationships with places and life forms (or resources), and interactions between institutions and cultures (Bennett and Dearden, 2014). Documenting socio-cultural values is particularly important, and generally overlooked relative to ecological and economic values, given they can contribute to sense of place, inform MSP and conservation objectives, and predict conflict between user-groups (Gee et al., 2017; Masterson et al., 2017; Strickland-Munro et al., 2016). Including place-based values in MSP can enable decisions about ocean access to be consistent with community relationships to ocean spaces (Moore et al., 2017). Despite being primary contributors toward the success (or not) of marine conservation and

planning processes, social data are often excluded (i.e., a ‘missing layer’) because of perceived challenges associated with gathering and analyzing social data and limited engagement with social sciences during planning and decision-making processes (Bennett et al., 2017; Margules et al., 2020; St. Martin and Hall-Arber, 2008).

One approach to capture place-based values in a spatial format that enables comparison with biophysical data is through participatory mapping (e.g., public participation geographic information systems, PPGIS, and participatory GIS, PGIS, see Brown and Kyttä (2014) for definitions and distinctions between terms). PPGIS and PGIS describe mapping approaches where the public use GIS and mapping technologies to participate in planning and decision-making processes (Fagerholm et al., 2021; Tulloch, 2008). Since 2008, when they were identified as a missing layer in decision-making (St. Martin and Hall-Arber, 2008), place-based values have been increasingly documented using participatory mapping techniques (e.g., surveys and interviews) to support land and marine spatial planning processes throughout the world (Brown et al., 2016; Karimi et al., 2015; Klain and Chan, 2012; Moore et al., 2017; Ramirez-Gomez et al., 2016). These participatory mapping studies employ variations of a landscape values typology established by Brown (2004), sometimes combined with additional value typologies (e.g., the Millennium Ecosystem Assessment, MEA (2005), ecosystem services frameworks, (Levine and Chan, 2013), relational-instrumental-intrinsic frameworks, (Chan et al., 2016)).

Participatory mapping can improve data inclusivity and strengthen community trust and inclusion in planning processes; however, there are inherent limitations associated with translating social data into maps (Brown and Kyttä, 2018). Traditional MSP decision-support tools (e.g., interactive GIS maps) enable visualizing how data layers (e.g., place-based values) overlap in space but do not describe changes through time or interactions between data layers (i.e., conflicts and compatibilities). Decision-makers often rely upon quantitative analyses (e.g., Marxan analysis, cumulative impact and conflict potential scores, machine learning) to identify areas of potential conflict based on the number and type of data layers that overlap in space (Ban et al., 2013a; Halpern et al., 2008; Moore et al., 2017; Stock et al., 2018). These quantitative approaches are appealing for large-scale MSP processes due to their standardization and replicability through time and space; however, they frequently involve technical experts making assumptions about data layer interactions that may contradict local

knowledge and be inconsistent or inaccurate within socio-cultural contexts (Halpern and Fujita, 2013; Raymond et al., 2010). For example, assuming that tourism is 'largely incompatible' with Indigenous cultural and biodiversity values or that human activities drive negative impacts to ecosystems when they overlap in space can obscure nuanced interactions between people and nature that vary across social-ecological systems (Halpern et al., 2015; Moore et al., 2017). Complementing quantitative analyses with qualitative approaches that explore relationships between people with each other and the water can reveal complex value interactions that enhance interpretations of spatial social data.

Inherent to meaningful participatory mapping and MSP is the empowerment of community members who are directly affected by planning outcomes and under-represented or marginalized in decision-making (Brown and Kyttä, 2014). Yet, the extent to which MSP knowledge creation, interpretation, and mobilization processes improve equity and re-distribute power in practice is contested (Flannery et al., 2016; Woodhouse et al., 2022). MSP can undermine its objectives when marginalized communities are not meaningfully engaged in setting objectives, contributing knowledge, and implementing plans. Mismatches between MSP goals and realized impacts have been particularly common when top-down MSP processes maintain status-quo stakeholder engagement (e.g., Northeast Ocean Planning Initiative, Flannery et al., 2018).

MSP and conservation processes can also perpetuate colonial systems of oppression when they fail to acknowledge and uphold Indigenous rights (Ban and Frid, 2018; Bennett et al., 2015). Maps have long served as a primary tool of colonization through supporting the appropriation of land, water, and relations from Indigenous rightsholders and the erasure of Indigenous knowledge systems and languages (Rose-Redwood et al., 2020). Indigenous knowledge refers to the understandings, skills, and philosophies developed by societies with long histories of interactions with their surroundings (IPCC, 2018). It is distinct from local knowledge, which refers to the understandings and skills developed by people specific to the place they live (IPCC, 2018). Despite the colonial history of many mapping processes, myriad Indigenous communities use maps to assert their Indigenous rights and title and document their knowledge about important places and life within their territories (Artelle et al., 2021; Buscher et al., 2021; Diggon et al., 2020; Kitikmeot Inuit Association, 2015; Polfus et al., 2016). Acknowledging the colonial power dynamics associated with maps and co-creating MSP

projects in partnership with Indigenous communities can support the implementation of equitable MSP and conservation processes (Buxton et al., 2021).

Co-creating projects across Indigenous and non-Indigenous partners requires a foundation of trust, consent, and mutual respect – core relational components that colonialism has eroded throughout the world (Whyte, 2020). In Canada, the term reconciliation references the need to heal relationships between Indigenous and non-Indigenous peoples that have been fractured and eroded by centuries of colonialism (Wong et al., 2020). Reconciliation is increasingly touted as a guiding principle for Canadian policy-development, governance, and management plans, especially following the publication of 94 calls-to-action to advance reconciliation (TRC, 2015). Yet, the gap between referencing and practicing reconciliation remains wide and seemingly challenging to narrow across many dimensions of Canadian society (White and Castleden, 2022; Wong et al., 2020). Realizing reconciliation through MSP will look different in each Indigenous community's territory due to the unique relationships each community has with land, water, and settler institutions. In British Columbia (B.C.), Canada's western-most province where many Indigenous groups (First Nations) never entered into treaties with the Canadian government, several MSP initiatives have upheld Indigenous rights and governance systems and been co-led by First Nations, provincial, and federal governments (e.g., Marine Planning Partnership on B.C.'s central and north coasts, Diggon et al., 2021; Nowlan, 2016). These initiatives provide guidance to regions elsewhere in the province (e.g., along the south coast where government-led MSP is in an earlier stage), and around the world to advance co-governance and co-management of equitable and decolonial MSP (Ban and Frid, 2018).

Here, I address persistent limitations of the knowledge creation phase of participatory MSP (i.e., the 'missing layer', failure to account for data interactions, and exclusion of local and Indigenous knowledge) by employing a co-created community-based participatory mapping approach that combines both quantitative and qualitative research techniques. Through a partnership with Indigenous, academic, and non-profit organizations in a near-urban Canadian Pacific fjord, I conducted surveys and semi-structured interviews to answer the following questions: 1) how do different community groups value water; 2) how do place-based aquatic values interact in space and with each other; and 3) what are the challenges and opportunities associated with decolonizing participatory mapping and MSP processes? Questions one and two seek largely to produce insights that directly apply to MSP in Átl'ka7tsem (i.e., place-based and problem-

focused social science research), while results from question three and the overall methodological approach contribute more broadly toward theoretical paradigms of participatory mapping and MSP (Bennett et al., 2022).

4.3 Methods

4.3.1 Átl'ka7tsem/Howe Sound context and community-based approach

This research took place in Átl'ka7tsem/Howe Sound (hereafter Átl'ka7tsem), a fjord within the Skwxwú7mesh Úxwumixw (Squamish Nation)'s ancestral territory in the southwest corner of B.C. (Fig 4.1, see Appendix C: C.1 for more information about the region, people, and pronunciation guide on the Skwxwú7mesh language). Átl'ka7tsem is one of three place names for the ocean within Skwxwú7mesh territory and references the journey by canoe from the head of the fjord in Squamish out toward the Salish Sea. The Salish Sea is an inland, urbanized, transboundary sea that contains the most heavily impacted bodies of water along B.C.'s coast (Ban et al., 2010) and extends across British Columbia, Canada and Washington State, USA. Átl'ka7tsem is home to approximately 50,000 residents, of which approximately 4,000 (i.e., 8%) are Skwxwú7mesh Úxwumixw members, and adjacent to Metro Vancouver (population 2.6 million), the third largest urban centre in Canada and third largest port in North America (Port of Vancouver, 2022; UNESCO, 2021). Given its proximity to urban environments, Átl'ka7tsem's social and ecological health is significantly impacted by human activities, including development, industry, tourism, and recreation (Bodtker, 2017; Miller, 2020). In 2018, the Skwxwú7mesh Úxwumixw, local governments, and regional non-profit organizations were motivated to collate information about Átl'ka7tsem in support of marine spatial planning and stewardship and developed a community-led MSP framework for the knowledge creation phase (Fig 4.2). Collaboratively, they launched a project (the Átl'ka7tsem/Howe Sound Marine Stewardship Initiative, MSI) that produced an interactive map in 2021 that visualizes over four hundred biophysical and human-use data layers about Átl'ka7tsem (MSI, 2021).

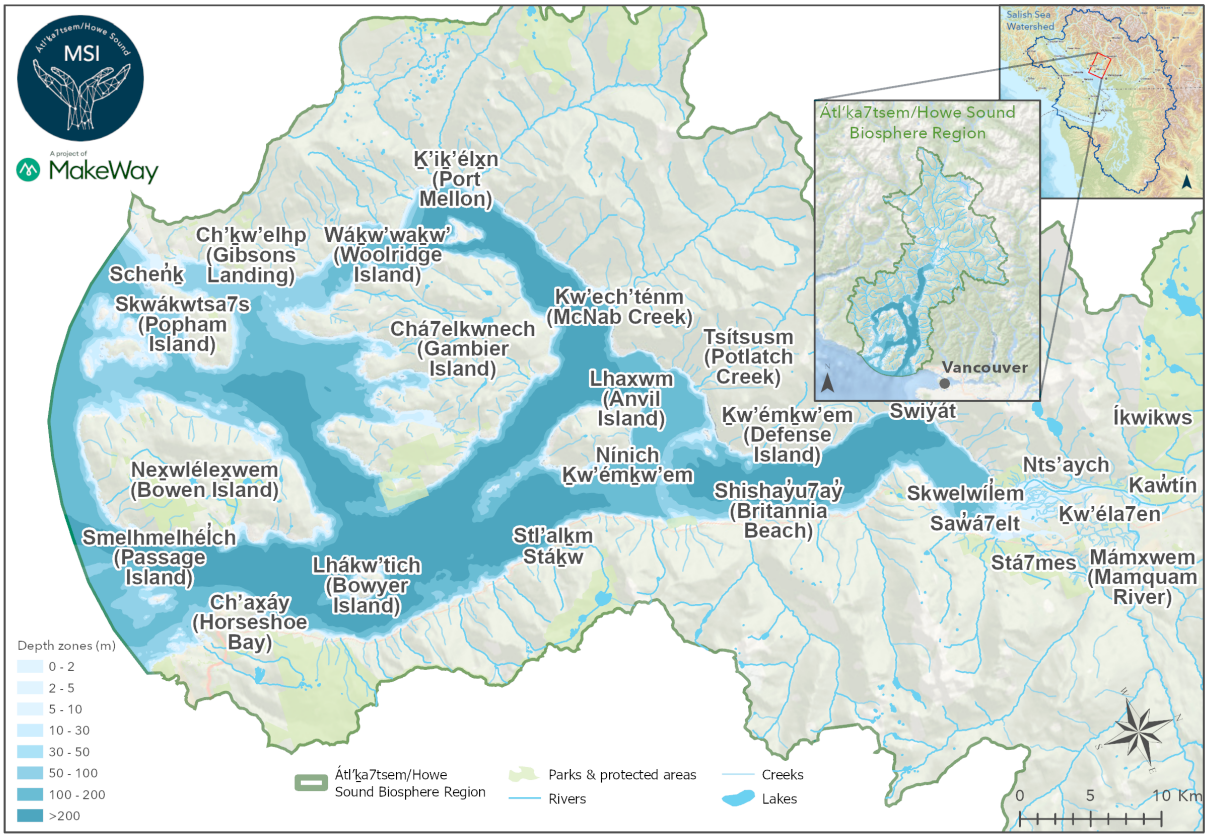

Figure 4.1. The study boundary includes small watersheds that flow into Átl'ka7tsem. The boundary was developed by the Province of B.C. for their Howe Sound Cumulative Effects Project and used by the Átl'ka7tsem/Howe Sound Marine Stewardship Initiative and Biosphere Region (FLNRORD, 2020). The marine surface is 350 km^2. Map provided by the Marine Stewardship Initiative.

The present study, an outcome of this collaborative project, contributes the 'missing' social data layers in this MSP decision-support tool. The research protocol was grounded in community-based and participatory action research principles, including community empowerment, relationality, and reciprocity (Baum, 2006). Individuals from the Skwxwú7mesh Úxwumixw, local governments, and marine sectors (tourism, conservation, forestry, research) formed a community advisory team, and researchers from the University of British Columbia, the Skwxwú7mesh Úxwumixw, and the MSI formed a joint research team. Together, the community advisory and research teams co-created the study's research questions, objectives, and methods (Fig 4.2, see Appendix C: M.2 for case study details of each stage). I secured ethics approval for this project from the Skwxwú7mesh Úxwumixw's elected council and the University of British Columbia's behavioural research ethics board (H20-01674). All research was

conducted according to the First Nations Principles of OCAP (www.fnigc.ca/ocap-training/). Since this research spanned the COVID-19 pandemic, all activities were conducted virtually.

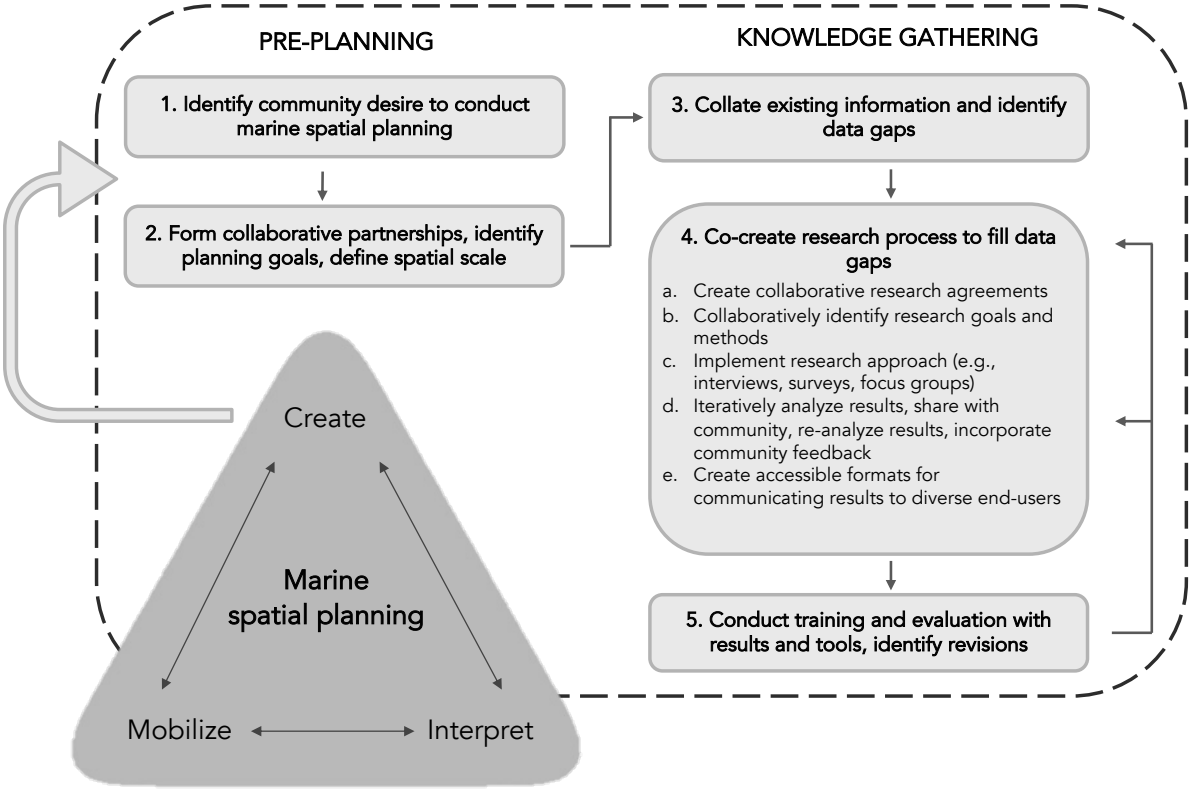

Figure 4.2. The community-led framework designed by this project to create knowledge that supports marine spatial planning. The three MSP phases (knowledge creation, interpretation, and mobilization) flow iteratively into one another. This chapter focuses on Stage 4. See Appendix C: C.2 for details of the framework's implementation in Átl'ka7tsem (i.e., Stages 1-5).

4.3.2 Survey design and recruitment

To understand how different community groups and sectors value the water that flows into and comprises Átl'ka7tsem, I used an online participatory mapping survey software (https://maptionnaire.com). Maptionnaire is flexible in representing diverse socio-cultural, ecological, and economic values, and has been applied in urban planning (García-Díez et al., 2020; Garcia-Martin et al., 2017). Following the co-design process (see Appendix C: C.3 for details), the final survey comprised seven sections. Here, I focus on a subset of questions that relate to demographics, place-based values, and participatory mapping. The values section comprised 18 value statements informed by prior PPGIS studies and refined by the research and community advisory teams to reflect regional context and Indigenous ways of knowing

(Appendix C: Table C.1, Brown et al., 2016; Brown and Raymond, 2007; Brown and Weber, 2012; Gee et al., 2017; Karimi et al., 2015; Moore et al., 2017; Van Riper and Kyle, 2014). Participants were asked to reflect on how much they value Átl'ka7tsem's water because of each statement (Appendix C: Table C.1). Value statements were randomized in each survey to reduce ordinal bias. Upon completing the demographic and values sections, participants were informed that the mapping section would take approximately 20-30 minutes and encouraged to either end the survey or complete the entire mapping section. The mapping section comprised five pages. Each page corresponded with a value category (economic, social, ecological, cultural, and special places) and included a short prompt describing the values associated with that category (Appendix C: Table C.1). Survey respondents were asked to draw up to five places associated with each value category. Upon drawing a shape (polygon), a pop-up asked participants to briefly elaborate on why that place is important to them (character limit of 250 to encourage short responses and balance the quantity of descriptions and mapped spatial data, Fagerholm et al., 2021).

I employed a snowball recruitment scheme for the survey as I aimed to engage as many participants as possible from diverse and hard to reach sectors and geographic regions (Collins, 2010; Moore et al., 2017; Onwuegbuzie and Collins, 2007). The target population was individuals who live in Átl'ka7tsem and thus have a stake in its future. I asked individuals from diverse professional sectors and governments (Indigenous, local, federal, and provincial) to recruit individuals and disseminate the survey through their networks. I also shared the survey through community and government listservs, email invitations, and social and local media networks. This non-random snowball sampling scheme aimed to enable broad public participation and leverage virtual communication networks; however, it could bias participation toward demographic and community clusters. As such, statistical results stemming from the survey are not necessarily generalizable to other study populations. The survey was live for 48 days (April 28-June 14th, 2020).

4.3.3 Interview design and recruitment

Following co-creation by community and research team members (see Appendix C: C.3 for details), the semi-structured interviews comprised four sections that enabled participants to articulate why Átl'ka7tsem is important to them, identify areas that support specific values, discuss how values interact with each other in space, and suggest ways to protect their values

and grow stewardship over time. Prior to each interview, participants were sent a table of value definitions, consent form, and map of the study area (Fig 4.1). Following community protocols, participants from the Sk̲wx̲wú7mesh Úxwumixw were also sent a shortened version of the interview questions and were interviewed by myself and my two Sk̲wx̲wú7mesh co-authors (Myia Antone and Jonathan Williams), whereas non-Sk̲wx̲wú7mesh participants were interviewed by myself alone. Interviews began with a short project description and a review of the consent form. Participants provided written consent in advance or oral consent during the interview.

All interviews were conducted using virtual video (Zoom, www.zoom.us/) and participatory mapping software (MyMaps, www.google.ca/maps/about/mymaps/). MyMaps is a free and accessible mapping software that uses Google Maps as a base and therefore was likely to be user-friendly to many participants. To the authors' knowledge, this is the first study to use MyMaps in support of MSP. One week in advance of each interview, participants were sent a private map link and tutorial video that described how to draw shapes on the map. During the interview, participants opened their MyMaps link, shared their screen through Zoom, and were prompted to identify and describe places that were important to them based on the values table (Appendix C: Table C.1).

I aimed to engage balanced interview participation across marine professional sectors, regional geography, age, and gender, and sought participants who aligned with the following inclusion criteria: 1) had multiple years of experience working with, living next to, or interacting with the marine environment in a professional or community leadership role; and 2) had a strong livelihood, social, and/or cultural connection to Átl'k̲a7tsem's water. The target sample size was 35 participants, reflecting the need to balance data quality and theoretical saturation with researcher capacity (Onwuegbuzie and Collins, 2007). To select and recruit interview participants, I conducted a stratified purposive (i.e., non-random) sampling scheme (Collins, 2010). I provided community advisory team members with a list of marine professional sectors, based upon those used in Yumagulova (2020), and asked them to identify individuals from various sectors who aligned with the two inclusion criteria. Next, I purposively selected interview participants from each sector who were commonly recommended by community advisory team members. Finally, I reached out to these individuals through email to invite them to participate in the interviews. Interviews were recorded in Zoom. One participant did not have computer

access; thus, I conducted this interview over the phone, typed notes, and did not include a participatory mapping section. Interview recordings were transcribed in Trint (https://trint.com/).

4.3.4 Non-spatial data analysis

To understand who participated in the survey and how they valued Átl'ka7tsem, I created descriptive tables that summarize demographics and agreement toward value statements. To understand general patterns of agreement within value categories (i.e., ecological, social, cultural, economic), I calculated composite scores that averaged value statement scores associated with each value category (e.g., biodiversity, conservation, aesthetic, and intrinsic were collapsed into the ecological category score). Calculating composite scores required complete responses across all value statements within each category (i.e., no NA responses). To avoid discarding survey responses that were missing less than 50% of responses within each composite metric, I conducted an NA correction using the 'mice' package (van Buuren and Groothuis-Oudshoorn, 2022). This package uses a model to predict and impute replacement values for multivariate missing data (Bennett et al., 2019b). Upon imputing missing data, I tested for internal coherence across the values within each category using Cronbach's alpha. If alpha values surpassed the threshold (0.7), I calculated composite scores by averaging scores across the values associated with each value category. Finally, to understand how community groups value water differently, I tested the univariate effects of age, sector, and gender on the composite and individual value scores. The community advisory team identified age, gender, and sector as the most important demographic traits to analyze. I used Kruskal-Wallis tests as the data were ordinal and included more than two categories. To ensure sufficient statistical power, I collapsed sectors with fewer than five responses into other sector categories, which resulted in clustering the arts, cultural heritage, and media categories and grouping all government respondents into one category. All analyses were conducted in R, version 4.1.2.

To characterize interactions among place-based values, interview transcripts were coded in NVivo version 1.3.2 according to theory-generated categories for place-based values (Brown, 2004; Karimi et al., 2015; Ryan and Bernard, 2003; Saldaña, 2014). Upon initial coding, the place-based value datasets were reviewed to identify value interactions (i.e., conflicts and compatibilities).

4.3.5 Spatial data analysis

Upon downloading the survey shapefiles and polygon pop-up descriptions from Maptionnaire, I coded the pop-up content according to the sixteen values used in both the survey and interviews (Appendix C: Table C.1). If survey respondents left polygon pop-ups blank, those polygons were grouped within the associated value category (e.g., ecology, cultural). If participants referenced multiple values within their description of a given polygon, I assigned up to three values to that polygon and copied the polygons accordingly. For example, if a respondent drew a polygon and described the area as being an especially beautiful place to boat, the polygon was duplicated: one polygon was assigned to recreation and the other to aesthetic. I uploaded all shapefiles and metadata into ArcGIS Pro (version 10.8).

I cleaned interview maps by labelling each polygon with the value that corresponded with participant descriptions. As with the survey, polygons that applied to multiple values were copied and assigned their respective values. I added additional polygons around places that participants explicitly described and spatially referenced on their screen but did not draw (e.g., specific beaches, camps, shorelines, whole region). I included these polygons, despite not being directly drawn by participants, as I assumed the technological effort required to draw polygons on the computer impacted the number of polygons participants could draw while sustaining conversation. This could be particularly true for participants with less technological familiarity. Cleaned shapefiles were downloaded from MyMaps and uploaded into ArcGIS Pro.

To visualize the spatial distribution of values, we created hotspot maps that visualize the density surface of mapped attributes (Brown et al., 2016; Fagerholm et al., 2021; Moore et al., 2017). Spatial data from both the interviews and survey were merged and clipped according to the study area boundary (Fig 4.1). We used the *Count Overlapping Features* tool to count overlapping polygons for each value and value category from the merged file. Hotspot maps symbolized five quantiles of overlapping polygon counts with different colours for each value category. Maps were validated through: 1) comparison with GIS data in the MSI's interactive map; 2) evaluation from the community advisory team; 3) evaluation from Sk̲wx̲wú7mesh Úxwumixw community members and interview participants. The purpose of these validation approaches was to identify misalignment between values and the geographic space and ensure reciprocal community engagement throughout the data collection, analysis, and interpretation processes (Fig 4.2, Ban et al., 2008; Fagerholm et al., 2021).

To understand the relationship between professional sector, age, and gender with the type of value mapped, I conducted a correspondence analysis following methods outlined in Brown et al (2016). I created a table of whether individuals mapped certain values or not (yes/no) - a categorical approach that controls for the bias of individuals who drew multiple polygons associated with a given value. Next, I conducted a correspondence analysis in R using the '*FactoMineR*' package to visualize the relationship between demographic variables with the mapped values.

4.3.6 Community evaluation and data sharing

Upon completing the preliminary analyses, I facilitated community meetings to share results with and gather feedback and revisions from the community advisory team and Sk̲wx̲wú7mesh Úxwumixw community (Ban et al., 2008, 2009). Following the incorporation of community feedback, I uploaded the spatial data into the MSI's interactive map and created narrative reports and story maps that unpack the spatial and non-spatial data from the interviews and surveys for six spatial units within Átl'k̲a7tsem. The narrative report and story-map structures were co-designed with the community advisory team to ensure the structure included the level of detail required to serve local MSP needs and the content was easy to access and interpret by diverse planning and community groups.

4.4 Results

4.4.1 Survey and interview sample

Of the 331 participants who completed the survey, the most common professional sector was 'retired' (17.4%), followed by community (14.5%) and government (13.5%), with the remainder of participants spread relatively evenly across the other sectors (Appendix C: Table C.2). The age of participants was skewed toward older categories: 37.9% identified as older than 60 and 27.4% between 46-60 years old. Majority participants were white (90.0%), and participation was relatively balanced between men (50.9%) and women (46.8%), while non-binary people comprised 2.2% (Appendix C: Table C.2). A quarter of survey participants reside or work in Squamish, followed by Bowen, the whole region, and Gambier (13.5, 9.4 and 8.8% respectively, Appendix C: Table C.2). I conducted 30 interviews with representation from 13 professional sectors and multiple communities throughout the region. Two-thirds of participants were men

and one-third were women, and most participants were middle-aged or older. Five participants (16%) identified as Indigenous, with four being from the Sk̲wx̲wú7mesh Úxwumixw.

4.4.2 Values

4.4.2.1 Value category comparisons

Survey respondents perceived ecological values as the most important values that Átl'k̲a7tsem supports, followed generally by social, cultural, and economic (Fig 4.3, 4.4; Appendix C: Table C.1). Upon summing respondent agreement and strong agreement toward the values that Átl'k̲a7tsem supports, biodiversity scored the highest, followed by aesthetic and therapeutic (Fig 4.3; Appendix C: Table C.1). Development and natural resources received the least support, with majority respondents disagreeing that they value Átl'k̲a7tsem because it supports these two statements (Fig 4.3; Appendix C: Table C.1). This trend in value category scores was mirrored in the composite scores across the three value categories where Cronbach alpha scores exceeded the 0.7 threshold: ecological composite scores were the highest (i.e., most support) followed by social and economic ($p < 0.001$, $df = 2$; Fig 4.4, Table 4.1). The Cronbach alpha score was below the 0.7 threshold for the cultural composite metric, thus I did not collapse the two metrics into one composite score. Average agreement that Átl'k̲a7tsem supports Indigenous cultural values was higher than non-Indigenous cultural values, the latter of which had the greatest variance across composite and average scores (Fig 4.4, Table 4.1). In the interviews, the most frequently discussed values were biodiversity/conservation (n = 276 references) and recreation (n = 262), while the least discussed was therapeutic (n = 20, Appendix C: Table C.3).

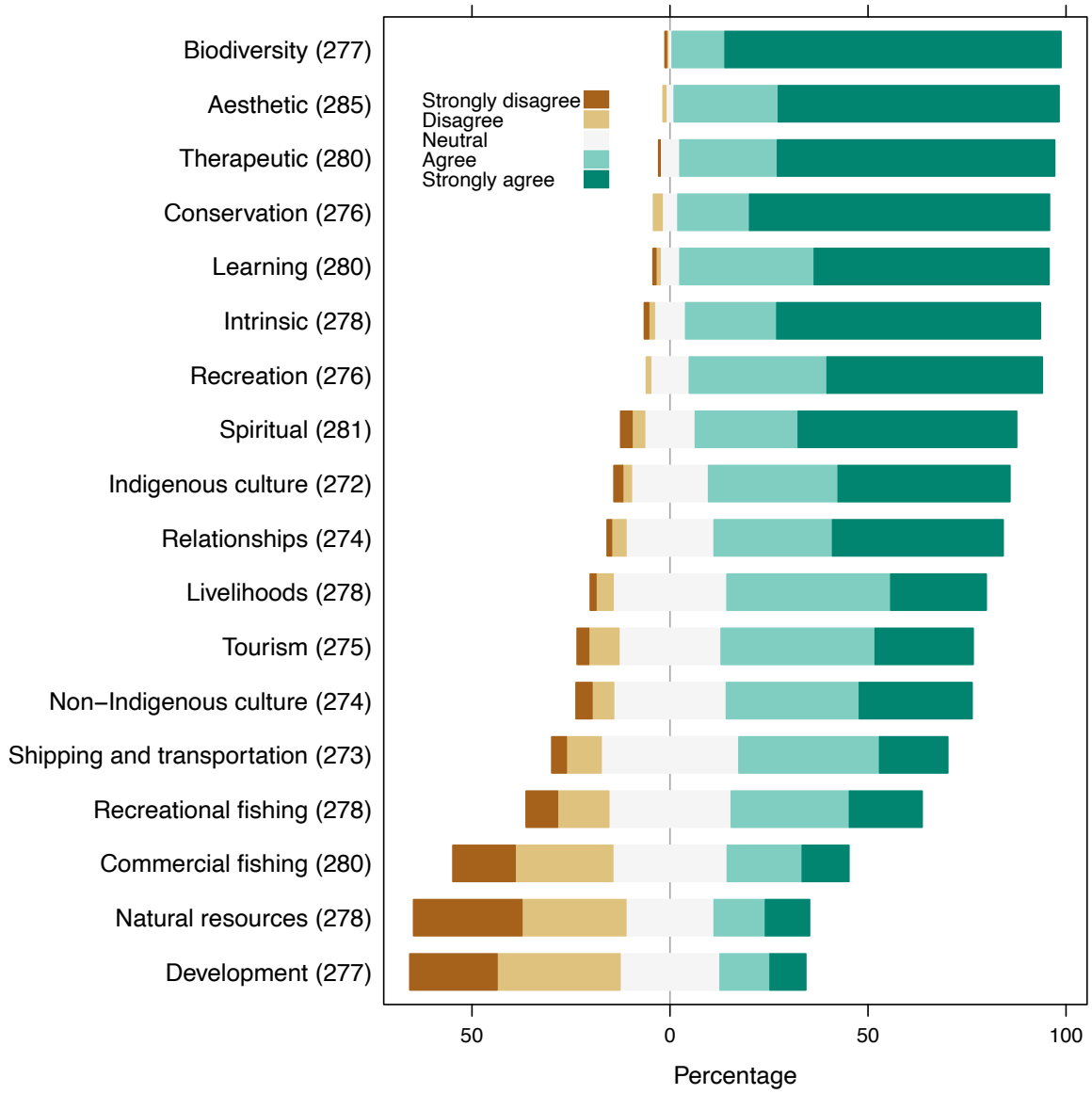

Figure 4.3. Level of agreement toward value statements that survey respondents perceived Átl'ka7tsem supports (see Appendix C: Table C.1 for full value statements). Value statements are arranged by the sum of agree and strongly agree. Sample sizes are provided in parentheses next to each value statement.

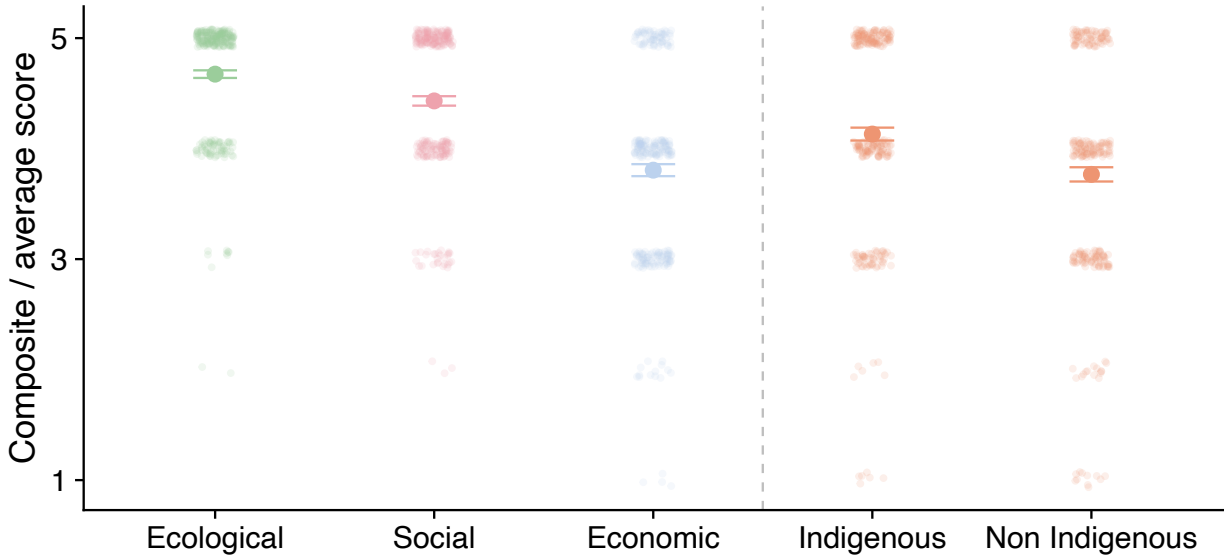

Figure 4.4. Mean composite scores for ecological, social, and economic value categories, and average scores across Indigenous and non-Indigenous cultural value metrics. Points (jittered vertically and horizontally) are individual survey respondents, plots show mean composite/average score ± SE. Scores: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree. Sample sizes are as follows: ecological n = 273, social n = 278, economic n = 277, Indigenous n = 266, non-Indigenous n = 266).

Table 4.1. Mean composite scores and cultural value metrics and effects of age, sector, and gender on the composite and value metric scores based on univariate Kruskal-Wallis tests. Scores: 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree.

Parameter	Mean (± SE)	Source	*df*	X^2	*p-value*
Ecological composite	4.674 (0.57)	Age	4	6.823	0.146
		Sector	10	9.543	0.482
		Gender	**2**	**15.79**	**<0.001***
Social composite	4.432 (0.71)	Age	4	0.524	0.971
		Sector	10	15.77	0.106
		Gender	2	3.055	0.217
Economic composite	3.801 (0.90)	Age	4	6.814	0.146
		Sector	**10**	**25.60**	**0.004***
		Gender	2	2.436	0.296
Indigenous cultural value	4.132 (0.95)	**Age**	**4**	**23.62**	**<0.001***
		Sector	**10**	**33.07**	**<0.001***
		Gender	**2**	**18.82**	**<0.001***
Non-Indigenous cultural value	3.767 (1.05)	Age	4	4.335	0.363
		Sector	10	4.244	0.936
		Gender	2	1.618	0.445

Upon collating the interview and survey maps, the size, distribution, and frequency of overlapping polygons varied substantially across value categories (Fig 4.5, Table 4.2, Appendix C: Fig C.1). In terms of spatial distribution, participants drew more ecological polygons that extended broadly across the region than other value categories, all value categories showed hotspots of overlapping polygons in Squamish, and each value category had additional unique hotspots (e.g., ecological values concentrated around Pam Rocks and Ramillies channel, social values around Collingwood channel, cultural values in specific regions throughout Átl'ka7tsem, economic around Horseshoe Bay and south of Chá7elkwnech/Gambier, and special around Pam Rocks and southern islands Fig 4.5; Appendix C: Fig C.1). Participants drew social values the most (n = 785 polygons), followed by ecological, economic, cultural, and special (Table 4.2). See the Appendix C: section C.4 for the relationship between demographic traits and the frequency of mapped values based on the correspondence analysis.

Table 4.2. Frequency metrics for values mapping by survey and interview participants.

Value category and value	Total polygon count	Min polygon area (m^2)	Max polygon area (km^2)	Mean polygon area (km^2)	Mean number of overlapping polygons	Range of overlapping polygons
Ecological	717	799	5047	124	73	1-130
Intrinsic, existence	81	799	989	136	10	1-20
Aesthetic, scenic, seascape	178	799	3416	141	22	1-40
Biodiversity, conservation	446	803	5047	109	40	1-80
Social	785	310	8207	97	60	1-116
Therapeutic, health	45	24480	2770	148	6	1-14
Spiritual	56	21899	858	151	8	1-15
Learning, education, research	124	2481	792	47	10	1-19
Recreation	539	310	8207	78	60	1-67
Culture	341	1440	3587	118	37	1-69
Indigenous culture	150	1440	3587	180	24	1-46
Non-Indigenous culture	174	2416	2124	52	13	1-29
Economic	643	2	5099	64	52	1-104
Development	68	157224	147	19	12	1-26
Fishing - commercial	18	2	75	13	2	1-5
Fishing - recreational	91	27910	486	33	7	1-18
Shipping and transportation	148	716	5099	84	22	1-53
Natural resources	94	276	853	25	12	1-27
Eco or nature-based tourism	206	676	2119	90	21	1-40
Special	289	799	8207	87	16	1-32

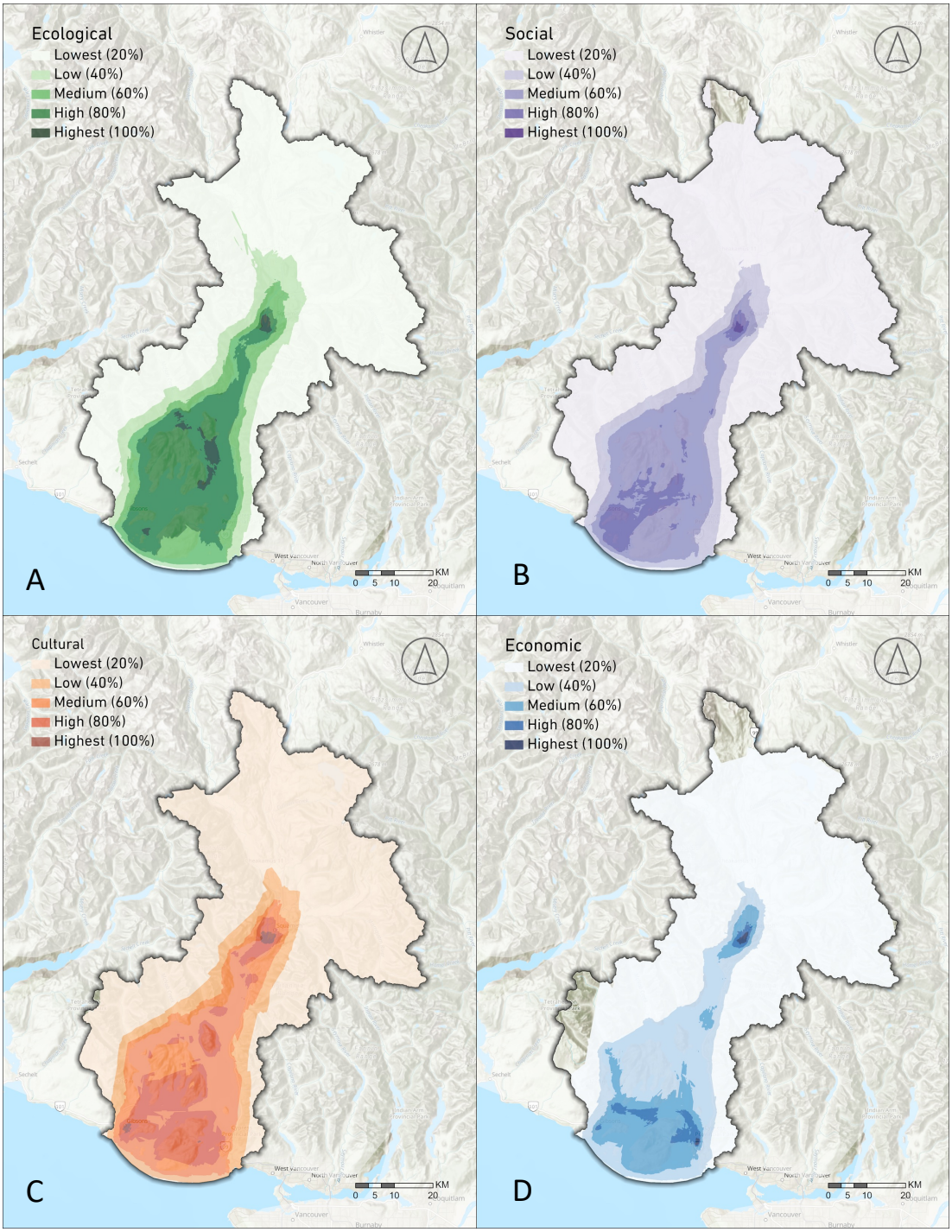

Figure 4.5. Spatial distribution and concentration of the four value categories (green is ecological, purple social, orange cultural, blue economic). The five colour breaks in each hotspot map indicate the quantiles of overlapping polygons drawn by interview (n = 29) and survey (n = 124) participants, where darker indicates more polygons and lighter areas indicate fewer. See Table 4.2 for the range of frequencies and total number of polygons drawn in each value category.

4.4.2.2 Ecological

Of the ecological values, 98.2% of survey respondents agreed or strongly agreed that they value Átl'ka7tsem because it supports biodiversity, followed closely by aesthetic, conservation, and intrinsic (Fig 4.3; Appendix C: Table C.1). Composite ecological scores varied across genders, with women scoring higher (i.e., more support toward ecological values) than men and non-binary people ($p < 0.001$; Table 4.1, Appendix C: Fig C.2; see Appendix C: C.5, for the relationship between demographic traits and individual values). Participants drew biodiversity/conservation polygons the most frequently, followed by aesthetic and intrinsic (Table 4.2). The size of polygons ordered in reverse, with intrinsic polygons drawn larger than aesthetic and biodiversity/conservation (Fig 4.6, Table 4.2). Squamish was a hotspot for aesthetic values, Squamish and Pam Rocks for biodiversity/conservation, and the water around Lhaxwm/Anvil for intrinsic; however, 80% of the overlapping polygons for aesthetic and intrinsic values covered a large extent of Átl'ka7tsem indicating slightly lower place specificity for these values than for biodiversity/conservation (Fig 4.6).

In terms of value interactions, interviewees positively associated intrinsic/existence value statements with ecological and select social values and expressed that the intrinsic value of species motivated them to engage in conservation activities: "There are [glass] sponges as big as your house, as big as your car. I mean, they're so impressive but also so delicate. You know, you really feel the sense that you want to protect them because they're so special" (Fig 4.7a, see Appendix C: Table C.4 for additional quotes). Access both increased and eroded the special value of Átl'ka7tsem (Appendix C: Table C.4).

Interviewees perceived that Átl'ka7tsem's aesthetic, scenic, and physical seascape supported values across all four categories and were negatively impacted by select economic values (Fig 4.7b). They described that the region's aesthetic beauty supported tourism and recreation, artistic and cultural practices, learning and research opportunities, and spiritual and emotional well-being. As with intrinsic values, the scenic value of places was also described as an underlying motivation for conservation (i.e., beautiful places need to be protected, Appendix C: Table C.4). Interviewees reflected upon the aesthetic value of the region as a whole and drew large polygons more than specific areas: "The whole region is special. So, this is where again, I would like everything [to be included], like all the viewscapes that you see along Howe Sound

and the Sea to Sky highway. When you're out on the water, this whole region is so special" (Fig 4.6, Appendix C: Table C.4). Natural resource extraction and development were two values referenced to negatively interact with Átl'ka7tsem's aesthetic values (Fig 4.7b).

Biodiversity and conservation values were discussed at both the whole region and place-specific scales and frequently associated with values from all four categories (Fig 4.7c). Participants acknowledged the strong interconnectivity across species and habitats throughout the region, emphasized the unique proximity of so much biodiversity to Vancouver, and described both the increase and decrease in marine life abundance over time (i.e., the decimation and partial recovery of certain marine species since contact with settler communities, Appendix C: Table C.4). Interviewees referenced strong interconnectivity across ecological and cultural values. As marine life and ecosystem health recovers, community and cultural connections to Átl'ka7tsem grow, especially for Skwxwú7mesh Úxwumixw community members: "I think [there's a connection between the health of the water and the health of our language and culture], because if the land is healing, we're healing as a people, right? The fish and sea life are overcoming a lot of barriers and obstacles now, I think our people are doing the same thing with the language. And, you know, once that all starts healing, things start coming back to our people. So, whether it's in the ocean, whether it's with us as human beings, I think we're moving in that direction. I feel like the spirit of it all is returning" (Appendix C: Table C.4).

At the place-specific scale, a loop emerged between biodiversity, natural resource extraction, conservation, and learning (Fig 4.7c). Places like the Squamish Estuary and Britannia Beach that have experienced ecological recovery following industrial degradation (e.g., forestry, fishing, mining) were perceived as critical areas to learn about the region's ecology and both destructive and restorative human behaviours. Strong emphasis was put on protecting these places for future generations to access and experience: "I think it's a past that was so incredibly destructive that [these sites] should be commemorated, not because they were great, but because we should learn from this, you know, and they should be acknowledged in a more significant way" (Appendix C: Table C.4). Interviewees expressed that Átl'ka7tsem's biodiversity supports recreation, tourism, fishing, and both non-Indigenous and Indigenous cultural values (e.g., hunting, food security, medicine, teachings, ancestral connection): "[At Tsítsusm, Potlatch creek], we saw some whales, some yéẇyews, and they hadn't been coming out very much into

the Sound at that point, so we rushed out into the Sound to watch them… it felt like a blessing that we actually got to say hello to the ancestors in our own territory" (Appendix C: Table C.4).

There were more references to conflicts between biodiversity/conservation and economic values than the other two ecological values; however, there were also nuanced discussions of the interplay between these values: "I guess, as tourism took off and became recognised as a financial incentive to have a pristine wilderness for people to visit, it became more of an incentive to protect it" (Fig 4.7c, Appendix C: Table C.4). See sections 4.3.2.3 and 4.3.2.5 for more details of negative interactions between biodiversity and socio-economic values. Interviewees also frequently referenced how they personally engaged in stewarding and connecting with nature when discussing biodiversity and conservation.

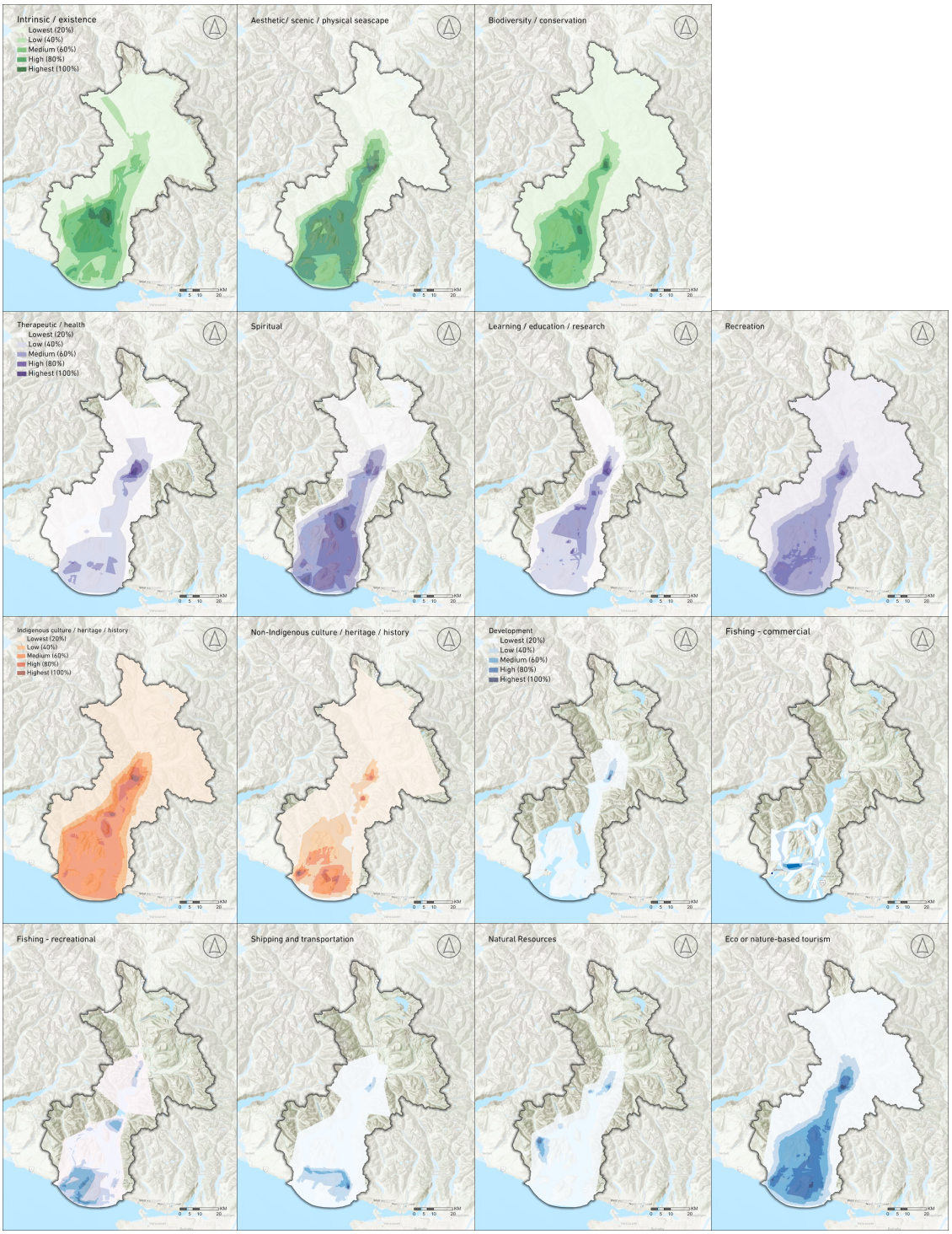

Figure 4.6. Spatial distribution and concentration of fifteen ocean-based values, where darker colours indicate more overlapping polygons drawn by interview (n = 29) and survey (n = 124) participants. Green colours correspond to the three ecological values, purple to the four social values, orange to the two cultural values, and blue to the six economic values. See Table 4.2 for the range of polygon frequencies and total number of polygons drawn for each value.

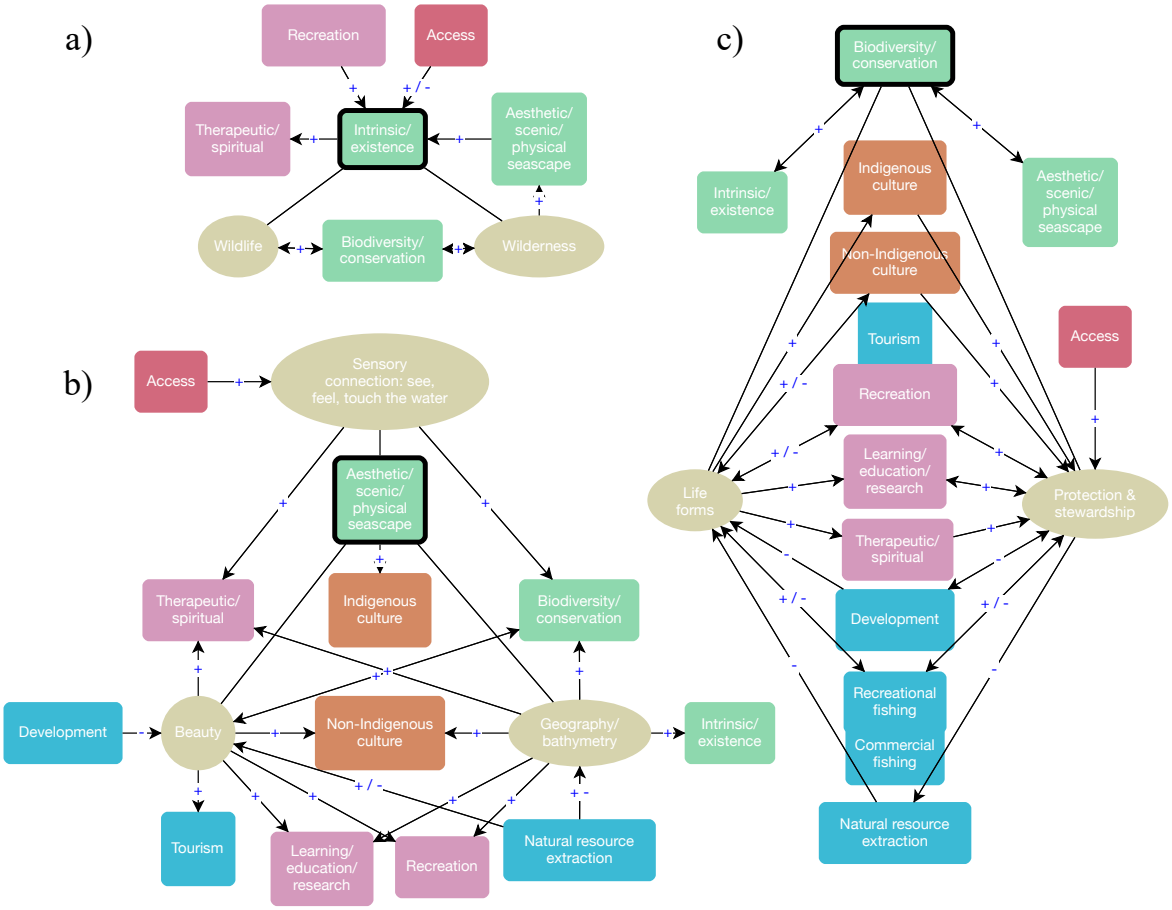

Figure 4.7. Interactions between values described in interviews (n = 30) for ecological values outlined in black: a) intrinsic / existence; b) aesthetic, scenic, physical seascape; c) biological / conservation. Box colours correspond to value category: green is ecological, blue is economic, pink is social, and orange is cultural. Tan circles depict recurring components of the focal value discussed by interviewees and are linked to the focal value by lines without arrows. Arrows with '+' signs denote positive relationships between the values in the direction indicated by the arrow (i.e., support, enable, strengthen). Arrows with '-' signs denote negative relationships between values, and those with '+ / -' indicate both positive and negative relationships were discussed.

4.4.2.3 Social

Ninety-five percent of survey respondents strongly agreed and agreed that Átl'ka7tsem supports therapeutic / health values, followed by learning education and research, recreation, spiritual, and relationships (Fig 4.3, Appendix C: Table C.1). There was strong cohesion (i.e., no significant difference) in composite social scores across gender, age, and sector (Table 4.1; Appendix C: Fig C.3). Recreation polygons were drawn five-fold more times than learning, education, and research polygons, which were drawn more than therapeutic and spiritual values

(Table 4.2). Spiritual and therapeutic values were drawn at larger spatial scales than recreation and learning polygons (Fig 4.6, Table 4.2). Learning, education, and research were the most place-specific social values and spiritual were the broadest (Fig 4.6).

Interviewees referenced the interconnected nature of therapeutic and spiritual values with recreation, Indigenous culture and language, and all three ecological values (Fig 4.8a): “the entire region for me is spiritual and therapeutic for my health… and I experience the spiritual and health benefits through the recreation that I do as well. So, it’s all connected” (Fig 4.6; Appendix C: Table C.4). Interviewees recounted transformative experiences with individual species (e.g., whales, glass sponge reefs), described accessing the water as restorative, and stated that the whole region protects and “takes care of people”: “Up at the Squamish River and on the Estuary… there’s another voice that speaks to me there… I feel I need to go there when I need to gain strength to recover” (Appendix C: Table C.4). Despite the joint reference during interviews, mapping data show distinct spatialization of therapeutic versus spiritual values, with therapeutic values localized to Squamish and the southern portion of Átl’ka7tsem, and spiritual values drawn at much larger scales throughout the middle of Átl’ka7tsem (Fig 4.6).

Places that support learning, education, and research values were positively associated with every other value category (Fig 4.8b). Site selection was quite localized: youth camps, restoration sites, and former industrial sites were frequently referenced as important areas to learn about the region’s history, culture, and biodiversity (Fig 4.6; Appendix C: Table C.4). Land-based education programs strengthen connections to Indigenous culture for both Squamish Nation members and non-Indigenous community members (Appendix C: Table C.4). Interviewees described that learning opportunities through recreation and outdoor education programs strengthen stewardship and connection to the region, and conservation values both enable and restrict access to research sites. Recreation and tourism are intertwined with learning and storytelling, and research programs directly inform commercial fisheries operations.

Recreation values were associated with all value categories in a largely positive way and the region was characterized as an “ocean playground” that supports both adventure sports and community/family gathering places (Fig 4.8c; Appendix C: Table C.4). Through accessing recreation opportunities, interviewees learn about ecological and cultural values. Recreation

was also described as a primary way people connected with the ocean and motivation for engaging in conservation: “I started scuba diving back in 2012. At the time, I wasn’t too concerned with the ocean. I knew it was there, but there wasn’t anything of great interest to me. But then I became extremely interested in it as a result of scuba diving. I became a dive instructor. And so, I’ve been very lucky to explore a lot of Howe Sound underwater and be involved with different groups who are looking to conserve these areas”. Spatial recreation hotspots include Squamish and Collingwood channel (Fig 4.6).

Access was a dominant theme associated with recreation. Geographic (e.g., steep cliffs) and economic factors (e.g., natural resource infrastructure, private development) can restrict access to marine recreation opportunities, while conservation was seen as an avenue to increase public access: “There should be more park space in Howe Sound, marine parks” (Appendix C: Table C.4). Interviewees expressed concern that the growth of recreation (and tourism) challenges the act of balancing water-access for recreation and other economic users and protection of ecological and cultural integrity: “Howe Sound is going to get more and more popular in terms of non-industrial use. Which is going to cause some conflicts for sure… So, you know, as population increases in the lower mainland, Howe Sound is gonna become a bigger, bigger playground. It can’t help not to be” (Appendix C: Table C.4).

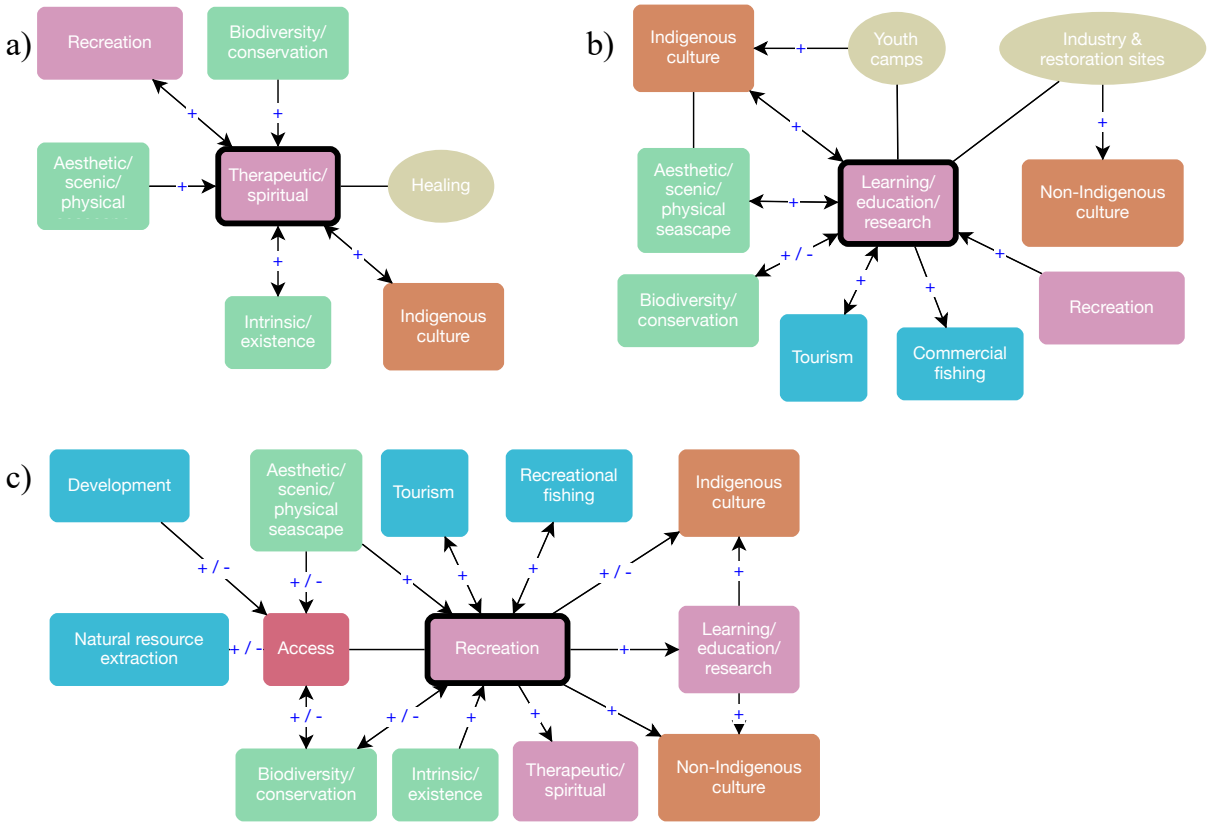

Figure 4.8. Interactions between values described in interviews (n = 30) for social values outlined in black: a) therapeutic / health & spiritual; b) learning/ education/ research; c) recreation. Box colours correspond to value category: green is ecological, blue is economic, pink is social, and orange is cultural. Tan circles depict recurring components of the focal value discussed by interviewees and are linked to the focal value by lines without arrows. Arrows with '+' signs denote positive relationships between the values in the direction indicated by the arrow (i.e., support, enable, strengthen). Arrows with '-' signs denote negative relationships between values, and those with '+ / -' indicate both positive and negative relationships were discussed.

4.4.2.4 Cultural

Seventy-six percent of survey respondents agreed and strongly agreed that Átl'ka7tsem supports Indigenous cultural values, while less agreed that the region supports non-Indigenous cultural values (Fig 4.3; Appendix C: Table C.1). Agreement toward Indigenous cultural values differed by gender, age, and sector, whereas there was no effect of these demographic variables on non-Indigenous cultural values (i.e., strong cohesion, Table 4.1; Appendix C: Fig C.4, C.5). For Indigenous values, men agreed to a lesser extent than women and non-binary people, younger participants [strongly] agreed more than older ones, and respondents from

academia, arts cultural heritage and media, NGO, and governmental sectors expressed the most agreement (Appendix C: Fig C.4, C.5). There was distinct spatialization of Indigenous and non-Indigenous values (Fig 4.6, Table 4.2). Indigenous values extended more broadly across the regions with hotspots in the upper region of Átl'ka7tsem, whereas non-Indigenous cultural hotspots were much smaller and localized to the southern portion, Britannia, and Squamish (Fig 4.6, Table 4.2).

Indigenous cultural values were positively associated with ecological and most social values, and positively and negatively associated with economic and non-Indigenous cultural values (Fig 4.9a). Interviewees explained that Indigenous cultural identities and languages are deeply rooted in the land, water, and life within the territory. Specific places were associated with stories that conveyed cultural Indigenous knowledge, teachings, protocols, and history: "They say that what created Shannon Falls is the tears from the sxw7úmten (Indian witch doctor). And it's a mark today to show how powerful [your emotions] are but also a reminder to be careful of your emotions because you could change and do things you weren't intending. That also comes from a sxw7úmpten story" (Fig 4.6; Appendix C: Table C.4).

There was a strong linkage between Indigenous culture, language and identity, and the land and water. Skwxwú7mesh Úxwumixw interviewees wanted greater access to the water and place-based learning opportunities to strengthen cultural connections that were degraded by colonization: "I felt like I had so much history around me [at Camp Fircom] because we had so much history about the island, and that's the same for everywhere in the Howe Sound. It's like the heart of the Squamish territory, right? But, when I go to some of these places, I just wish there was some way for our people to have more access to these areas for their traditional gathering and hunting and taking kids out" (Appendix C: Table C.4). Strengthening intercultural understanding and knowledge sharing across Indigenous and non-Indigenous communities was perceived as a critical way to improve stewardship, relationships, and trust (Appendix C: Table C.4). Recreation, place-based education programs, and tourism were identified as opportunities to strengthen education and learning opportunities about Indigenous culture in the region, while natural resource extraction, recreation, and tourism were viewed as potential conflicts with protecting and respecting culturally important places and the whole territory.

The interaction between non-Indigenous and Indigenous culture was generally described in negative terms with respect to the past and positive or neutral with respect to the present and future. Many non-Indigenous interviewees expressed knowledge gaps associated with Indigenous culturally important places, and, in the absence of knowledge, associated the whole region as being culturally important: “First Nations have been here for thousands of years, and they were everywhere. So anywhere that’s safe and accessible was important to them, and you’ll find that evidence everywhere” (Fig 4.6).

Non-Indigenous cultural values were more place-specific than Indigenous cultural values and concentrated around regions associated with historic natural resource extraction (e.g., Britannia copper mine), transportation / access points (e.g., Horseshoe Bay, Gibsons), and recreation areas (Fig 4.6, Fig 4.9b). As described earlier, the colonial history of natural resource exploitation and colonization followed by remediation, ecological recovery, and intercultural relationship building was identified as a critical story to share and teach throughout the region (Appendix C: Table C.4). Interviewees referenced culturally important areas that support contemporary lifestyles (e.g., a culture of getting out on the water, being in nature, away from crowds, a logging culture in certain communities) and discussed a contemporary cultural shift away from natural resource extraction and toward recreation and tourism: “The community culture of Gibsons, of living on the coast is about slowing down, it is about going to the beach… Howe Sound in general allows for that culture of getting on the water”.

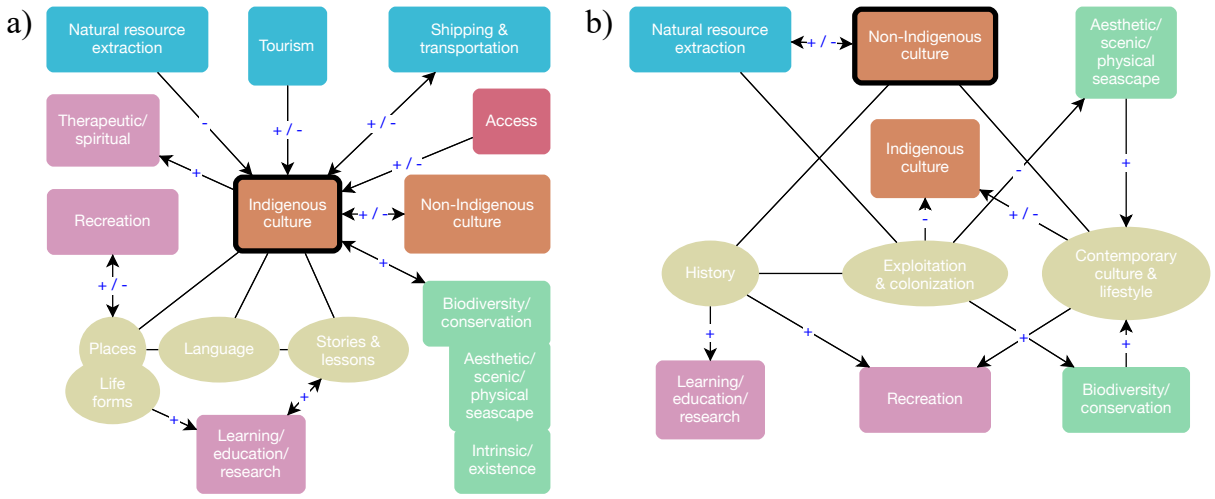

Figure 4.9. Interactions between values described in interviews (n = 30) for cultural values outlined in black: a) Indigenous culture; b) Non-Indigenous culture. Box colours correspond to value category: green is ecological, blue is economic, pink is social, and orange is cultural. Tan

circles depict recurring components of the focal value discussed by interviewees and are linked to the focal value by lines without arrows. Arrows with '+' signs denote positive relationships between the values in the direction indicated by the arrow (i.e., support, enable, strengthen). Arrows with '-' signs denote negative relationships between values, and those with '+ / -' indicate both positive and negative relationships were discussed.

4.4.2.5 Economic

The only economic values that majority survey respondents valued Átl'ka7tsem for supporting were livelihoods (66%), tourism (64%), and shipping and transportation (53%, Fig 4.3; Appendix C: Table C.1). Majority respondents disagreed or strongly disagreed that they value Átl'ka7tsem because it supports development (53%) and natural resources (54%, Fig 4.3; Appendix C: Table C.1). Economic composite scores differed significantly across sector, with the highest scores by tourism, industry, and NGO sectors and the lowest by the education and retired sectors ($p = 0.004$, Table 4.1; Appendix C: Fig C.6). Across economic values, participants drew the most tourism polygons, followed by shipping and transportation, natural resources, recreational fishing, development, and commercial fishing (Table 4.2). Each economic value was highly place-specific except tourism, where polygons were drawn at both region-wide and place-specific scales (Fig 4.6).

Development was described in a largely negative way due to conflicting with economic, social, and ecological values (i.e., restricting access to forestry or recreation sites, degrading biodiversity and aesthetic values) and driving polarization within communities throughout Átl'ka7tsem (Fig 4.10a; Appendix C: Table C.4). Most development polygons were centered around Squamish, where residential development has soared since the early 2000s (Fig 4.6; Appendix C: Table C.4). Development can both provide and restrict access to the water for various user groups and residents and was associated with enabling cultural shifts throughout the region away from industry-based livelihoods and toward remote-work and tourism-recreation economies (Appendix C: Table C.4).

Interviewees characterized Átl'ka7tsem's commercial fisheries as smaller than in the past, comprised mainly of prawn, shrimp, and crab fisheries (Fig 4.10b; Appendix C: Table C.4). Most activities were described and mapped as being based from Gibsons/Ch'kw'elhp harbour and focused south of Gambier (Fig 4.6). The only value that interviewees referenced in conflict with commercial fishing was biodiversity/conservation, as protected areas can restrict access to fishing locations and fishing can reduce the abundance of marine life. Interviewees referenced

the relative sustainability of the prawn fishery and its potential to provide local seafood to local markets (Appendix C: Table C.4). Participants also noted that research and monitoring activities contribute toward the sustainable management of commercial fisheries, and the existence of commercial fishing vessels enables the flow of resources toward commercial harbours, in turn supporting local transportation industries and maritime culture (Appendix C: Table C.4).

The economic dimensions of recreational fishing were primarily associated with ecological values, recreation, and [non-Indigenous] culture (Fig 4.10c). Places that support recreational fishing were very localized for salmon and depth-specific for crab and prawns, with an emphasis around Nexwlélexwem, Lhek̲'tínes, and K̲w'émk̲w'em (Bowen, Keats, and Defense Islands, Fig 4.6). Átl'k̲a7tsem was seen as a particularly important area for supporting salmon guide operations in the Salish Sea (Appendix C: Table C.4). As with commercial fisheries, recreational fishing interacted positively and negatively with biodiversity and conservation. Fishers reported caring about protecting ocean health, acknowledged the interdependencies of species and habitats in supporting fishing opportunities, and actively participated in conservation, research, and enforcement processes; however, conservation designations can restrict access to important sport fishing areas. Finally, interviewees discussed how access to recreational fishing can grow a culture of respect for the ocean and life within it (Appendix C: Table C.4).

Shipping and transportation routes enable multiple economic and social values and were perceived as less controversial than other economic values in Átl'k̲a7tsem (Fig 4.10d). The only value that respondents considered shipping and transportation to negatively impact was biodiversity, specifically in reference to potential LNG shipping routes. Transportation routes include those moving goods, which support natural resource and development industries, and those moving people. The latter comprise ferry, water taxi, highway routes, and marinas, described as critical access points that enable personal connection with Átl'k̲a7tsem (Appendix C: Table C.4). Most polygons are associated with the ferry route between Horseshoe Bay and Langdale (Fig 4.6).

Natural resource extraction activities discussed by interviewees fell into three categories: forestry (log harvesting, processing, and the pulp and paper mills); the proposed liquified natural gas (LNG) project; and past, present, and proposed mining (Fig 4.10e). All three categories negatively impacted ecological values; however, interviewees emphasized the need to balance

natural resource economic and ecological values and perceived that contemporary industrial operations are more sustainable and have a smaller spatial footprint than in the past. Interviewees expressed the greatest concern that log harvesting (especially old growth) and proposed LNG and gravel mine projects degrade social, ecological, and cultural values (Appendix C: Table C.4). In contrast, sites associated with log processing and the pulp and paper mills were not perceived to be as controversial and several interviewees referenced the importance of protecting existing localized industrial areas from development, tourism, and recreation pressures: “The thing is, especially around the forest industry, I don’t believe it’s going anywhere anytime soon, but it is fairly centralized. So, when you look at the area as a whole, on the water side, the marine side, it’s fairly compact. Between Howe Sound Pulp and Paper at Port Mellon and Langdale is where most of the industry is centered. And the rest is pretty much open to everybody else to recreate” (Fig 4.6, Appendix C: Table C.4). Finally, by supporting local livelihoods and providing economic revenue, natural resource extraction industries both contribute to and cause conflict within non-Indigenous and Indigenous cultural communities.

Tourism was perceived as the primary economic driver in Átl’ka7tsem, especially along the Sea-to-Sky corridor and in Squamish, marking a transition from the historic economic dependence on natural resource extraction: “It’s easy to see the [economic] transition from resource-based to tourism. I wouldn’t even say we’re in transition. I would say we have transitioned”. Places that support tourism were positively associated with myriad economic, social, and ecological values and indirectly contributed toward cultural values by increasing access to learning and education experiences (Fig 4.6, Fig 4.10f). Tourism was perceived as a critical way to build personal connections with the ocean, which can increase support for biodiversity conservation, stewardship, and management activities: “the value to me for the eco part is huge and the tourism part is huge because it is the vessel through which we gain support to preserve these areas”. Majority of Átl’ka7tsem’s tourism operations are recreation-based and depend on healthy and beautiful ecosystems; thus, activities that impact the region’s aesthetic or biodiversity values (e.g., natural resource extraction, development) can negatively impact tourism. That said, respondents worried that as tourism grows it will degrade ecological integrity and reduce access to natural resource extraction sites (Appendix C: Table C.4).

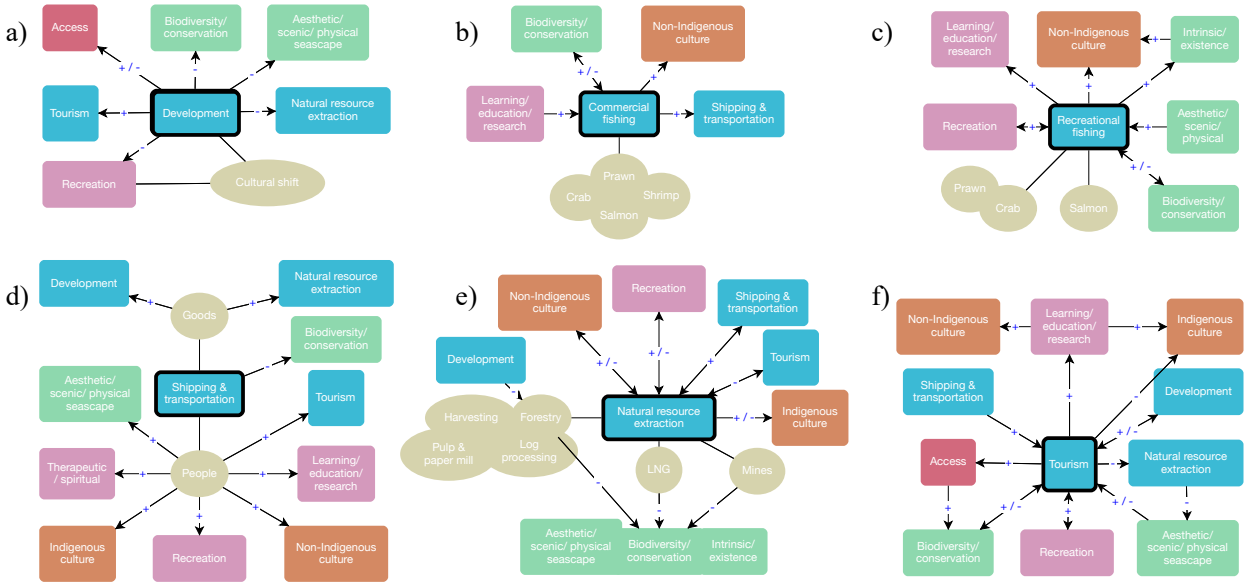

Figure 4.10. Interactions between values described in interviews (n = 30) for economic values outlined in black: a) development; b) commercial fishing; c) recreational fishing; d) shipping & transportation; e) natural resource extraction; f) tourism. Box colours correspond to value category: green is ecological, blue is economic, pink is social, and orange is cultural. Tan circles depict recurring components of the focal value discussed by interviewees and are linked to the focal value by lines without arrows. Arrows with '+' signs denote positive relationships between the values in the direction indicated by the arrow (i.e., support, enable, strengthen). Arrows with '-' signs denote negative relationships between values, and those with '+ / -' indicate both positive and negative relationships were discussed.

4.5 Discussion

This study characterized the spatial distribution and interactions between place-based values in a coastal social-ecological system using a powerful blend of quantitative and qualitative research techniques. I revealed patterns of valuation of Átl'ka7tsem across demographic groups, and an overall trend of high support toward ecological values, followed by social, Indigenous cultural, economic, and non-Indigenous cultural values. The spatial distribution of values across Átl'ka7tsem differed substantially: values associated with physical infrastructure and species and habitats were the most spatially localized, while many others spread across the whole region. Perceived interactions among values were complex and frequently multi-directional, where the positive or negative effects of values on one another depended on context. These nuanced value interactions support the expectation that Indigenous and local knowledge about value interactions can contradict underlying assumptions of some quantitative

mapping analyses that predict areas of conflict based on the spatial overlap of value data layers. Finally, relationship building, collaboration, and reciprocity were centered throughout the participatory mapping process to advance reconciliation. Below, I discuss how these results can inform MSP within Átl'ka7tsem, discuss replicating the mixed-methods and community-driven approach across complex urban seascapes, and outline four opportunities and two outstanding challenges associated with advancing equitable MSP knowledge creation.

The survey and interview findings identify several locations to consider spatial plans that can protect and minimize conflict between ocean-based ecological, social, cultural, and economic values in Átl'ka7tsem. The consistently high valuation of biodiversity and conservation across the mixed-methods suggests that protecting marine ecological health aligns with community perspectives. This result also aligns with other participatory mapping studies where biodiversity was the most frequently mapped value (e.g., Moore et al., 2017). The high concentration of ecological values in the centre of Átl'ka7tsem (surrounding Ramillies channel) indicates a potential area to consider for marine conservation. Existing marine conservation designations within this region include Halkett Bay Marine Provincial Park, two rockfish conservation areas, several glass sponge reef marine refuges, and a migratory bird sanctuary (MSI, 2021). Enhancing connectivity across these small marine conservation areas through the establishment of a larger marine conservation designation could improve biodiversity outcomes and monitoring and compliance with conservation regulations (Lancaster et al., 2015). Non-ecological values that overlap moderately (i.e., greater than 60% overlapping polygons) with this region include spiritual, learning/education/research, recreation, Indigenous cultural values, and tourism. All these values were perceived as interacting positively with ecological values except for recreation and tourism, which can both enhance public support for conservation and biodiversity and degrade ecological values if inadequately managed (Bennett, 2016). These interactions indicate that maintaining human access to a marine conservation area in Ramillies channel is critical for social buy-in and to support social and Indigenous cultural values, yet identify specific human activities (e.g., recreation and tourism) that need to be well managed to reduce conflict and ensure positive ecological outcomes.

Cultural values are essential to center alongside ecological goals in the identification of marine protected areas and Indigenous protected and conserved areas (IPCAs, Ban and Frid, 2018; Tran et al., 2020). The high concentrations of Indigenous cultural values around Ramillies

channel, Lhaxwm (Anvil Island), and K̲w'émk̲w'em (Defense Islands) indicate that a marine protected area or IPCA expanding across this region could protect both cultural and ecological values. Within this slightly extended region, values perceived to interact negatively with Indigenous culture and biodiversity were recreation, tourism, and recreational fishing, yet interactions among these values were also described in neutral and mutually beneficial terms. This indicates that a conservation area extending from Halkett Bay around Lhaxwm to K̲w'émk̲w'em and Kw'ech'ténm (McNab Creek) could protect biodiversity and Indigenous cultural values and benefit diverse social and economic values, yet must involve meaningful engagement with recreation, tourism, and fishing stakeholders and in-depth consultation across Indigenous and non-Indigenous governments and communities. These potential conservation opportunities should be interpreted with caution as findings only reflect the knowledge and perceptions shared through this limited research engagement (see below for elaboration) and do not represent decisions or opinions of rightsholders, including the Sk̲wx̲wú7mesh Úxwumixw.

This participatory mapping exercise effectively captured many, but not all, place-based values, illustrating the importance of characterizing people-place relationships using multiple techniques. Therapeutic values were the second least frequently mapped place-based value in the survey and interview mapping exercise, which could lead to the interpretation that they are not an important part of community relationships with Átl'k̲a7tsem. However, survey respondents identified that therapeutic values were the third most important value Átl'k̲a7tsem supports and interviewees described deep interconnectivity between therapeutic, ecological, and cultural values. This illustrates that some values, potentially more relational ones, might not translate as effectively into maps yet comprise integral components of human relationships with the sea (Chan et al., 2016; Klain et al., 2017). Thus, researchers and planners should strive to complement maps with non-spatial data to avoid wrongful interpretations and ensure that socio-cultural and relational objectives are meaningfully included in marine conservation and planning processes.

Values were described by interview participants as being compatible with one another more often than in conflict, which has important implications for conflict analyses that predict conflict likelihood based on spatial overlap of values. In addition, economic values were quite localized within select regions in Átl'k̲a7tsem based on species distributions (fishing) and physical infrastructure (development, natural resource extraction, shipping). The exception to this trend

was tourism, which extended throughout the region and was perceived as the principle and growing economic driver. This generally high localization indicates that, when values are perceived to conflict with one another, the spatial extent of conflict could be quite small. Interviewee recommendations to reduce conflict between economic and other value categories included protecting and enhancing (but not necessarily expanding the footprint of) existing economic infrastructure (e.g., industrial parks along Thornbrough channel, residential development in Squamish) and ensuring that increased access to Átl'ka7tsem via tourism, recreation, and development is guided by principles of stewardship, sustainability, and respect for relationships between people and place.

Moving beyond place-specific results, this mixed-methods knowledge creation approach enhances the interpretation of spatial data and can be replicated to inform MSP processes in complex urban and/or working seascapes. These regions are characterized by a high degree of human use, influence, and presence that can complicate planning and conservation processes (Bennett et al., 2022). For example, the recurring hotspots around Squamish across all ocean-based value categories indicate that establishing large single-use zones could generate conflict among rightsholder and stakeholder groups. Rather, integrated conservation and planning strategies that respect people-place relationships and are grounded in community-led stewardship and sustainable use could generate less conflict yet still achieve outcomes that benefit people and nature (Bennett et al., 2022; Chan et al., 2016; Voyer et al., 2012). This framework can support the development of smaller-scale integrated management plans by revealing demographic variation in values, disentangling perceived interactions between place-based values, and enhancing participatory engagement in local decision-making. That said, implementing qualitative, quantitative, and participatory mapping methods requires substantial investment of research and community resources (e.g., time, energy, knowledge). If replicating these full methods is not feasible given spatial and social-ecological considerations, an alternative approach could involve starting with participatory mapping surveys and focusing qualitative methods only in areas where there are many overlapping values to disentangle value interactions.

The abundance of values that spread across the whole region and interconnectivity across values lend support toward the call for harmonizing decision-making and planning process across varying governance and ecological scales (i.e., expand beyond sectoral, species-

specific, and local government administrative boundaries). Conducting planning at the scale of First Nations territories and regional ecological units, such as watershed and estuaries, is an increasingly recommended planning approach to respect Indigenous rights, values, and knowledge while navigating complex management structures (Diggon et al., 2021; Jones et al., 2021). On the central and north coasts of B.C., Indigenous-led MSP has involved implementing participatory planning methods at the scale of coastal First Nations territories and then harmonizing territorial plans at a sub-regional scale. This approach supports Indigenous rights and governance while enhancing coordinated planning capacity at larger regional scales (Diggon et al., 2021). In the Salish Sea, which spans more than 65 Tribal and First Nations territories, 45 watersheds, and two countries, implementing a similar "nested planning process" based on territorial boundaries and watersheds would be extremely complex and require substantial flexibility during the plan coordination and harmonizing phase (Sobocinski, 2021). Yet, the growing emergence of local and Indigenous-driven MSP projects (e.g., this project, those led by the Tsleil-Waututh Nation (Brownlee et al., 2020; Tsleil-Waututh, 2017), Pacific Salmon Foundation (Skinner, 2020), and Snohomish and Stillaguamish districts (Mauger et al., 2018)) justifies strong consideration of a coordinated and nested planning approach by Indigenous and federal governments on both sides of the international border. Weaving together nodes of local and Indigenous-led planning can strengthen relationships and awareness required for MSP implementation activities (e.g., monitoring and compliance), enhance collaborative and holistic planning across complex seascapes, and promote just ocean planning that respectfully includes local and Indigenous knowledge (Bennett, 2018; Diggon et al., 2020; Wen et al., 2022).

This study implemented four approaches to decolonize both the process and content of participatory mapping that contribute toward the MSP reconciliation journey yet should be built upon with care to avoid perpetuating the notion of pan-Indigeneity (i.e., there is no cookie-cutter approach to reconciliation, Von Der Porten, 2012). First, we centered relationality and ensured that Indigenous and non-Indigenous team members co-led the research process from start to finish. We also upheld Indigenous rights and strengthened consent by co-developing a research agreement between UBC and the Sk̲wx̲wú7mesh Úxwumixw's council and implementing the First Nations principles of OCAP (Whyte, 2020; Wong et al., 2020). Second, during the research co-design process, Sk̲wx̲wú7mesh Úxwumixw members identified a desired outcome of empowering Indigenous youth and strengthening intergenerational knowledge sharing.

Accordingly, Sk̲wx̲wú7mesh youth co-led the research design, implementation, and evaluation with me. Indigenous youth leadership during the mapping process elevated inclusion and respect for cultural protocols and ensured that power dynamics associated with knowledge sharing were held by Indigenous peoples, critical components of decolonizing mapping (Rose-Redwood et al., 2020). Third, we recentered Sk̲wx̲wú7mesh sníchim (Squamish language) and place names throughout the research process and in the maps to advance Indigenous resurgence, reconciliation, and Article 13 of the United Nations Declaration on the Rights of Indigenous Peoples (Rose-Redwood et al., 2020; United Nations, 2007; Wong et al., 2020). Finally, we ensured that methods and research documents (i.e., survey, interview guide) meaningfully included cultural values that are emphasized by Indigenous peoples as key goals associated with management, governance, and stewardship (Ban et al., 2018; Ban and Frid, 2018; Polfus et al., 2016). By developing collaborative relationships and centering Indigenous youth, language, and cultural values, this process strengthened trust, consent, and reciprocity, which are key elements associated with decolonizing MSP and advancing justice and equity.

This project advanced elements of reconciliation/decolonization; however, it failed to resolve certain colonial cartographic practices associated with participatory mapping and MSP. Traditional MSP decision-support tools (i.e., interactive maps) require data layers that associate individual values with specific places. The process of categorizing and localizing values does not accurately reflect holistic worldviews that embrace interdependence and connectivity across values. While I attempted to reflect value connectivity by using colour gradients and describing interactions across values, both Indigenous and non-Indigenous participants often expressed resistance or difficulty in parsing apart individual values. Ascribing fixed boundaries to values on maps can also inaccurately reflect the inherent fluidity of values across space and time and lead to incorrect assumptions that values have abrupt starts and ends or that places without polygons are devoid of values (Klain and Chan, 2012). Alternative approaches to visualizing place-based values and species include using imagery and language (Council of the Haida Nation, 2011), countermapping (Rose-Redwood et al., 2020), and cybercartographic approaches that weave together oral, written, visual, and spatial knowledge (Ljubicic et al., 2014). Decolonizing MSP requires decision-makers to move beyond unilateral dependence on GIS-based interactive maps and toward referencing diverse cartographic tools.

Despite the goals for this participatory mapping process to equitably engage communities affected by MSP, the project experienced two significant events that impacted participatory engagement and could lead to data gaps and biases. First, the global COVID-19 pandemic required the survey and interviews be conducted virtually. This restricted public communications opportunities, which may have reduced the ability for the snowball recruitment processes to reach hard-to-access groups who have historically engaged less in collective decision-making networks (e.g., industry, Parker et al., 2019). Recruited participants also varied in access and familiarity with virtual communication and mapping technologies due to socio-economic, professional, and demographic factors, which could impact the quantity and quality of spatial data shared. Second, we paused the research with Sḵwx̱wú7mesh Úxwumixw members following the revelation of unmarked graves of Indigenous children at sites of former residential schools in the spring of 2021 (Thorne and Moss, 2022). Upon resuming, the research team had a restricted capacity to interview as many Sḵwx̱wú7mesh participants as initially intended, which could lead to data gaps in the maps and descriptions of value interactions. This exemplifies an additional barrier to participating in knowledge creation processes imposed upon Indigenous communities by colonialism. Gaps in spatial data can also arise when local and Indigenous knowledge are intentionally withheld to protect knowledge sovereignty and sensitive places from harm (Rose-Redwood et al., 2020). Unless information is explicitly provided on the absence of data in an area, data gaps should be interpreted as potential areas that support data rather than areas where that data does not exist. Additionally, those using maps created by participatory processes need to interpret the data in the context of who was (and was not) involved in producing it.

This study directly fulfils community planning needs and provides an inclusive, community-driven approach to participatory mapping and MSP that is grounded in equity, reciprocity, and relationality. I contribute missing social data about marine place-based values using a mixed-methods technique that indicates strong community support toward ecological values, identifies spatial conservation opportunities, reveals nuanced value interactions, and enables knowledge system plurality. I also outline how this community-led approach to understanding where and why people value the ocean can be replicated in other coastal communities to enhance the harmonization of MSP across governance and ecological scales. Finally, I advance elements of reconciliation, outline further opportunities to decolonize MSP, and emphasize the need to dismantle inequitable power dynamics associated with the design, creation, and interpretation of

maps. Overall, it is critical that both the means and the ends (i.e., the process and deliverables) of marine spatial planning processes equitably include non-Indigenous and Indigenous community perspectives so that both ocean and community health are meaningfully protected.

Chapter 5:

"Change is the only constant"

– Heraclitus

"The trees, rocks, salmon, water around us are life, not resources"

– Jonathan Williams

5.1 Connecting the dots across scales and disciplines to understand human interactions with the sea

As humans gain awareness about the extent to which our extractive behaviours and systems drive negative changes in the world around us, we are compelled to understand how we can do better (Gunderson and Holling, 2002). How do we mitigate destructive drivers of change? How do we protect sensitive life and places? How do we enable ecosystems and human communities to positively respond to stress and disturbance? In essence, how do we reduce vulnerability of social-ecological systems to anthropogenic drivers? My thesis explored these questions by unpacking the vulnerability of marine animals to climate change and exploring how life in and around urban seas responds to anthropogenic drivers. I applied methods that integrate across spatial scales (global to regional to watershed), disciplines (natural and social sciences), and knowledge systems (western science, Indigenous and local knowledge) to quantify the sensitivity of marine ectothermic animals to ocean acidification and warming and explore a local and Indigenous-led approach to marine spatial planning. In this chapter, I review the individual (Table 5.1) and synthesized implications of my three data chapters and outline opportunities to build upon these findings to transform how we study, manage, and nurture human relationships with the sea around us.

My meta-analysis of marine ectothermic sensitivity to climate change revealed that (i) ocean acidification and warming have largely negative effects across response variables, (ii) sensitivity varies across organismal traits and environmental context, and (iii) certain predictive hypotheses have low empirical support and require refinement before guiding future research (Chapter 2, Table 2.1, 5.1). My investigation of intraspecific variability in thermal performance across populations of *Nucella lamellosa* revealed high vulnerability to ongoing ocean warming in

populations within an urban sea (the Salish Sea) and low vulnerability in populations along a more exposed coastline (the Central Coast) because of varying alignment between thermal sensitivity and local rates of environmental change (Chapter 3, Table 5.1). Finally, my work with the Sk̲wx̲ú7mesh Úxwumixw (Squamish Nation) and community groups in Átl'k̲a7tsem/Howe Sound, within the Salish Sea, provided a framework for regional (e.g., watershed-scale) analyses of relationships between people and the sea to inform knowledge-creation and decolonize mapping exercises in support of marine spatial planning. I also illustrated how this framework can be replicated and woven together with other regional community-led mapping initiatives to improve the coordination and participatory dimensions of marine spatial planning in complex urban seascapes (Chapter 4, Table 5.1). Collectively, these results reinforce the understanding that climate change has direct and negative impacts on marine life throughout the world, identify regions of greater climate change vulnerability when rates of environmental change surpass global averages, and provide a framework for community-led implementation of marine spatial planning to protect vulnerable places, values, and life forms.

Table 5.1. Research findings associated with driving question/objectives.

Driving question	Findings
What is the vulnerability of marine animals to climate change, specifically ocean acidification and warming?	Ch 2: I quantified the sensitivity of marine ectothermic animals to ocean acidification and warming using a meta-analysis of nearly 500 experiments and identified refinements for hypotheses that predict sensitivity based on organismal traits and environmental conditions Ch 3: I quantified variation in growth, feeding rates, and survival across present and future seawater temperatures in populations of a marine snail, *Nucella lamellosa*, from the middle of its species range and demonstrated intraspecific variability in vulnerability to ocean warming due to different relationships between thermal performance and local rates of ocean warming
How does life in and around urban seas respond to anthropogenic drivers of change	Ch 3: I quantified the growth and survival in *N. lamellosa* populations across an urban sea (Salish Sea) and the Central Coast of B.C., and found that the Salish Sea is a climate change hot spot for these molluscs due to rapid rates of warming that surpass upper thermal performance limits (specifically survival) Ch 4: I implemented a mixed-methods approach to document place-based values in support of community and Indigenous-led marine spatial planning within the Salish Sea and identified ways to center equity and

	inclusivity in participatory mapping processes. Results from our survey and interviews clarified high support toward marine ecological values, identified potential areas for integrated marine conservation, and described complex interactions and interdependencies across ecological, social, cultural, and economic values. These results can enhance regional decision-making to support the adaptive capacity and reduce vulnerability to human impacts at the scale of First Nations' territories and watersheds

The application of research findings, both to scientific and management contexts, depends on the scale at which work is conducted. For example, global meta-analytical results are valuable in refining theoretical hypotheses, establishing confidence about general effects, and informing global policy agendas (Koricheva et al., 2013). However, meta-analytical results can be challenging to apply to specific research and management contexts in the absence of local empirical data. Similarly, results from empirical and place-based studies can be challenging to extrapolate to external social-ecological systems in the absence of theoretical frameworks that anticipate common processes and feedbacks (Bennett et al., 2022). Improving connectivity across spatial scales and disciplines was a key motivation for this dissertation. Here, I outline how my multi-scalar and interdisciplinary approach advances our understanding of the vulnerability of coastal social-ecological systems to anthropogenic drivers and discuss opportunities for expansion and continual growth.

In Chapters 2 and 3, I integrate the effects of climate change drivers across spatial scales using global synthesis and regional empirical approaches. My meta-analysis quantified empirical evidence for nine hypotheses that predict the sensitivity of marine ectothermic animals to ocean acidification and warming based on organismal traits and environmental context. The results indicated mixed or low support for most tested hypotheses; however, one prediction my data supported is that species from tropic latitudes performed poorly under warming. This expectation was driven by the understanding that tropical species tend to inhabit environments where maximum environmental temperatures are close to upper thermal limits (i.e., thermal safety margins are small), and rapid warming could therefore surpass lethal tolerance thresholds faster than species can evolutionarily adapt (Lenoir et al., 2020; Sunday et al., 2014). Species from temperate latitudes also experienced large performance reductions under warming, a trend mirrored in my Chapter 3 results where temperate snail populations demonstrated high vulnerability to ocean warming when they inhabited one of the warmest

regions of their range. The growing awareness about mosaic patterns of overlapping environmental drivers is prompting global change scientists to consider temporal and spatial heterogeneity more substantially, especially those working on species range shifts and population vulnerability within complex coastal and estuarine environments (Lauchlan and Nagelkerken, 2020). Future investigations and management of ecological vulnerability to climate change, particularly environmental warming, should focus on regions where organisms are exposed to the most extreme levels of individual drivers and anticipate driver magnitudes to vary in a mosaic fashion rather than linearly with latitude (i.e., latitude is not a guaranteed proxy for organismal vulnerability to temperature).

Synthesizing research across scales can enhance the development of predictive hypotheses; however, it can also reveal methodological limitations. In Chapter 3, I illustrate that the interpretation of organismal vulnerability to climate change depends upon regional rates of environmental change, where populations from a cooler region that is warming at a slower rate were less vulnerable than those in a warmer, faster warming region. That is, despite being less than 500 km apart and situated within the same temperate latitudinal zone, environmental conditions at the two research sites along B.C.'s coast were different enough to drive varying vulnerability to climate change. This intraspecific and within-latitude-class variability challenges the accuracy of grouping organismal responses by taxonomic group and latitude, as I did in Chapter 2. For example, the lack of significant effects of ocean warming and acidification on polar organisms could be an underestimate of the true biological effects of climate change if experiments used global projections for warming and acidification that are slower than local changes. Data about regional environmental projections is becoming increasingly accessible due to technological advances in environmental measurements (e.g., satellite, remote observation). Thus, both terrestrial (Korell et al., 2020) and marine research communities (Kroeker et al., 2020a) are increasingly advocating for experimental conditions to be manipulated based on regional projections. Wherever possible, factorial experiments should select control and treatment levels based on local projections of environmental change and factorial meta-analyses should incorporate local rates of change into inclusion criteria, analyses, and interpretation.

The ability to extrapolate and generalize research findings is enhanced by working across research disciplines in addition to spatial scales, as interdisciplinary work can create more

holistic understandings of social-ecological system feedbacks and processes (McDonald et al., 2018). While my third chapter was largely influenced by eco-evolutionary theory and experimental design, I strove to contextualize the work within regional oceanographic data because of the call for greater connectivity across ecological and oceanographic fields (Harley et al., 2006). My conclusion that snail populations in the Salish Sea are more vulnerable to ocean warming than those along an exposed coastline could be extrapolated to regions with similar social and biophysical characteristics. For example, the faster local rate of ocean warming in the Salish Sea could be due to the altered flow and rising temperature of freshwater from the Fraser River (Amos et al., 2015; Riche et al., 2014) or the high level of regional shoreline development that removes microhabitats and disrupts biophysical processes between terrestrial and marine systems (Biffard et al., 2014; Sobocinski, 2021). These hydrological and social factors could be present in other urban or inland seas (e.g., the Baltic Sea) and combine to increase the vulnerability to climate change of marine life within (Greene et al., 2022). Confidence in these extrapolations could be deepened through more substantial collaboration across ecologists, oceanographers, social scientists, hydrologists, and coastal engineers.

Through co-creating Chapter 4, I explored guiding principles that can enhance the quality and impact of research yet are infrequently referenced within natural science domains: respect, relationality, and reciprocity. These 'three Rs' form the cornerstones of Indigenous research methodologies and participatory action and community-based research approaches (Baum, 2006; Wilson, 2008). Within the context of Chapter 4, centering respect for Átl'ka7tsem and its people explicitly shaped my research goal of creating research that positively contributes toward the community and compelled me to ensure my methods built space to uplift multiple ways of knowing (Cochran et al., 2008; Grenz, 2020). Understanding relationality involved re-contextualizing my relationship with Átl'ka7tsem and becoming cognisant of language and methods that continue to sever people from the life and places we are embedded within and dependent upon. For example, the term 'resources' renders inert the trees, salmon, rocks, and water that live around us and create our homes, and the concept of 'wilderness' can perpetuate the notion that people are separate from and at odds with nature (e.g., fortress conservation, Cannon, 2022; Dowie, 2009). Seeing life-forms around me as holding agency, autonomy, and relational value and understanding my relationship to them not as a hierarchy or dominion but rather as one of millions of species we share this earth with transforms how I strive to respect, interact, and relate with the myriad life-forms around me.

Finally, the principle of reciprocity challenged me to critically examine what I am contributing back to those who give to me. What is the value of my research outside of my personal acquisition of knowledge and experience? How will it actually contribute to healing our earth and communities from destructive human behaviours? In many ways, measuring the impact of research requires longer timespans that exist within a graduate degree or falls outside of tangible impact metrics, and inevitably, we fall short of lofty intentions. My goal for Chapter 4 was to create a research process and outputs that positively impact decision-making and strengthen relationships with people and places, and I do feel I made incremental progress toward this goal. Yet, there is always room for improvement, acknowledgement of limitations, and critical evaluation of the meaningful contribution that academic work provides to society and the world (Knight et al., 2008).

Upon reflecting on my methods used in Chapter 3, and in many field and laboratory experiments, I see substantial opportunity to center the three Rs within natural sciences and elevate anticolonial research methods (Liboiron, 2021; Reid et al., 2021). This is especially true for invertebrate research, where ethical guidelines informing the use of invertebrates in science are inconsistent across countries and ethics training is not always available or required within undergraduate or graduate programs (Drinkwater et al., 2019). My field and laboratory experiments were designed to test the upper thermal performance limits of snails to understand their vulnerability to climate change. I exposed snails to highly stressful and lethal seawater temperatures based on the justification that the knowledge I created could benefit these populations, the species, or even marine ecosystems more broadly. During the experiments, I felt physically and emotionally distressed about the harm I was inflicting on these individual snails, yet I continued. Sacrificing lives for the pursuit of scientific knowledge is a cornerstone of many empirical western research practices and it is difficult to envision a world where this does not occur without significantly restricting the production of scientific knowledge. However, it is incumbent upon empirical scientists to critically evaluate this justification paradigm and consider where our actions fall on the spectrums of being rude to respectful, impersonal to relational, extractive to reciprocal (Drinkwater et al., 2019; Liboiron, 2021).

Examining the ends (i.e., outputs, impacts, outcomes) of research projects in the context of the means (i.e., methods) and centering the three Rs are two avenues to transform research

approaches from harmful to healing paradigms (Grenz, 2020; Shah et al., 2018; Wong et al., 2020). In climate change research, the end goal is often the production of knowledge intended to inform mitigation or adaptation policy and actions – at least, that was my motivation for Chapters 2 and 3. However, scientific confidence about the negative social-ecological effects of climate change has grown substantially over the past several decades and is underscored by my Chapter 2 and 3 results (Knutti, 2019). Thus, the production of more knowledge about climate change's negative effects (i.e., understanding sensitivity and who will perish) may not be as meaningful to adaptation planning as identifying processes and attributes that build and sustain resilience and adaptive capacity (i.e., understanding who will persist and why, Leung et al., 2022; McEvoy et al., 2013). My selection of *Nucella lamellosa* was based on the expectation that this species is sensitive to climate change because of its life-history traits. That is, I predicted these snails would react negatively to future seawater conditions and set my lab experiment up knowing I would likely expose them to stressful and lethal conditions. If I had re-framed my research to test a species that I anticipated would be more resilient to climate change, I could potentially have avoided the same levels of suffering inflicted during the experiment and informed what life could persist in the Salish Sea as it rapidly warms and why. A similar framing transition is occurring in science communication fields. Communication efforts oriented at shifting human attitudes and behaviours about societal problems, such as climate change, have often followed an 'information-deficit model', where changing public opinion involves a one-way transmission of information about the problem from technical experts to the public (Suldovsky, 2018). Recognition of the failure of this one-way and issue-oriented communication approach has inspired a transition toward two-way communication dialogues and sharing solutions-oriented content that provides roadmaps and guiding principles to navigate intertwined crises (Thier and Lin, 2022). The exploration of vulnerability to resilience and problems to solutions exist on a framing continuum, where characterizing resilience involves understanding vulnerability and identifying solutions depends upon defining the problems. However, researchers should evaluate the context in which they are producing knowledge to understand where on that continuum they can position their work to produce the most meaningful outcomes for protecting social-ecological systems from anthropogenic drivers.

5.2 Conclusion

My goal in graduate school was to create and share knowledge that strengthens society's ability to care for ecosystems and communities impacted by extractive human systems. Achieving this

goal will be a life-long journey, yet my dissertation contributes baby steps forward. Three ways my PhD informs our ability to identify and protect vulnerable places and species from anthropogenic drivers include:

1. My global synthesis and place-based empirical results refine our understanding of organismal traits and environmental contexts that increase ecological vulnerability to climate change. By connecting these multi-scalar research methods, I contribute a research agenda that can refine scientific evaluation of the individual and interactive effects of ocean acidification and warming on marine ectothermic animals and clarify vulnerability of marine life in inland and/or urban seas.
2. My partnership with local and Indigenous groups generated place-based knowledge about human relationships with the ocean and enabled the inclusion of social and qualitative data in maps and marine spatial planning decision-support tools. I also highlight four opportunities and two challenges with advancing reconciliation and contribute toward advancing equity and inclusivity in marine spatial planning.
3. Finally, through studying social-ecological vulnerability using an interdisciplinary approach that drew from natural and social sciences, I identify opportunities to evaluate research paradigms and center Indigenous and participatory action research values (e.g., respect, relationality, reciprocity) more broadly in natural sciences to advance the equitable creation of meaningful science.

Beyond these scholarly contributions, my dissertation reflects the growing call for interdisciplinary and collaborative research to address the climate, biodiversity, and social inequity crises (Bennett et al., 2017; McDonald et al., 2018; Moon and Blackman, 2014). My graduate school journey started with basic science questions and my audience was largely other climate change researchers (Chapter 2 and 3). Pursuing these questions taught me invaluable quantitative and empirical research skills; yet the call for public impact-oriented conservation and climate science (Knight et al., 2008) compelled me to weave applied science into my degree with a defined community audience (Chapter 4). While the result is a wide-ranging thesis, I am confident the interdisciplinary research and diverse skills I acquired through my journey will equip me for my work ahead stewarding ecosystems and communities.

That said, I am still grappling with the mismatch between my expectations for the applicability of my research, and the reality. In my first iteration of writing Chapter 4, I refrained from synthesizing the data to identify spatial conservation opportunities because I was hesitant to extend myself into the realm of providing recommendations. However, upon circulating drafts amongst co-authors and advisors, I realized that it was incumbent upon me to do the work to identify specific recommendations stemming from my research. I know the material best, therefore, I must step up to the challenge of communicating my work in a way that makes sense to and serves my intended audience, even if it is slightly uncomfortable at first. I look forward to continuing this journey of learning how to connect the dots between research and impact.

I bring forward this discussion of research-audiences and impact to emphasize the importance of reflecting on the value of a PhD to students and society in the twenty-first century. Contributing toward scholarly literature is a primary function of academia; however, it is not the sole metric of success, especially as researchers increasingly take responsibility for connecting our work to non-academic audiences (e.g., policymakers) and generating 'real-world' positive impacts (e.g., community well-being, biodiversity conservation; Evans and Cvitanovic, 2018). "Escaping the ivory tower" involves curating skill sets (e.g., science communication) and investing time and energy into building relationships with community partners and practitioners (Baron, 2010; Hoffman, 2021; Whyte, 2020). While many traditional academic programs and funding systems still do not recognize or reward researchers who invest time in developing skills and growing relationships (Blickley et al., 2013; Muir and Schwartz, 2009), a paradigm shift of academic methods and 'metrics-of-success' is slowly occurring, as evidenced by the emergence of new impact assessment frameworks and training and funding programs that bridge the science-to-society gap (e.g., Ocean Leaders, Public Scholars Institute, Liber-Ero, Earth Leadership programs, Morgan Jones et al., 2022). Overall, I hope my dissertation encourages other researchers to expand their work across disciplines and audiences, and advances academia's ability to serve societal needs and generate meaningful impacts that protect the life around us.

References

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change, Resilience, Vulnerability, and Adaptation: A Cross-Cutting Theme of the International Human Dimensions Programme on Global Environmental Change 16, 268–281. https://doi.org/10.1016/j.gloenvcha.2006.02.006

AHSBRI, 2022. History of the Howe Sound Community Forum 2000-2013 [WWW Document]. Howe Sound Biosphere Reg. Initiat. URL https://www.howesoundbri.org/howe-sound-community-forum/2020/10/11/history-and-evolution-of-the-howe-sound-community-forum (accessed 12.1.22).

Albrecht, G., 2016. 'Solastalgia' : a new concept in health and identity. https://doi.org/10.4225/03/584f410704696

Amos, C.L., Martino, S., Sutherland, T.F., Al Rashidi, T., 2015. Sea Surface Temperature Trends in the Coastal Zone of British Columbia, Canada. J. Coast. Res. 300, 434–446. https://doi.org/10.2112/JCOASTRES-D-14-00114.1

Angilletta, M.J., 2009. Thermal adaptation: a theoretical and empirical synthesis, Oxford biology. Oxford University Press, Oxford, UK ; New York.

Appleton, R.D., Palmer, A.R., 1988. Water-borne stimuli released by predatory crabs and damaged prey induce more predator-resistant shells in a marine gastropod. Proc. Natl. Acad. Sci. U. S. A. 85, 4387–4391.

Artelle, K.A., Adams, M.S., Bryan, H.M., Darimont, C.T., Housty, J. ('Cúagilákv), Housty, W.G. (Dúqváísḷa), Moody, J.E., Moody, M.F., Neasloss, D. (Muq'vas G., Service, C.N., Walkus, J., 2021. Decolonial Model of Environmental Management and Conservation: Insights from Indigenous-led Grizzly Bear Stewardship in the Great Bear Rainforest. Ethics Policy Environ. 24, 283–323. https://doi.org/10.1080/21550085.2021.2002624

Aze, T., Barry, J., Bellerby, R., Secretariat of the Convention on Biological Diversity, 2014. An updated synthesis of the impacts of ocean acidification on marine biodiversity.

Bahr, K.D., Rodgers, K.S., Jokiel, P.L., 2018. Ocean warming drives decline in coral metabolism while acidification highlights species-specific responses. Mar. Biol. Res. 14, 924–935. https://doi.org/10.1080/17451000.2018.1551616

Ban, N., Picard, C., Vincent, A., 2008. Moving Toward Spatial Solutions in Marine Conservation with Indigenous Communities. Ecol. Soc. 13. https://doi.org/10.5751/ES-02473-130132

Ban, N.C., Alidina, H.M., Ardron, J.A., 2010. Cumulative impact mapping: Advances, relevance and limitations to marine management and conservation, using Canada's Pacific waters as a case study. Mar. Policy 34, 876–886. https://doi.org/10.1016/j.marpol.2010.01.010

Ban, N.C., Bodtker, K.M., Nicolson, D., Robb, C.K., Royle, K., Short, C., 2013a. Setting the stage for marine spatial planning: Ecological and social data collation and analyses in Canada's Pacific waters. Mar. Policy 39, 11–20. https://doi.org/10.1016/j.marpol.2012.10.017

Ban, N.C., Frid, A., 2018. Indigenous peoples' rights and marine protected areas. Mar. Policy 87, 180–185. https://doi.org/10.1016/j.marpol.2017.10.020

Ban, N.C., Frid, A., Reid, M., Edgar, B., Shaw, D., Siwallace, P., 2018. Incorporate Indigenous perspectives for impactful research and effective management. Nat. Ecol. Evol. 2, 1680–1683. https://doi.org/10.1038/s41559-018-0706-0

Ban, N.C., Mills, M., Tam, J., Hicks, C.C., Klain, S., Stoeckl, N., Bottrill, M.C., Levine, J., Pressey, R.L., Satterfield, T., Chan, K.M., 2013b. A social–ecological approach to conservation planning: embedding social considerations. Front. Ecol. Environ. 11, 194–202. https://doi.org/10.1890/110205

Ban, N.C., Picard, C.R., Vincent, A.C.J., 2009. Comparing and Integrating Community-Based and Science-Based Approaches to Prioritizing Marine Areas for Protection. Conserv. Biol. 23, 899–910.

Barclay, K.M., Gaylord, B., Jellison, B.M., Shukla, P., Sanford, E., Leighton, L.R., 2019. Variation in the effects of ocean acidification on shell growth and strength in two intertidal gastropods. Mar. Ecol. Prog. Ser. 626, 109–121. https://doi.org/10.3354/meps13056

Barley, J.M., Cheng, B.S., Sasaki, M., Gignoux-Wolfsohn, S., Hays, C.G., Putnam, A.B., Sheth, S., Villeneuve, A.R., Kelly, M., 2021. Limited plasticity in thermally tolerant ectotherm populations: evidence for a trade-off. Proc. R. Soc. B Biol. Sci. 288, 20210765. https://doi.org/10.1098/rspb.2021.0765

Baron, N., 2010. Escape from the Ivory Tower: A Guide to Making Your Science Matter. Island Press, Cambridge, UNITED STATES.

Bates, D., Maechler, M., Bolker, B., Walker, S., Christensen, R., Singmann, H., Scheipl, F., Grothendieck, G., Green, P., Fox, J., Bauer, A., Krivitsky, P., 2022. R Package "lme4."

Bates, N., Astor, Y., Church, M., Currie, K., Dore, J., Gonaález-Dávila, M., Lorenzoni, L., Muller-Karger, F., Olafsson, J., Santa-Casiano, M., 2014. A Time-Series View of Changing

Ocean Chemistry Due to Ocean Uptake of Anthropogenic CO2 and Ocean Acidification. Oceanography 27, 126–141. https://doi.org/10.5670/oceanog.2014.16

Baum, F., 2006. Participatory action research. J. Epidemiol. Community Health 60, 854–857. https://doi.org/10.1136/jech.2004.028662

Bennett, N.J., 2018. Navigating a just and inclusive path towards sustainable oceans. Mar. Policy 97, 139–146. https://doi.org/10.1016/j.marpol.2018.06.001

Bennett, N.J., 2016. Using perceptions as evidence to improve conservation and environmental management. Conserv. Biol. 30, 582–592. https://doi.org/10.1111/cobi.12681

Bennett, N.J., Alava, J.J., Ferguson, C.E., Blythe, J., Morgera, E., Boyd, D., Côté, I.M., 2023. Environmental (in)justice in the Anthropocene ocean. Mar. Policy 147, 105383. https://doi.org/10.1016/j.marpol.2022.105383

Bennett, N.J., Blythe, J., Tyler, S., Ban, N.C., 2016. Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures. Reg. Environ. Change 16, 907–926. https://doi.org/10.1007/s10113-015-0839-5

Bennett, N.J., Cisneros-Montemayor, A.M., Blythe, J., Silver, J.J., Singh, G., Andrews, N., Calò, A., Christie, P., Franco, A.D., Finkbeiner, E.M., Gelcich, S., Guidetti, P., Harper, S., Hotte, N., Kittinger, J.N., Billon, P.L., Lister, J., Lama, R.L. de la, McKinley, E., Scholtens, J., Solås, A.-M., Sowman, M., Talloni-Álvarez, N., Teh, L.C.L., Voyer, M., Sumaila, U.R., 2019a. Towards a sustainable and equitable blue economy. Nat. Sustain. 1–3. https://doi.org/10.1038/s41893-019-0404-1

Bennett, N.J., Dearden, P., 2014. Why local people do not support conservation: Community perceptions of marine protected area livelihood impacts, governance and management in Thailand. Mar. Policy 44, 107–116. https://doi.org/10.1016/j.marpol.2013.08.017

Bennett, N.J., Dodge, M., Akre, T.S., Canty, S.W.J., Chiaravalloti, R., Dayer, A.A., Deichmann, J.L., Gill, D., McField, M., McNamara, J., Murphy, S.E., Nowakowski, A.J., Songer, M., 2022. Social science for conservation in working landscapes and seascapes. Front. Conserv. Sci. 3, 954930. https://doi.org/10.3389/fcosc.2022.954930

Bennett, N.J., Franco, A.D., Calò, A., Nethery, E., Niccolini, F., Milazzo, M., Guidetti, P., 2019b. Local support for conservation is associated with perceptions of good governance, social impacts, and ecological effectiveness. Conserv. Lett. 0, e12640. https://doi.org/10.1111/conl.12640

Bennett, N.J., Govan, H., Satterfield, T., 2015. Ocean grabbing. Mar. Policy 57, 61–68. https://doi.org/10.1016/j.marpol.2015.03.026

Bennett, N.J., Roth, R., Klain, S.C., Chan, K., Christie, P., Clark, D.A., Cullman, G., Curran, D., Durbin, T.J., Epstein, G., Greenberg, A., Nelson, M.P., Sandlos, J., Stedman, R., Teel, T.L., Thomas, R., Veríssimo, D., Wyborn, C., 2017. Conservation social science: Understanding and integrating human dimensions to improve conservation. Biol. Conserv. 205, 93–108. https://doi.org/10.1016/j.biocon.2016.10.006

Biffard, D., Stevens, T., Rao, A., Woods, B., 2014. BC Parks shoreline sensitivity to sea level rise model: user guide. BC Parks and SeaChange Marine Conservation Society.

Blickley, J.L., Deiner, K., Garbach, K., Lacher, I., Meek, M.H., Porensky, L.M., Wilkerson, M.L., Winford, E.M., Schwartz, M.W., 2013. Graduate Student's Guide to Necessary Skills for Nonacademic Conservation Careers. Conserv. Biol. 27, 24–34. https://doi.org/10.1111/j.1523-1739.2012.01956.x

Bodtker, K.M., 2017. Ocean Watch: Howe Sound Edition. Ocean Wise Marine Conservation Association.

British Columbia, Ministry of Environment, 2016. Indicators of climate change for British Columbia, 2016 update. Ministry of Environment, Victoria, B.C.

Brown, G., 2004. Mapping Spatial Attributes in Survey Research for Natural Resource Management: Methods and Applications. Soc. Nat. Resour. 18, 17–39. https://doi.org/10.1080/08941920590881853

Brown, G., Kyttä, M., 2018. Key issues and priorities in participatory mapping: Toward integration or increased specialization? Appl. Geogr. 95, 1–8. https://doi.org/10.1016/j.apgeog.2018.04.002

Brown, G., Kyttä, M., 2014. Key issues and research priorities for public participation GIS (PPGIS): A synthesis based on empirical research. Appl. Geogr. 46, 122–136. https://doi.org/10.1016/j.apgeog.2013.11.004

Brown, G., Raymond, C., 2007. The relationship between place attachment and landscape values: Toward mapping place attachment. Appl. Geogr. 27, 89–111. https://doi.org/10.1016/j.apgeog.2006.11.002

Brown, G., Strickland-Munro, J., Kobryn, H., Moore, S.A., 2016. Stakeholder analysis for marine conservation planning using public participation GIS. Appl. Geogr. 67, 77–93. https://doi.org/10.1016/j.apgeog.2015.12.004

Brown, G., Weber, D., 2012. Measuring change in place values using public participation GIS (PPGIS). Appl. Geogr. 34, 316–324. https://doi.org/10.1016/j.apgeog.2011.12.007

Brown, N.E.M., Bernhardt, J.R., Anderson, K.M., Harley, C.D.G., 2018. Increased food supply mitigates ocean acidification effects on calcification but exacerbates effects on growth. Sci. Rep. 8, 1–9.

Brownlee, G.R.P., 2022. Thermal history, heatwaves, and the costs and benefits to physiological plasticity in the California mussel (Mytilus californianus). University of British Columbia. https://doi.org/10.14288/1.0413627

Brownlee, G.R.P., Lang, C., Oldford, G., Urcelay, A.V., 2020. Data & Decision Support for MSP in Burrard Inlet.

Burford MO, Scarpa J, Cook BJ, Hare MP, 2014. Local adaptation of a marine invertebrate with a high dispersal potential: evidence from a reciprocal transplant experiment of the eastern oyster Crassostrea virginica. Mar. Ecol. Prog. Ser. 505, 161–175.

Burger, F.A., Terhaar, J., Frölicher, T.L., 2022. Compound marine heatwaves and ocean acidity extremes. Nat. Commun. 13, 4722. https://doi.org/10.1038/s41467-022-32120-7

Burrows, M.T., Schoeman, D.S., Buckley, L.B., Moore, P., Poloczanska, E.S., Brander, K.M., Brown, C., Bruno, J.F., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., Kiessling, W., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F.B., Sydeman, W.J., Richardson, A.J., 2011. The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science 334, 652–655. https://doi.org/10.1126/science.1210288

Burt, J.M., 2019. Navigating coexistence: Ecological drivers and social implications of predator-induced regime shifts in the Northeast Pacific. Simon Fraser University.

Burt, J.M., Tinker, M.T., Okamoto, D.K., Demes, K.W., Holmes, K., Salomon, A.K., 2018. Sudden collapse of a mesopredator reveals its complementary role in mediating rocky reef regime shifts. Proc. R. Soc. B Biol. Sci. 285, 20180553. https://doi.org/10.1098/rspb.2018.0553

Buscher, E., Mathews, D.L., Bryce, C., Bryce, K., Joseph, D., Ban, N.C., 2021. Differences and similarities between Indigenous and conventional marine conservation planning: The case of the Songhees Nation, Canada. Mar. Policy 129, 104520. https://doi.org/10.1016/j.marpol.2021.104520

Buxton, R.T., Bennett, J.R., Reid, A.J., Shulman, C., Cooke, S.J., Francis, C.M., Nyboer, E.A., Pritchard, G., Binley, A.D., Avery-Gomm, S., Ban, N.C., Beazley, K.F., Bennett, E., Blight, L.K., Bortolotti, L.E., Camfield, A.F., Gadallah, F., Jacob, A.L., Naujokaitis-Lewis,

I., Raudsepp-Hearne, C., Roche, D.G., Soulard, F., Stralberg, D., Sadler, K.D., Solarik, K.A., Ziter, C.D., Brandt, J., McKindsey, C.W., Greenwood, D.A., Boxall, P.C., Ngolah, C.F., Chan, K.M.A., Lapen, D., Poser, S., Girard, J., DiBacco, C., Hayne, S., Orihel, D., Lewis, D., Littlechild, D., Marshall, S.J., McDermott, L., Whitlow, R., Browne, D., Sunday, J., Smith, P.A., 2021. Key information needs to move from knowledge to action for biodiversity conservation in Canada. Biol. Conserv. 108983. https://doi.org/10.1016/j.biocon.2021.108983

Cannon, S., 2022. Coral reef ecology and conservation in the tropical Pacific Ocean. University of British Columbia. https://doi.org/10.14288/1.0417523

Cattano, C., Claudet, J., Domenici, P., Milazzo, M., 2018. Living in a high CO2 world: a global meta-analysis shows multiple trait-mediated fish responses to ocean acidification. Ecol. Monogr. 88, 320–335. https://doi.org/10.1002/ecm.1297

Chan, K.M.A., Balvanera, P., Benessaiah, K., Chapman, M., Díaz, S., Gómez-Baggethun, E., Gould, R., Hannahs, N., Jax, K., Klain, S., Luck, G.W., Martín-López, B., Muraca, B., Norton, B., Ott, K., Pascual, U., Satterfield, T., Tadaki, M., Taggart, J., Turner, N., 2016. Opinion: Why protect nature? Rethinking values and the environment. Proc. Natl. Acad. Sci. 113, 1462–1465. https://doi.org/10.1073/pnas.1525002113

Chandler, P.C., King, S.A., Boldt, J.L., Institute of Ocean Sciences, P.B., 2018. State of the physical, biological, and selected fishery resources of Pacific Canadian marine ecosystems in 2017.

Cochran, P.A.L., Marshall, C.A., Garcia-Downing, C., Kendall, E., Cook, D., McCubbin, L., Gover, R.M.S., 2008. Indigenous Ways of Knowing: Implications for Participatory Research and Community. Am. J. Public Health 98, 22–27. https://doi.org/10.2105/AJPH.2006.093641

Collins, K.M.T., 2010. Advanced Sampling Designs in Mixed Research: Current Practices and Emerging Trends in the Social and Behavioral Sciences, in: SAGE Handbook of Mixed Methods in Social & Behavioral Research. SAGE Publications, Inc., 2455 Teller Road, Thousand Oaks California 91320 United States, pp. 353–378. https://doi.org/10.4135/9781506335193.n15

Compton, T.J., Rijkenberg, M.J.A., Drent, J., Piersma, T., 2007. Thermal tolerance ranges and climate variability: A comparison between bivalves from differing climates. J. Exp. Mar. Biol. Ecol. 352, 200–211. https://doi.org/10.1016/j.jembe.2007.07.010

Cornwall, C.E., Harvey, B.P., Comeau, S., Cornwall, D.L., Hall-Spencer, J.M., Peña, V., Wada, S., Porzio, L., 2022. Understanding coralline algal responses to ocean acidification: Meta-analysis and synthesis. Glob. Change Biol. 28, 362–374. https://doi.org/10.1111/gcb.15899

Costello, M.J., Chaudhary, C., 2017. Marine Biodiversity, Biogeography, Deep-Sea Gradients, and Conservation. Curr. Biol. 27, R511–R527. https://doi.org/10.1016/j.cub.2017.04.060

Côté, I.M., Darling, E.S., Brown, C.J., 2016. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B Biol. Sci. 283, 20152592. https://doi.org/10.1098/rspb.2015.2592

Council of the Haida Nation, 2011. Ocean & Way of Life Map.

Crain, C.M., Kroeker, K., Halpern, B.S., 2008. Interactive and cumulative effects of multiple human stressors in marine systems. Ecol. Lett. 11, 1304–1315. https://doi.org/10.1111/j.1461-0248.2008.01253.x

Darling, E.S., Côté, I.M., 2008. Quantifying the evidence for ecological synergies. Ecol. Lett. 11, 1278–1286. https://doi.org/10.1111/j.1461-0248.2008.01243.x

De Boeck, H.J., Vicca, S., Roy, J., Nijs, I., Milcu, A., Kreyling, J., Jentsch, A., Chabbi, A., Campioli, M., Callaghan, T., Beierkuhnlein, C., Beier, C., 2015. Global Change Experiments: Challenges and Opportunities. BioScience 65, 922–931. https://doi.org/10.1093/biosci/biv099

Deutsch, C.A., Tewksbury, J.J., Huey, R.B., Sheldon, K.S., Ghalambor, C.K., Haak, D.C., Martin, P.R., 2008. Impacts of Climate Warming on Terrestrial Ectotherms across Latitude. Proc. Natl. Acad. Sci. U. S. A. 105, 6668–6672.

Dey, C.J., Koops, M.A., 2021. The consequences of null model selection for predicting mortality from multiple stressors. Proc. R. Soc. B Biol. Sci. 288, 20203126. https://doi.org/10.1098/rspb.2020.3126

DFO, 2022. Tides, currents, and water levels [WWW Document]. Ecosyst. Oceans Sci. Dep. Fish. Oceans Can. URL https://tides.gc.ca/ (accessed 3.16.22).

Diggon, S., Bones, J., Short, C.J., Smith, J.L., Dickinson, M., Wozniak, K., Topelko, K., Pawluk, K.A., 2020. The Marine Plan Partnership for the North Pacific Coast – MaPP: A collaborative and co-led marine planning process in British Columbia. Mar. Policy 104065. https://doi.org/10.1016/j.marpol.2020.104065

Diggon, S., Butler, C., Heidt, A., Bones, J., Jones, R., Outhet, C., 2021. The Marine Plan Partnership: Indigenous community-based marine spatial planning. Mar. Policy 132, 103510. https://doi.org/10.1016/j.marpol.2019.04.014

Douvere, F., 2008. The importance of marine spatial planning in advancing ecosystem-based sea use management. Mar. Policy, The Role of Marine Spatial Planning in Implementing Ecosystem-based, Sea Use Management 32, 762–771. https://doi.org/10.1016/j.marpol.2008.03.021

Dowie, M., 2009. Conservation Refugees: The Hundred-Year Conflict between Global Conservation and Native Peoples. https://doi.org/10.7551/mitpress/7532.001.0001

Drinkwater, E., Robinson, E.J.H., Hart, A.G., 2019. Keeping invertebrate research ethical in a landscape of shifting public opinion. Methods Ecol. Evol. 10, 1265–1273. https://doi.org/10.1111/2041-210X.13208

Etter, R.J., 1988. Physiological Stress and Color Polymorphism in the Intertidal Snail Nucella Lapillus. Evolution 42, 660–680. https://doi.org/10.1111/j.1558-5646.1988.tb02485.x

Evans, M.C., Cvitanovic, C., 2018. An introduction to achieving policy impact for early career researchers. Palgrave Commun. 4, 1–12. https://doi.org/10.1057/s41599-018-0144-2

Evans, W., Lebon, G.T., Harrington, C.D., Takeshita, Y., Bidlack, A., 2022. Marine CO2 system variability along the northeast Pacific Inside Passage determined from an Alaskan ferry. Biogeosciences 19, 1277–1301. https://doi.org/10.5194/bg-19-1277-2022

Fabry, V.J., Seibel, B.A., Feely, R.A., Orr, J.C., 2008. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES J. Mar. Sci. 65, 414–432. https://doi.org/10.1093/icesjms/fsn048

Fagerholm, N., Raymond, C.M., Olafsson, A.S., Brown, G., Rinne, T., Hasanzadeh, K., Broberg, A., Kyttä, M., 2021. A methodological framework for analysis of participatory mapping data in research, planning, and management. Int. J. Geogr. Inf. Sci. 35, 1848–1875. https://doi.org/10.1080/13658816.2020.1869747

Feely, R.A., 2004. Impact of Anthropogenic CO2 on the CaCO3 System in the Oceans. Science 305, 362–366. https://doi.org/10.1126/science.1097329

Figuerola, B., Hancock, A.M., Bax, N., Cummings, V.J., Downey, R., Griffiths, H.J., Smith, J., Stark, J.S., 2021. A Review and Meta-Analysis of Potential Impacts of Ocean Acidification on Marine Calcifiers From the Southern Ocean. Front. Mar. Sci. 8, 24. https://doi.org/10.3389/fmars.2021.584445

Flannery, W., Ellis, G., Ellis, G., Flannery, W., Nursey-Bray, M., van Tatenhove, J.P.M., Kelly, C., Coffen-Smout, S., Fairgrieve, R., Knol, M., Jentoft, S., Bacon, D., O'Hagan, A.M., 2016. Exploring the winners and losers of marine environmental governance. Plan. Theory Pract. 17, 121–151. https://doi.org/10.1080/14649357.2015.1131482

Flannery, W., Healy, N., Luna, M., 2018. Exclusion and non-participation in Marine Spatial Planning. Mar. Policy 88, 32–40. https://doi.org/10.1016/j.marpol.2017.11.001

FLNRORD, 2020. Howe Sound Cumulative Effects Project - Province of British Columbia. Province of British Columbia.

Foley, M.M., Halpern, B.S., Micheli, F., Armsby, M.H., Caldwell, M.R., Crain, C.M., Prahler, E., Rohr, N., Sivas, D., Beck, M.W., Carr, M.H., Crowder, L.B., Emmett Duffy, J., Hacker, S.D., McLeod, K.L., Palumbi, S.R., Peterson, C.H., Regan, H.M., Ruckelshaus, M.H., Sandifer, P.A., Steneck, R.S., 2010. Guiding ecological principles for marine spatial planning. Mar. Policy 34, 955–966. https://doi.org/10.1016/j.marpol.2010.02.001

Folke, C., Carpenter, S., Walker, B., Scheffer, M., Elmqvist, T., Gunderson, L., Holling, C.S., 2004. Regime Shifts, Resilience, and Biodiversity in Ecosystem Management. Annu. Rev. Ecol. Evol. Syst. 35, 557–581.

Forster, J., Turner, R.A., Fitzsimmons, C., Peterson, A.M., Mahon, R., Stead, S.M., 2017. Evidence of a common understanding of proximate and distal drivers of reef health. Mar. Policy 84, 263–272. https://doi.org/10.1016/j.marpol.2017.07.017

Fox, J., Weisberg, S., Price, B., Adler, D., Bates, D., Baud-Bovy, G., Bolker, B., Ellison, S., Firth, D., Friendly, M., Gorjanc, G., Graves, S., Heiberger, R., Krivitsky, P., Laboissiere, R., Maechler, M., Monette, G., Murdoch, D., Nilsson, H., Ogle, D., Ripley, B., Venables, W., Walker, S., Winsemius, D., Zeileis, A., R-Core, 2021. car: Companion to Applied Regression.

Frazão Santos, C., Ehler, C.N., Agardy, T., Andrade, F., Orbach, M.K., Crowder, L.B., 2019. Chapter 30 - Marine Spatial Planning, in: Sheppard, C. (Ed.), World Seas: An Environmental Evaluation (Second Edition). Academic Press, pp. 571–592. https://doi.org/10.1016/B978-0-12-805052-1.00033-4

Friel, S., Arthur, M., Frank, N., 2022. Power and the planetary health equity crisis. The Lancet 400, 1085–1087. https://doi.org/10.1016/S0140-6736(22)01544-6

García-Díez, V., Link to external site, this link will open in a new window, García-Llorente, M., Link to external site, this link will open in a new window, González, J.A., Link to external site, this link will open in a new window, 2020. Participatory Mapping of Cultural

Ecosystem Services in Madrid: Insights for Landscape Planning. Land 9, 244. http://dx.doi.org/10.3390/land9080244

Garcia-Martin, M., Link to external site, this link will open in a new window, Fagerholm, N., Bieling, C., Gounaridis, D., Kizos, T., Printsmann, A., Müller, M., Lieskovský, J., Plieninger, T., 2017. Participatory mapping of landscape values in a Pan-European perspective. Landsc. Ecol. 32, 2133–2150. http://dx.doi.org/10.1007/s10980-017-0531-x

Gee, K., Kannen, A., Adlam, R., Brooks, C., Chapman, M., Cormier, R., Fischer, C., Fletcher, S., Gubbins, M., Shucksmith, R., Shellock, R., 2017. Identifying culturally significant areas for marine spatial planning. Ocean Coast. Manag. 136, 139–147. https://doi.org/10.1016/j.ocecoaman.2016.11.026

Gilman, S., Hayford, H., Craig, C., Carrington, E., 2015. Body temperatures of an intertidal barnacle and two whelk predators in relation to shore height, solar aspect, and microhabitat. Mar. Ecol. Prog. Ser. 536, 77–88. https://doi.org/10.3354/meps11418

Gilman, S.E., Wethey, D.S., Helmuth, B., 2006. Variation in the sensitivity of organismal body temperature to climate change over local and geographic scales. Proc. Natl. Acad. Sci. 103, 9560–9565. https://doi.org/10.1073/pnas.0510992103

Government of Canada, F. and O.C., 2019. Data from BC lightstations [WWW Document]. URL https://www.dfo-mpo.gc.ca/science/data-donnees/lightstations-phares/index-eng.html (accessed 6.25.22).

Gräns, A., Jutfelt, F., Sandblom, E., Jönsson, E., Wiklander, K., Seth, H., Olsson, C., Dupont, S., Ortega-Martinez, O., Einarsdottir, I., Björnsson, B.T., Sundell, K., Axelsson, M., 2014. Aerobic scope fails to explain the detrimental effects on growth resulting from warming and elevated CO2 in Atlantic halibut. J. Exp. Biol. 217, 711–717. https://doi.org/10.1242/jeb.096743

Greene, G.H., Delaney, J.R., Sulc, A.A., 2022. The Marginal Salish Sea as an Urban Sea – Comparisons with the Baltic Sea, in: Assessing the Baltic Sea Earth System. Presented at the Baltic Earth Conference, Geesthacht, pp. 232–233.

Grenz, J.B., 2020. Healing the Land by Reclaiming an Indigenous Ecology: A journey exploring the application of the Indigenous worldview to invasion biology and ecology (PhD). University of British Columbia.

Gunderson, L.H., Holling, C.S. (Eds.), 2002. Panarchy: understanding transformations in human and natural systems. Island Press, Washington.

Gurevitch, J., Morrison, J.A., Hedges, L.V., 2000. The Interaction between Competition and Predation: A Meta-analysis of Field Experiments. Am. Nat. 155, 435–453. https://doi.org/10.1086/303337

Halpern, B.S., Frazier, M., Potapenko, J., Casey, K.S., Koenig, K., Longo, C., Lowndes, J.S., Rockwood, R.C., Selig, E.R., Selkoe, K.A., Walbridge, S., 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. Nat. Commun. 6, 7615. https://doi.org/10.1038/ncomms8615

Halpern, B.S., Fujita, R., 2013. Assumptions, challenges, and future directions in cumulative impact analysis. Ecosphere 4, art131. https://doi.org/10.1890/ES13-00181.1

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., Watson, R., 2008. A Global Map of Human Impact on Marine Ecosystems. Science 319, 948–952.

Hamman, E.A., Pappalardo, P., Bence, J.R., Peacor, S.D., Osenberg, C.W., 2018. Bias in meta-analyses using Hedges' *d*. Ecosphere 9, e02419. https://doi.org/10.1002/ecs2.2419

Harley, C.D.G., Connell, S.D., Doubleday, Z.A., Kelaher, B., Russell, B.D., Sarà, G., Helmuth, B., 2017. Conceptualizing ecosystem tipping points within a physiological framework. Ecol. Evol. 7, 6035–6045. https://doi.org/10.1002/ece3.3164

Harley, C.D.G., Emry, S., Beaty, F., Li, J., Gehman, A., Brownlee, G., Burtlake, C., Kennedy, J., Hesketh, A., 2023. Mortality patterns at multiple scales following an extreme heatwave: An intertidal post-mortem of the 2021 Western North American Heat Dome. Prep.

Harley, C.D.G., Randall Hughes, A., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L., Williams, S.L., 2006. The impacts of climate change in coastal marine systems. Ecol. Lett. 9, 228–241. https://doi.org/10.1111/j.1461-0248.2005.00871.x

Harvey, B.P., Gwynn-Jones, D., Moore, P.J., 2013. Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecol. Evol. 3, 1016–1030. https://doi.org/10.1002/ece3.516

Harvey, B.P., Marshall, K.E., Harley, C.D.G., Russell, B.D., 2021. Predicting responses to marine heatwaves using functional traits. Trends Ecol. Evol. S0169534721002500. https://doi.org/10.1016/j.tree.2021.09.003

Hawkes, C.V., Sullivan, J.J., 2001. The Impact of Herbivory on Plants in Different Resource Conditions: A Meta-Analysis. Ecology 82, 2045–2058. https://doi.org/10.1890/0012-9658(2001)082[2045:TIOHOP]2.0.CO;2

Hayford, H., Gilman, S., Carrington, E., 2015. Foraging behavior minimizes heat exposure in a complex thermal landscape. Mar. Ecol. Prog. Ser. 518, 165–175. https://doi.org/10.3354/meps11053

Hayford, H.A., Gilman, S.E., Carrington, E., 2021. Tidal cues reduce thermal risk of climate change in a foraging marine snail. Clim. Change Ecol. 1, 100003. https://doi.org/10.1016/j.ecochg.2021.100003

Hayford, H.A., O'Donnell, M.J., Carrington, E., 2018. Radio tracking detects behavioral thermoregulation at a snail's pace. J. Exp. Mar. Biol. Ecol. 499, 17–25. https://doi.org/10.1016/j.jembe.2017.12.005

Hedges, L.V., Gurevitch, J., Curtis, P.S., 1999. The Meta-Analysis of Response Ratios in Experimental Ecology. Ecology 80, 1150–1156. https://doi.org/10.1890/0012-9658(1999)080[1150:TMAORR]2.0.CO;2

Hedges, L.V., Pigott, T.D., 2004. The Power of Statistical Tests for Moderators in Meta-Analysis. Psychol. Methods 9, 426–445. https://doi.org/10.1037/1082-989X.9.4.426

Hedges, Olkin, 1985. Estimation of a Single Effect Size: Parametric and Nonparametric Methods 32.

Helmuth, B., Broitman, B.R., Blanchette, C.A., Gilman, S., Halpin, P., Harley, C.D.G., O'Donnell, M.J., Hofmann, G.E., Menge, B., Strickland, D., 2006. Mosaic Patterns of Thermal Stress in the Rocky Intertidal Zone: Implications for Climate Change. Ecol. Monogr. 76, 461–479.

Helmuth, B., Harley, C.D.G., Halpin, P.M., O'Donnell, M., Hofmann, G.E., Blanchette, C.A., 2002. Climate Change and Latitudinal Patterns of Intertidal Thermal Stress. Science 298, 1015–1017.

Hendry, A.P., Gonzalez, A., 2008. Whither adaptation? Biol. Philos. 23, 673. https://doi.org/10.1007/s10539-008-9126-x

Hereford, J., Elle, A.E.E., Geber, E.M.A., 2009. A Quantitative Survey of Local Adaptation and Fitness Trade-Offs. Am. Nat. 173, 579–588. https://doi.org/10.1086/597611

Heuer, R.M., Grosell, M., 2014. Physiological impacts of elevated carbon dioxide and ocean acidification on fish. Am. J. Physiol.-Regul. Integr. Comp. Physiol. 307, R1061–R1084. https://doi.org/10.1152/ajpregu.00064.2014

Hill, T.S., Hoogenboom, M.O., 2022. The indirect effects of ocean acidification on corals and coral communities. Coral Reefs 41, 1557–1583. https://doi.org/10.1007/s00338-022-02286-z

Hoffman, A.J., 2021. The Engaged Scholar: Expanding the Impact of Academic Research in Today's World. Stanford University Press, Stanford.

Holling, C.S., 1973. Resilience and Stability of Ecological Systems. Annu. Rev. Ecol. Syst. 4, 1–23. https://doi.org/10.1146/annurev.es.04.110173.000245

Huey, R.B., 2002. Plants Versus Animals: Do They Deal with Stress in Different Ways? Integr. Comp. Biol. 42, 415–423. https://doi.org/10.1093/icb/42.3.415

Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J., Lough, J.M., Marshall, P., Nyström, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B., Roughgarden, J., 2003. Climate Change, Human Impacts, and the Resilience of Coral Reefs. Science 301, 929–933. https://doi.org/10.1126/science.1085046

Ianson, D., Allen, S.E., Moore-Maley, B.L., Johannessen, S.C., Macdonald, and R.W., 2016. Vulnerability of a semienclosed estuarine sea to ocean acidification in contrast with hypoxia. Geophys. Res. Lett. 43, 2016GL068996. https://doi.org/10.1002/2016GL068996

IPBES, Brondízio, E.S., Settele, J., Díaz, S., Ngo, H.T., 2019. Global assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES secretariat, Bonn, Germany.

IPCC, 2021. Summary for Policymakers, Climate Change 2012: They Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Cambridge University Press.

IPCC, 2019. Summary for Policymakers (In press.), In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. IPCC, [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)].

IPCC, 2018. Global Warming of 1.5°C: IPCC Special Report on impacts of global warming of 1.5°C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty, 1st ed. Cambridge University Press. https://doi.org/10.1017/9781009157940

Iwabuchi, B.L., Gosselin, L.A., 2020. Implications of acute temperature and salinity tolerance thresholds for the persistence of intertidal invertebrate populations experiencing climate change. Ecol. Evol. 10, 7739–7754. https://doi.org/10.1002/ece3.6498

Jarnıkova, T., 2022. A submesoscale modelling approach to understanding the past, present, and future carbonate chemistry balance of the Salish Sea. University of British Columbia, Vancouver, B.C. Canada.

Jaureguiberry, P., Titeux, N., Wiemers, M., Bowler, D.E., Coscieme, L., Golden, A.S., Guerra, C.A., Jacob, U., Takahashi, Y., Settele, J., Díaz, S., Molnár, Z., Purvis, A., 2022. The direct drivers of recent global anthropogenic biodiversity loss. Sci. Adv. 8, eabm9982. https://doi.org/10.1126/sciadv.abm9982

Johannessen, S., Macdonald, R., 2009. Effects of local and global change on an inland sea: the Strait of Georgia, British Columbia, Canada. Clim. Res. 40, 1–21. https://doi.org/10.3354/cr00819

Jones, J., Keller, P., van der Flier Keller, E., 2021. Review of official responsibility for the Salish Sea marine environment. Ocean Coast. Manag. 211, 105748. https://doi.org/10.1016/j.ocecoaman.2021.105748

JPL MUR MEaSUREs Project., 2015. GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis. Ver. 4.1. PO.DAAC, CA, USA. [WWW Document]. Phys. Oceanogr. Distrib. Act. Arch. Cent. PODAAC. URL https://doi.org/10.5067/GHGMR-4FJ04 (accessed 6.24.22).

Jutfelt, F., Norin, T., Ern, R., Overgaard, J., Wang, T., McKenzie, D.J., Lefevre, S., Nilsson, G.E., Metcalfe, N.B., Hickey, A.J.R., Brijs, J., Speers-Roesch, B., Roche, D.G., Gamperl, A.K., Raby, G.D., Morgan, R., Esbaugh, A.J., Gräns, A., Axelsson, M., Ekström, A., Sandblom, E., Binning, S.A., Hicks, J.W., Seebacher, F., Jørgensen, C., Killen, S.S., Schulte, P.M., Clark, T.D., 2018. Oxygen- and capacity-limited thermal tolerance: blurring ecology and physiology. J. Exp. Biol. 221. https://doi.org/10.1242/jeb.169615

Karimi, A., Brown, G., Hockings, M., 2015. Methods and participatory approaches for identifying social-ecological hotspots. Appl. Geogr. 63, 9–20. https://doi.org/10.1016/j.apgeog.2015.06.003

Kawecki, T.J., Ebert, D., 2004. Conceptual issues in local adaptation. Ecol. Lett. 7, 1225–1241. https://doi.org/10.1111/j.1461-0248.2004.00684.x

Kehoe, L.J., Lund, J., Chalifour, L., Asadian, Y., Balke, E., Boyd, S., Carlson, D., Casey, J.M., Connors, B., Cryer, N., Drever, M.C., Hinch, S., Levings, C., MacDuffee, M., McGregor,

H., Richardson, J., Scott, D.C., Stewart, D., Vennesland, R.G., Wilkinson, C.E., Zevit, P., Baum, J.K., Martin, T.G., 2021. Conservation in heavily urbanized biodiverse regions requires urgent management action and attention to governance. Conserv. Sci. Pract. 3, e310. https://doi.org/10.1111/csp2.310

Kingsolver, J.G., 2009. The Well-Temperatured Biologist: (American Society of Naturalists Presidential Address). Am. Nat. 174, 755–768. https://doi.org/10.1086/648310

Kingsolver, J.G., Huey, R.B., 2008. Size, temperature, and fitness: three rules. Evol. Ecol. Res. 10, 251–268.

Kitikmeot Inuit Association, 2015. Naonaiyaotit Traditional Knowledge Project Atlas.

Klain, S.C., Chan, K.M.A., 2012. Navigating coastal values: Participatory mapping of ecosystem services for spatial planning. Ecol. Econ. 82, 104–113. https://doi.org/10.1016/j.ecolecon.2012.07.008

Klain, S.C., Olmsted, P., Chan, K.M.A., Satterfield, T., 2017. Relational values resonate broadly and differently than intrinsic or instrumental values, or the New Ecological Paradigm. PLOS ONE 12, e0183962. https://doi.org/10.1371/journal.pone.0183962

Knight, A.T., Cowling, R.M., Rouget, M., Balmford, A., Lombard, A.T., Campbell, B.M., 2008. Knowing but Not Doing: Selecting Priority Conservation Areas and the Research-Implementation Gap. Conserv. Biol. 22, 610–617.

Knutti, R., 2019. Closing the Knowledge-Action Gap in Climate Change. One Earth 1, 21–23. https://doi.org/10.1016/j.oneear.2019.09.001

Korell, L., Auge, H., Chase, J.M., Harpole, S., Knight, T.M., 2020. We need more realistic climate change experiments for understanding ecosystems of the future. Glob. Change Biol. 26, 325–327. https://doi.org/10.1111/gcb.14797

Koricheva, J., Gurevitch, J., Mengersen, K. (Eds.), 2013. Handbook of meta-analysis in ecology and evolution. Princeton University Press, Princeton.

Kroeker, K.J., Bell, L.E., Donham, E.M., Hoshijima, U., Lummis, S., Toy, J.A., Willis-Norton, E., 2020a. Ecological change in dynamic environments: Accounting for temporal environmental variability in studies of ocean change biology. Glob. Change Biol. 26, 54–67. https://doi.org/10.1111/gcb.14868

Kroeker, K.J., Bell, L.E., Donham, E.M., Hoshijima, U., Lummis, S., Toy, J.A., Willis-Norton, E., 2020b. Ecological change in dynamic environments: Accounting for temporal environmental variability in studies of ocean change biology. Glob. Change Biol. 26, 54–67. https://doi.org/10.1111/gcb.14868

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.-P., 2013a. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob. Change Biol. 19, 1884–1896. https://doi.org/10.1111/gcb.12179

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.-P., 2013b. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Glob. Change Biol. 19, 1884–1896. https://doi.org/10.1111/gcb.12179

Kroeker, K.J., Kordas, R.L., Harley, C.D.G., 2017. Embracing interactions in ocean acidification research: confronting multiple stressor scenarios and context dependence. Biol. Lett. 13, 20160802. https://doi.org/10.1098/rsbl.2016.0802

Kuo, E.S.L., Sanford, E., 2009. Geographic variation in the upper thermal limits of an intertidal snail: implications for climate envelope models. Mar. Ecol. Prog. Ser. 388, 137–146. https://doi.org/10.3354/meps08102

Lajeunesse, M.J., 2015. Bias and correction for the log response ratio in ecological meta-analysis. Ecology 96, 2056–2063. https://doi.org/10.1890/14-2402.1

Lajeunesse, M.J., 2011. On the meta-analysis of response ratios for studies with correlated and multi-group designs. Ecology 92, 2049–2055. https://doi.org/10.1890/11-0423.1

Lancaster, D., Dearden, P., Ban, N.C., 2015. Drivers of recreational fisher compliance in temperate marine conservation areas: A study of Rockfish Conservation Areas in British Columbia, Canada. Glob. Ecol. Conserv. 4, 645–657. https://doi.org/10.1016/j.gecco.2015.11.004

Lauchlan, S.S., Nagelkerken, I., 2020. Species range shifts along multistressor mosaics in estuarine environments under future climate. Fish Fish. 21, 32–46. https://doi.org/10.1111/faf.12412

Lefevre, S., 2016. Are global warming and ocean acidification conspiring against marine ectotherms? A meta-analysis of the respiratory effects of elevated temperature, high CO2 and their interaction. Conserv. Physiol. 4. https://doi.org/10.1093/conphys/cow009

Lenoir, J., Bertrand, R., Comte, L., Bourgeaud, L., Hattab, T., Murienne, J., Grenouillet, G., 2020. Species better track climate warming in the oceans than on land. Nat. Ecol. Evol. 4, 1044–1059. https://doi.org/10.1038/s41559-020-1198-2

Leung, J.Y.S., Zhang, S., Connell, S.D., 2022. Is Ocean Acidification Really a Threat to Marine Calcifiers? A Systematic Review and Meta-Analysis of 980+ Studies Spanning Two Decades. Small n/a, 2107407. https://doi.org/10.1002/smll.202107407

Levin, S., Xepapadeas, T., Crépin, A.-S., Norberg, J., al, et, 2013. Social-ecological systems as complex adaptive systems: modeling and policy implications. Environ. Dev. Econ. 18, 111–132. https://doi.org/10.1017/S1355770X12000460

Levine, J., Chan, K.M.A., 2013. Global human dependence on ecosystem services, in: Ecosystem Services and Global Trade of Natural Resources: Ecology, Economics and Policies. Routledge, pp. 28–45. https://doi.org/10.4324/9780203816639-11

Liboiron, M., 2021. Pollution Is Colonialism. https://doi.org/10.1215/9781478021445

Lindo, J., Achilli, A., Perego, U.A., Archer, D., Valdiosera, C., Petzelt, B., Mitchell, J., Worl, R., Dixon, E.J., Fifield, T.E., Rasmussen, M., Willerslev, E., Cybulski, J.S., Kemp, B.M., DeGiorgio, M., Malhi, R.S., 2017. Ancient individuals from the North American Northwest Coast reveal 10,000 years of regional genetic continuity. Proc. Natl. Acad. Sci. U. S. A. 114, 4093–4098. https://doi.org/10.1073/pnas.1620410114

Ljubicic, G.J., Pulsifer, P.L., Hayes, A., Taylor, D.R.F., 2014. Chapter 14 - The Creation of the Inuit siku (Sea Ice) Atlas, in: Taylor, D.R.F. (Ed.), Modern Cartography Series, Developments in the Theory and Practice of Cybercartography. Academic Press, pp. 201–218. https://doi.org/10.1016/B978-0-444-62713-1.00014-3

Locke, H., Ellis, E.C., Venter, O., Schuster, R., Ma, K., Shen, X., Woodley, S., Kingston, N., Bhola, N., Strassburg, B.B.N., Paulsch, A., Williams, B., Watson, J.E.M., 2019. Three global conditions for biodiversity conservation and sustainable use: an implementation framework. Natl. Sci. Rev. 6, 1080–1082. https://doi.org/10.1093/nsr/nwz136

Lucey, N.M., Lombardi, C., DeMarchi, L., Schulze, A., Gambi, M.C., Calosi, P., 2015. To brood or not to brood: Are marine invertebrates that protect their offspring more resilient to ocean acidification? Sci. Rep. 5, 12009. https://doi.org/10.1038/srep12009

Margules, C., Boedhihartono, A.K., Langston, J.D., Riggs, R.A., Sari, D.A., Sarkar, S., Sayer, J.A., Supriatna, J., Winarni, N.L., 2020. Transdisciplinary science for improved conservation outcomes. Environ. Conserv. 1–10. https://doi.org/10.1017/S0376892920000338

Marko, P.B., 2004. 'What's larvae got to do with it?' Disparate patterns of post-glacial population structure in two benthic marine gastropods with identical dispersal potential. Mol. Ecol. 13, 597–611. https://doi.org/10.1046/j.1365-294X.2004.02096.x

Marshall, D.J., Pettersen, A.K., Bode, M., White, C.R., 2020. Developmental cost theory predicts thermal environment and vulnerability to global warming. Nat. Ecol. Evol. 4, 406–411. https://doi.org/10.1038/s41559-020-1114-9

Marshall, D.J., Rezende, E.L., Baharuddin, N., Choi, F., Helmuth, B., 2015. Thermal tolerance and climate warming sensitivity in tropical snails. Ecol. Evol. 5, 5905–5919. https://doi.org/10.1002/ece3.1785

Marshall, K.E., Anderson, K.M., Brown, N.E.M., Dytnerski, J.K., Flynn, K.L., Bernhardt, J.R., Konecny, C.A., Gurney-Smith, H., Harley, C.D.G., 2021. Whole-organism responses to constant temperatures do not predict responses to variable temperatures in the ecosystem engineer Mytilus trossulus. Proc. R. Soc. B Biol. Sci. 288, 20202968. https://doi.org/10.1098/rspb.2020.2968

Masterson, V.A., Stedman, R.C., Enqvist, J., Tengö, M., Giusti, M., Wahl, D., Svedin, U., 2017. The contribution of sense of place to social-ecological systems research: a review and research agenda. Ecol. Soc. 22.

Mauger, G., Smith, A., Dittbrenner, C., Lee, S.-Y., Won, J., 2018. Mapping the future of flood risk in the Snohomish and Stillaguamish basins, in: Salish Sea Ecosystem Conference.

Mavson, O., Basf, R., Palmer, A.R., 2018. Lamellose Axial Shell Sculpture Reduces Gastropod Vulnerability to Sea Star Predation. Biol. Bull. 235, 24–30.

MCA, 2019. Atl'ka7tsem/Howe Sound Conservation [WWW Document]. URL https://howesoundconservation.ca/mapapp/ (accessed 11.25.22).

McDonald, K.S., Hobday, A.J., Fulton, E.A., Thompson, P.A., 2018. Interdisciplinary knowledge exchange across scales in a globally changing marine environment. Glob. Change Biol. 24, 3039–3054. https://doi.org/10.1111/gcb.14168

McEvoy, D., Fünfgeld, H., Bosomworth, K., 2013. Resilience and Climate Change Adaptation: The Importance of Framing. Plan. Pract. Res. 28, 280–293. https://doi.org/10.1080/02697459.2013.787710

MEA (Ed.), 2005. Ecosystems and Human Well-being. A framework for assessment, Chapter 6. Concepts of ecosystem value and valuating approaches. Island Press, Washington, DC.

Meester, L.D., Stoks, R., Brans, K.I., 2018. Genetic adaptation as a biological buffer against climate change: Potential and limitations. Integr. Zool. 13, 372–391. https://doi.org/10.1111/1749-4877.12298

Miller, A., 2020. Ocean Watch: Howe Sound/Atl'ka7tsem Edition, Ocean Watch. Ocean Wise Marine Conservation Association, Vancouver, B.C. Canada.

Miller, F., Osbahr, H., Boyd, E., Thomalla, F., Bharwani, S., Ziervogel, G., Walker, B., Birkmann, J., van der Leeuw, S., Rockström, J., Hinkel, J., Downing, T., Folke, C., Nelson, D., 2010. Resilience and Vulnerability: Complementary or Conflicting Concepts? Ecol. Soc. 15. https://doi.org/10.5751/ES-03378-150311

Monaco, C.J., Helmuth, B., 2011. Chapter Three - Tipping Points, Thresholds and the Keystone Role of Physiology in Marine Climate Change Research, in: Lesser, M. (Ed.), Advances in Marine Biology, Advances in Marine Biology. Academic Press, pp. 123–160. https://doi.org/10.1016/B978-0-12-385529-9.00003-2

Moon, K., Blackman, D., 2014. A Guide to Understanding Social Science Research for Natural Scientists. Conserv. Biol. 28, 1167–1177. https://doi.org/10.1111/cobi.12326

Moore, S.A., Brown, G., Kobryn, H., Strickland-Munro, J., 2017. Identifying conflict potential in a coastal and marine environment using participatory mapping. J. Environ. Manage. 197, 706–718. https://doi.org/10.1016/j.jenvman.2016.12.026

Morgan Jones, M., Manville, C., Chataway, J., 2022. Learning from the UK's research impact assessment exercise: a case study of a retrospective impact assessment exercise and questions for the future. J. Technol. Transf. 47, 722–746. https://doi.org/10.1007/s10961-017-9608-6

Morley, S.A., Peck, L.S., Sunday, J.M., Heiser, S., Bates, A.E., 2019. Physiological acclimation and persistence of ectothermic species under extreme heat events. Glob. Ecol. Biogeogr. 0. https://doi.org/10.1111/geb.12911

Morris, W.F., Hufbauer, R.A., Agrawal, A.A., Bever, J.D., Borowicz, V.A., Gilbert, G.S., Maron, J.L., Mitchell, C.E., Parker, I.M., Power, A.G., Torchin, M.E., Vázquez, D.P., 2007. Direct and Interactive Effects of Enemies and Mutualists on Plant Performance: A Meta-Analysis. Ecology 88, 1021–1029. https://doi.org/10.1890/06-0442

MSI, 2021. Átl'k̲a7tsem/Howe Sound Marine Stewardship Initiative. URL https://howesoundguide.ca/ (accessed 11.2.22).

Muir, M.J., Schwartz, M.W., 2009. Academic Research Training for a Nonacademic Workplace: a Case Study of Graduate Student Alumni Who Work in Conservation. Conserv. Biol. 23, 1357–1368. https://doi.org/10.1111/j.1523-1739.2009.01325.x

Munday, P.L., Warner, R.R., Monro, K., Pandolfi, J.M., Marshall, D.J., 2013. Predicting evolutionary responses to climate change in the sea. Ecol. Lett. 16, 1488–1500. https://doi.org/10.1111/ele.12185

Nay, T.J., Johansen, J.L., Habary, A., Steffensen, J.F., Rummer, J.L., 2015. Behavioural thermoregulation in a temperature-sensitive coral reef fish, the five-lined cardinalfish (Cheilodipterus quinquelineatus). Coral Reefs 34, 1261–1265. https://doi.org/10.1007/s00338-015-1353-4

Nowlan, L., 2016. Brave New Wave: Marine Spatial Planning and Ocean Regulation on Canada's Pacific. J. Environ. Law Pract. 29, 151–201.

Ocean Studies Board, 2022. Cross-Cutting Themes for U.S. Contributions to the UN Ocean Decade. National Academy of Sciences. https://doi.org/10.17226/26363

O'Connor, M.I., Bruno, J.F., Gaines, S.D., Halpern, B.S., Lester, S.E., Kinlan, B.P., Weiss, J.M., 2007. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. Proc. Natl. Acad. Sci. U. S. A. 104, 1266–1271. https://doi.org/10.1073/pnas.0603422104

O'Dea, R.E., Lagisz, M., Jennions, M.D., Koricheva, J., Noble, D.W.A., Parker, T.H., Gurevitch, J., Page, M.J., Stewart, G., Moher, D., Nakagawa, S., 2021. Preferred reporting items for systematic reviews and meta-analyses in ecology and evolutionary biology: a PRISMA extension. Biol. Rev. 96, 1695–1722. https://doi.org/10.1111/brv.12721

OECD, 2016. The Ocean Economy in 2030. OECD Publishing, Paris.

O'Hara, G., 2007. Water Management Aspects of the Britannia Mine Remediation Project, British Columbia, Canada. Mine Water Environ. 26, 46–54. https://doi.org/10.1007/s10230-007-0148-4

Onwuegbuzie, A.J., Collins, K.M.T., 2007. A Typology of Mixed Methods Sampling Designs in Social Science Research 38.

Orr, J.A., Vinebrooke, R.D., Jackson, M.C., Kroeker, K.J., Kordas, R.L., Mantyka-Pringle, C., Van den Brink, P.J., De Laender, F., Stoks, R., Holmstrup, M., Matthaei, C.D., Monk, W.A., Penk, M.R., Leuzinger, S., Schäfer, R.B., Piggott, J.J., 2020. Towards a unified study of multiple stressors: divisions and common goals across research disciplines. Proc. R. Soc. B Biol. Sci. 287, 20200421. https://doi.org/10.1098/rspb.2020.0421

Ostrom, E., 2009. A General Framework for Analyzing Sustainability of Social-Ecological Systems. Science 325, 419–422. https://doi.org/10.1126/science.1172133

Otto, S.P., 2018. Adaptation, speciation and extinction in the Anthropocene. Proc. R. Soc. B Biol. Sci. 285, 20182047. https://doi.org/10.1098/rspb.2018.2047

Pacifici, M., Foden, W.B., Visconti, P., Watson, J.E.M., Butchart, S.H.M., Kovacs, K.M., Scheffers, B.R., Hole, D.G., Martin, T.G., Akçakaya, H.R., Corlett, R.T., Huntley, B.,

Bickford, D., Carr, J.A., Hoffmann, A.A., Midgley, G.F., Pearce-Kelly, P., Pearson, R.G., Williams, S.E., Willis, S.G., Young, B., Rondinini, C., 2015. Assessing species vulnerability to climate change. Nat. Clim. Change 5, 215–224. https://doi.org/10.1038/nclimate2448

Padilla-Gamiño, J.L., Gaitán-Espitia, J.D., Kelly, M.W., Hofmann, G.E., 2016. Physiological plasticity and local adaptation to elevated $p\,CO_2$ in calcareous algae: an ontogenetic and geographic approach. Evol. Appl. 9, 1043–1053. https://doi.org/10.1111/eva.12411

Paine, R.T., Tegner, M.J., Johnson, E.A., 1998. Compounded Perturbations Yield Ecological Surprises. Ecosystems 1, 535–545. https://doi.org/10.1007/s100219900049

Palacios-Abrantes, J., Frölicher, T.L., Reygondeau, G., Sumaila, U.R., Tagliabue, A., Wabnitz, C.C.C., Cheung, W.W.L., 2022. Timing and magnitude of climate-driven range shifts in transboundary fish stocks challenge their management. Glob. Change Biol. 28, 2312–2326. https://doi.org/10.1111/gcb.16058

Palmer, A.R., 1982. Growth in marine gastropods: a non-destructive technique for independently measuring shell and body weight. Malacologia, 1 63–73.

Pandori, L.L.M., Sorte, C.J.B., 2019. The weakest link: sensitivity to climate extremes across life stages of marine invertebrates. Oikos 128, 621–629. https://doi.org/10.1111/oik.05886

Parker, C., Scott, S., Geddes, A., 2019. Snowball Sampling, in: SAGE Research Methods Foundations. SAGE Publications Ltd, 1 Oliver's Yard, 55 City Road, London EC1Y 1SP United Kingdom. https://doi.org/10.4135/9781526421036831710

Pecl, G.T., Araújo, M.B., Bell, J.D., Blanchard, J., Bonebrake, T.C., Chen, I.-C., Clark, T.D., Colwell, R.K., Danielsen, F., Evengård, B., Falconi, L., Ferrier, S., Frusher, S., Garcia, R.A., Griffis, R.B., Hobday, A.J., Janion-Scheepers, C., Jarzyna, M.A., Jennings, S., Lenoir, J., Linnetved, H.I., Martin, V.Y., McCormack, P.C., McDonald, J., Mitchell, N.J., Mustonen, T., Pandolfi, J.M., Pettorelli, N., Popova, E., Robinson, S.A., Scheffers, B.R., Shaw, J.D., Sorte, C.J.B., Strugnell, J.M., Sunday, J.M., Tuanmu, M.-N., Vergés, A., Villanueva, C., Wernberg, T., Wapstra, E., Williams, S.E., 2017. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. Science 355. https://doi.org/10.1126/science.aai9214

Petersen, B., Aslan, C., Stuart, D., Beier, P., 2018. Incorporating Social and Ecological Adaptive Capacity into Vulnerability Assessments and Management Decisions for Biodiversity Conservation. BioScience 68, 371–380. https://doi.org/10.1093/biosci/biy020

Pick, J.L., Nakagawa, S., Noble, D.W.A., 2019. Reproducible, flexible and high-throughput data extraction from primary literature: The metaDigitise r package. Methods Ecol. Evol. 10, 426–431. https://doi.org/10.1111/2041-210X.13118

Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L., Sunday, J.M., 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature 569, 108–111. https://doi.org/10.1038/s41586-019-1132-4

Polfus, J.L., Manseau, M., Simmons, D., Neyelle, M., Bayha, W., Andrew, F., Andrew, L., Klütsch, C.F.C., Rice, K., Wilson, P., 2016. Łeghágots'enetę (learning together): the importance of indigenous perspectives in the identification of biological variation. Ecol. Soc. 21. https://doi.org/10.5751/ES-08284-210218

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C.V., O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A., Richardson, A.J., 2013. Global imprint of climate change on marine life. Nat. Clim. Change 3, 919–925. https://doi.org/10.1038/nclimate1958

Pörtner, H., 2012. Integrating climate-related stressor effects on marine organisms: unifying principles linking molecule to ecosystem-level changes. Mar. Ecol. Prog. Ser. 470, 273–290. https://doi.org/10.3354/meps10123

Pörtner, H.-O., 2021. Climate impacts on organisms, ecosystems and human societies: integrating OCLTT into a wider context. J. Exp. Biol. 224, jeb238360. https://doi.org/10.1242/jeb.238360

Pörtner, H.-O., 2010. Oxygen- and capacity-limitation of thermal tolerance: a matrix for integrating climate-related stressor effects in marine ecosystems. J. Exp. Biol. 213, 881–893. https://doi.org/10.1242/jeb.037523

Pörtner, H.O., Farrell, A.P., 2008. Physiology and Climate Change. Science 322, 690–692. https://doi.org/10.1126/science.1163156

Przeslawski, R., Byrne, M., Mellin, C., 2015. A review and meta-analysis of the effects of multiple abiotic stressors on marine embryos and larvae. Glob. Change Biol. 21, 2122–2140. https://doi.org/10.1111/gcb.12833

Ramirez-Gomez, S.O.I., Brown, G., Verweij, P.A., Boot, R., 2016. Participatory mapping to identify indigenous community use zones: Implications for conservation planning in southern Suriname. J. Nat. Conserv. 29, 69–78. https://doi.org/10.1016/j.jnc.2015.11.004

Raymond, C.M., Fazey, I., Reed, M.S., Stringer, L.C., Robinson, G.M., Evely, A.C., 2010. Integrating local and scientific knowledge for environmental management. J. Environ. Manage. 91, 1766–1777. https://doi.org/10.1016/j.jenvman.2010.03.023

Raymond, W.W., Barber, J.S., Dethier, M.N., Hayford, H.A., Harley, C.D.G., King, T.L., Paul, B., Speck, C.A., Tobin, E.D., Raymond, A.E.T., McDonald, P.S., 2022. Assessment of the impacts of an unprecedented heatwave on intertidal shellfish of the Salish Sea. Ecology 103, e3798. https://doi.org/10.1002/ecy.3798

Reid, A.J., Eckert, L.E., Lane, J.-F., Young, N., Hinch, S.G., Darimont, C.T., Cooke, S.J., Ban, N.C., Marshall, A., 2021. "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management. Fish Fish. 22, 243–261. https://doi.org/10.1111/faf.12516

Riche, O., Johannessen, S.C., Macdonald, R.W., 2014. Why timing matters in a coastal sea: Trends, variability and tipping points in the Strait of Georgia, Canada. J. Mar. Syst. 131, 36–53. https://doi.org/10.1016/j.jmarsys.2013.11.003

Rodolfo-Metalpa, R., Lombardi, C., Cocito, S., Hall-Spencer, J.M., Gambi, M.C., 2010. Effects of ocean acidification and high temperatures on the bryozoan Myriapora truncata at natural CO2 vents. Mar. Ecol. 31, 447–456. https://doi.org/10.1111/j.1439-0485.2009.00354.x

Rohr, J.R., Civitello, D.J., Cohen, J.M., Roznik, E.A., Sinervo, B., Dell, A.I., 2018. The complex drivers of thermal acclimation and breadth in ectotherms. Ecol. Lett. 21, 1425–1439. https://doi.org/10.1111/ele.13107

Rosenthal, R., 1979. The file drawer problem and tolerance for null results. Psychol. Bull. 86, 638–641. https://doi.org/10.1037/0033-2909.86.3.638

Rose-Redwood, R., Barnd, N.B., Lucchesi, A.H., Dias, S., Patrick, W., 2020. Decolonizing the Map: Recentering Indigenous Mappings. Cartogr. Int. J. Geogr. Inf. Geovisualization 55, 151–162.

Rubio-Aparicio, M., López-López, J.A., Viechtbauer, W., Marín-Martínez, F., Botella, J., Sánchez-Meca, J., 2020. Testing Categorical Moderators in Mixed-Effects Meta-analysis in the Presence of Heteroscedasticity. J. Exp. Educ. 88, 288–310. https://doi.org/10.1080/00220973.2018.1561404

Ryan, G.W., Bernard, H.R., 2003. Techniques to Identify Themes. Field Methods 15, 85–109. https://doi.org/10.1177/1525822X02239569

Saldaña, J., 2014. Coding and Analysis Strategies, in: Leavy, P. (Ed.), The Oxford Handbook of Qualitative Research. Oxford University Press, pp. 580–598. https://doi.org/10.1093/oxfordhb/9780199811755.013.001

Salomon, A.K., Quinlan, A.E., Pang, G.H., Okamoto, D.K., Vazquez-Vera, L., 2019. Measuring social-ecological resilience reveals opportunities for transforming environmental governance. Ecol. Soc. 24.

Sanford, E., Kelly, M.W., 2010. Local Adaptation in Marine Invertebrates. Annu. Rev. Mar. Sci. 3, 509–535. https://doi.org/10.1146/annurev-marine-120709-142756

Sanford, E., Roth, M.S., Glenn C. Johns, Wares, J.P., Somero, G.N., 2003. Local Selection and Latitudinal Variation in a Marine Predator-Prey Interaction. Science 300, 1135–1137.

Sanford, E., Worth, D.J., 2010. Local adaptation along a continuous coastline: Prey recruitment drives differentiation in a predatory snail. Ecology 91, 891–901.

Schiffers, K., Bourne, E.C., Lavergne, S., Thuiller, W., Travis, J.M.J., 2013. Limited evolutionary rescue of locally adapted populations facing climate change. Philos. Trans. R. Soc. B Biol. Sci. 368, 20120083. https://doi.org/10.1098/rstb.2012.0083

SeaChange, 2022. Salish Sea Nearshore Habitat Recovery Project. SeaChange Mar. Conserv. Soc. URL https://seachangesociety.com/restorationpg/ (accessed 11.25.22).

Shah, S.H., Rodina, L., Burt, J.M., Gregr, E.J., Chapman, M., Williams, S., Wilson, N.J., McDowell, G., 2018. Unpacking social-ecological transformations: Conceptual, ethical and methodological insights. Anthr. Rev. 5, 250–265. https://doi.org/10.1177/2053019618817928

Shwartz, A., Turbé, A., Julliard, R., Simon, L., Prévot, A.-C., 2014. Outstanding challenges for urban conservation research and action. Glob. Environ. Change 28, 39–49. https://doi.org/10.1016/j.gloenvcha.2014.06.002

Sinclair, B.J., Marshall, K.E., Sewell, M.A., Levesque, D.L., Willett, C.S., Slotsbo, S., Dong, Y., Harley, C.D.G., Marshall, D.J., Helmuth, B.S., Huey, R.B., 2016. Can we predict ectotherm responses to climate change using thermal performance curves and body temperatures? Ecol. Lett. 19, 1372–1385. https://doi.org/10.1111/ele.12686

Skinner, B., 2020. Utility of the Strait of Georgia Data Centre as a Marine Spatial Planning Tool, in: Salish Sea Ecosystem Conference.

Skwxwú7mesh Úxwumixw, 2022. Skwxwú7mesh Úxwumixw Strategic Plan 2026.

Sobocinski, K., 2021. The State of the Salish Sea. Salish Sea Institute, Western Washington University.

Sokolova, I.M., 2013. Energy-Limited Tolerance to Stress as a Conceptual Framework to Integrate the Effects of Multiple Stressors. Integr. Comp. Biol. 53, 597–608. https://doi.org/10.1093/icb/ict028

Somero, G.N., 2010. The physiology of climate change: how potentials for acclimatization and genetic adaptation will determine ‘winners’ and ‘losers.’ J. Exp. Biol. 213, 912–920. https://doi.org/10.1242/jeb.037473

Sorte, C.J.B., Hofmann, G.E., 2005. Thermotolerance and heat-shock protein expression in Northeastern Pacific<Emphasis Type="Italic"> Nucella</Emphasis> species with different biogeographical ranges. Mar. Biol. 146, 985–993. https://doi.org/10.1007/s00227-004-1508-2

Spight, T.M., 1974. Sizes of Populations of a Marine Snail. Ecology 55, 712–729. https://doi.org/10.2307/1934409

Spight, T.M., 1973. Ontogeny, environment, and shape of a marine snail Thais lamellosa Gmelin. J. Exp. Mar. Biol. Ecol. 13, 215–228. https://doi.org/10.1016/0022-0981(73)90068-3

St. Martin, K., Hall-Arber, M., 2008. The missing layer: Geo-technologies, communities, and implications for marine spatial planning. Mar. Policy 32, 779–786. https://doi.org/10.1016/j.marpol.2008.03.015

Stevenson, A., Archer, S.K., Schultz, J.A., Dunham, A., Marliave, J.B., Martone, P., Harley, C.D.G., 2020. Warming and acidification threaten glass sponge Aphrocallistes vastus pumping and reef formation. Sci. Rep. 10, 8176. https://doi.org/10.1038/s41598-020-65220-9

Stewart, N.L., Konar, B., 2012. Kelp Forests versus Urchin Barrens: Alternate Stable States and Their Effect on Sea Otter Prey Quality in the Aleutian Islands [WWW Document]. J. Mar. Biol. https://doi.org/10.1155/2012/492308

Stock, A., Haupt, A.J., Mach, M.E., Micheli, F., 2018. Mapping ecological indicators of human impact with statistical and machine learning methods: Tests on the California coast. Ecol. Inform. 48, 37–47. https://doi.org/10.1016/j.ecoinf.2018.07.007

Strickland-Munro, J., Kobryn, H., Brown, G., Moore, S.A., 2016. Marine spatial planning for the future: Using Public Participation GIS (PPGIS) to inform the human dimension for large marine parks. Mar. Policy 73, 15–26. https://doi.org/10.1016/j.marpol.2016.07.011

Suldovsky, B.S., 2018. The Information Deficit Model and Climate Change Communication, in: The Oxford Encyclopedia of Climate Change Communication. Oxford University Press.

Sumaila, R., Konar, M., Hart, B., 2020. 7 Ways to Bridge the Blue Finance Gap.

Sunday, J.M., Bates, A.E., Dulvy, N.K., 2012. Thermal tolerance and the global redistribution of animals. Nat. Clim. Change 2, 686–690. https://doi.org/10.1038/nclimate1539

Sunday, J.M., Bates, A.E., Dulvy, N.K., 2011a. Global analysis of thermal tolerance and latitude in ectotherms. Proc. R. Soc. B Biol. Sci. 278, 1823–1830. https://doi.org/10.1098/rspb.2010.1295

Sunday, J.M., Bates, A.E., Kearney, M.R., Colwell, R.K., Dulvy, N.K., Longino, J.T., Huey, R.B., 2014. Thermal-safety margins and the necessity of thermoregulatory behavior across latitude and elevation. Proc. Natl. Acad. Sci. 111, 5610–5615. https://doi.org/10.1073/pnas.1316145111

Sunday, J.M., Crim, R.N., Harley, C.D.G., Hart, M.W., 2011b. Quantifying Rates of Evolutionary Adaptation in Response to Ocean Acidification. PLOS ONE 6, e22881. https://doi.org/10.1371/journal.pone.0022881

Tangwancharoen, S., Semmens, B.X., Burton, R.S., 2020. Allele-Specific Expression and Evolution of Gene Regulation Underlying Acute Heat Stress Response and Local Adaptation in the Copepod Tigriopus californicus. J. Hered. 111, 539–547. https://doi.org/10.1093/jhered/esaa044

Thier, K., Lin, T., 2022. How Solutions Journalism Shapes Support for Collective Climate Change Adaptation. Environ. Commun. 0, 1–19. https://doi.org/10.1080/17524032.2022.2143842

Thompson, P.L., MacLennan, M.M., Vinebrooke, R.D., 2018. An improved null model for assessing the net effects of multiple stressors on communities. Glob. Change Biol. 24, 517–525. https://doi.org/10.1111/gcb.13852

Thorne, N., Moss, M., 2022. Unmarked Graves: Yet another Legacy of Canada's Residential School System: An Interview with Niki Thorne. New Am. Stud. J. Forum 72. https://doi.org/10.18422/72-24

Tran, T.C., Ban, N.C., Bhattacharyya, J., 2020. A review of successes, challenges, and lessons from Indigenous protected and conserved areas. Biol. Conserv. 241, 108271. https://doi.org/10.1016/j.biocon.2019.108271

TRC, 2015. Truth and Reconciliation Commission of Canada: Calls to Action. Truth and Reconciliation Commission of Canada, Winnepeg, Manitoba Canada.

Tsleil-Waututh, 2017. Burrard Inlet Action Plan. Kerr Wood Leidal.

Tulloch, D., 2008. Public Participation GIS (PPGIS), in: Encyclopedia of Geographic Information Science. SAGE Publications, Inc., Thousand Oaks, pp. 352–354. https://doi.org/10.4135/9781412953962

United Nations, 2007. United Nations Declaration on the Rights of Indigenous Peoples.

Valladares, F., Matesanz, S., Guilhaumon, F., Araújo, M.B., Balaguer, L., Benito-Garzón, M., Cornwell, W., Gianoli, E., Kleunen, M. van, Naya, D.E., Nicotra, A.B., Poorter, H., Zavala, M.A., 2014. The effects of phenotypic plasticity and local adaptation on forecasts of species range shifts under climate change. Ecol. Lett. 17, 1351–1364. https://doi.org/10.1111/ele.12348

van Buuren, S., Groothuis-Oudshoorn, K., 2022. R package “mice.”

van Heerwaarden, B., Kellermann, V., 2020. Does Plasticity Trade Off With Basal Heat Tolerance? Trends Ecol. Evol. 35, 874–885. https://doi.org/10.1016/j.tree.2020.05.006

van Heerwaarden, B., Sgrò, C.M., 2021. Male fertility thermal limits predict vulnerability to climate warming. Nat. Commun. 12, 2214. https://doi.org/10.1038/s41467-021-22546-w

Van Riper, C.J., Kyle, G.T., 2014. Capturing multiple values of ecosystem services shaped by environmental worldviews: A spatial analysis. J. Environ. Manage. 145, 374–384. https://doi.org/10.1016/j.jenvman.2014.06.014

Vasseur, D.A., DeLong John P., Gilbert Benjamin, Greig Hamish S., Harley Christopher D. G., McCann Kevin S., Savage Van, Tunney Tyler D., O’Connor Mary I., 2014. Increased temperature variation poses a greater risk to species than climate warming. Proc. R. Soc. B Biol. Sci. 281, 20132612. https://doi.org/10.1098/rspb.2013.2612

Viechtbauer, W., 2010. Conducting Meta-Analyses in *R* with the **metafor** Package. J. Stat. Softw. 36. https://doi.org/10.18637/jss.v036.i03

Vincent, A.C.J., 2011. Saving the shallows: focusing marine conservation where people might care. Aquat. Conserv. Mar. Freshw. Ecosyst. 21, 495–499. https://doi.org/10.1002/aqc.1226

Von Der Porten, S., 2012. Canadian Indigenous Governance Literature: A Review. Altern. Int. J. Indig. Peoples 8, 1–14. https://doi.org/10.1177/117718011200800101

Voyer, M., Gladstone, W., Goodall, H., 2012. Methods of social assessment in Marine Protected Area planning: Is public participation enough? Mar. Policy 36, 432–439. https://doi.org/10.1016/j.marpol.2011.08.002

Waters, C.N., Zalasiewicz, J., Summerhayes, C., Barnosky, A.D., Poirier, C., Gałuszka, A., Cearreta, A., Edgeworth, M., Ellis, E.C., Ellis, M., Jeandel, C., Leinfelder, R., McNeill,

J.R., Richter, D. deB., Steffen, W., Syvitski, J., Vidas, D., Wagreich, M., Williams, M., Zhisheng, A., Grinevald, J., Odada, E., Oreskes, N., Wolfe, A.P., 2016. The Anthropocene is functionally and stratigraphically distinct from the Holocene. Science 351, aad2622. https://doi.org/10.1126/science.aad2622

Watts, N., Adger, W.N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., Chaytor, S., Colbourn, T., Collins, M., Cooper, A., Cox, P.M., Depledge, J., Drummond, P., Ekins, P., Galaz, V., Grace, D., Graham, H., Grubb, M., Haines, A., Hamilton, I., Hunter, A., Jiang, X., Li, M., Kelman, I., Liang, L., Lott, M., Lowe, R., Luo, Y., Mace, G., Maslin, M., Nilsson, M., Oreszczyn, T., Pye, S., Quinn, T., Svensdotter, M., Venevsky, S., Warner, K., Xu, B., Yang, J., Yin, Y., Yu, C., Zhang, Q., Gong, P., Montgomery, H., Costello, A., 2015. Health and climate change: policy responses to protect public health. The Lancet 386, 1861–1914. https://doi.org/10.1016/S0140-6736(15)60854-6

Weber, C.T., 2019. Towards a framework to guide and facilitate interdisciplinary social-ecological system research in practice. (Doctoral thesis). UiT The Arctic University of Norway.

Wen, W., Samudera, K., Adrianto, L., Johnson, G.L., Brancato, M.S., White, A., 2022. Towards Marine Spatial Planning Implementation in Indonesia: Progress and Hindering Factors. Coast. Manag. 50, 469–489. https://doi.org/10.1080/08920753.2022.2126262

White, I., Castleden, H., 2022. Time as an instrument of settler evasion: Circumventing the implementation of truth and reconciliation in Canadian geography departments. Can. Geogr. Géographe Can. 66, 639–652. https://doi.org/10.1111/cag.12793

Whitney, C.K., Bennett, N.J., Ban, N.C., Allison, E.H., Armitage, D., Blythe, J.L., Burt, J.M., Cheung, W., Finkbeiner, E.M., Kaplan-Hallam, M., Perry, I., Turner, N.J., Yumagulova, L., 2017. Adaptive capacity: from assessment to action in coastal social-ecological systems. Ecol. Soc. 22. https://doi.org/10.5751/ES-09325-220222

Whyte, K., 2020. Too late for indigenous climate justice: Ecological and relational tipping points. WIREs Clim. Change 11, e603. https://doi.org/10.1002/wcc.603

Williams, S.E., Shoo, L.P., Isaac, J.L., Hoffmann, A.A., Langham, G., 2008. Towards an Integrated Framework for Assessing the Vulnerability of Species to Climate Change. PLoS Biol. 6, e325. https://doi.org/10.1371/journal.pbio.0060325

Willis, S.G., Foden, W., Baker, D.J., Belle, E., Burgess, N.D., Carr, J.A., Doswald, N., Garcia, R.A., Hartley, A., Hof, C., Newbold, T., Rahbek, C., Smith, R.J., Visconti, P., Young, B.E., Butchart, S.H.M., 2015. Integrating climate change vulnerability assessments from

species distribution models and trait-based approaches. Biol. Conserv. 190, 167–178. https://doi.org/10.1016/j.biocon.2015.05.001

Wilson, S., 2008. Research is ceremony: Indigenous research methods. Fernwood Publishing, Black Point, Nova Scotia.

Wolfe, K., Dworjanyn, S.A., Byrne, M., 2013. Effects of ocean warming and acidification on survival, growth and skeletal development in the early benthic juvenile sea urchin (Heliocidaris erythrogramma). Glob. Change Biol. 19, 2698–2707. https://doi.org/10.1111/gcb.12249

Wong, C., Ballegooyen, K., Ignace, L., Johnson, M.J. (Gùdia), Swanson, H., 2020. Towards reconciliation: 10 Calls to Action to natural scientists working in Canada. FACETS 5, 769–783. https://doi.org/10.1139/facets-2020-0005

Woodhouse, E., Bedelian, C., Barnes, P., Cruz-Garcia, G.S., Dawson, N., Gross-Camp, N., Homewood, K., Jones, J.P.G., Martin, A., Morgera, E., Schreckenberg, K., 2022. Rethinking entrenched narratives about protected areas and human wellbeing in the Global South. UCL Open Environ. 4. https://doi.org/10.14324/111.444/ucloe.000050

Yeager, L.A., Estrada, J., Holt, K., Keyser, S.R., Oke, T.A., 2020. Are Habitat Fragmentation Effects Stronger in Marine Systems? A Review and Meta-analysis. Curr. Landsc. Ecol. Rep. 5, 58–67. https://doi.org/10.1007/s40823-020-00053-w

Yumagulova, L., 2020. Understanding Ocean Literacy in Canada: Pacific Regional Report. Canadian Ocean Literacy Coalition.

Appendices

Appendix A Supplementary information for Chapter 2: A comprehensive meta-analysis of the interactive effects of ocean acidification and warming across marine ectothermic animals reveals widespread negative effects and challenges assumptions

A.1 Bias corrected lnRR factorial equations, provided by Marc Lajeunesse

Log response ratios ($\ln RR$) were introduced by Hedges et al., (1999) and Morris et al., (2007) later modified this effect size metric to quantify the overall (O) and interaction (I) effects of a 2×2 factorial experiment; but also see Hawkes and Sullivan, (2001) for an early but incomplete version of the factorial $\ln RR$. Lajeunesse (2011) further modified the factorial $\ln RR$ to account for statistical dependencies. Here we update the log response ratio for the overall-effect ($\ln RR^{\mathrm{O}}$) and the interaction-effect ($\ln RR^{\mathrm{I}}$) to account for small sample bias following Lajeunesse (2015). Effect sizes in general suffer from small sample bias because they are often derived using asymptotic theory—which keeps metrics simple and calculator-friendly but does not guarantee good performance when sample sizes are low (e.g., consistent unbiased estimation of the effect and its variance). Adjustments or corrections are possible, and here we use the multivariate second-order Delta method (Dobb 1935) to approximate corrections for $\ln RR^{\mathrm{O}}$ and $\ln RR^{\mathrm{I}}$.

Derivation of the log response ratio for the overall effect of a factorial experiment

Keeping with the original formatting by Morris et al., (2007), the overall effect of a 2×2 factorial experiment contrasting means ($\bar{X}$) from the control (C) and treatment (T) groups by each effect-agent group A and P is:

$$\ln RR^{\mathrm{O}} = \ln\left(\frac{\bar{X}_{\mathrm{T}}^{\mathrm{A}} + \bar{X}_{\mathrm{C}}^{\mathrm{A}}}{\bar{X}_{\mathrm{T}}^{\mathrm{P}} + \bar{X}_{\mathrm{C}}^{\mathrm{P}}}\right), \tag{A.1}$$

which has a variance $\mathrm{VAR}\left(\ln RR^{\mathrm{O}}\right)$ of:

$$\mathrm{VAR}\left(\ln RR^{\mathrm{O}}\right) = \left(\frac{1}{\bar{X}_{\mathrm{T}}^{\mathrm{A}} + \bar{X}_{\mathrm{C}}^{\mathrm{A}}}\right)^2 \left(\frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}}\right]^2}{N_{\mathrm{T}}^{\mathrm{A}}} + \frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}}\right]^2}{N_{\mathrm{C}}^{\mathrm{A}}}\right) + \left(\frac{1}{\bar{X}_{\mathrm{T}}^{\mathrm{P}} + \bar{X}_{\mathrm{C}}^{\mathrm{P}}}\right)^2 \left(\frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}}\right]^2}{N_{\mathrm{T}}^{\mathrm{P}}} + \frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}}\right]^2}{N_{\mathrm{C}}^{\mathrm{P}}}\right), \tag{A.2}$$

and where SD and N are the standard deviations and sample sizes of each group. Both $\ln RR^{\mathrm{O}}$ and $\mathrm{VAR}\left(\ln RR^{\mathrm{O}}\right)$ are first-order approximations and examples of how they were derived using the first-order Delta method are in Appendix A of Lajeunesse (2011). Briefly following

Lajeunesse (2015), the estimator of $\ln RR^{\mathrm{O}}$ has a population expectation ($\mathbb{E}$) up to the second-order Taylor expansion:

$$\mathbb{E}\left(\ln RR^{\mathrm{O}}\right) \approx \lambda + \mathbf{J}'(\boldsymbol{x} - \boldsymbol{\mu}) + \frac{1}{2}\mathrm{tr}[\mathbf{H}\boldsymbol{\Sigma}] + \varepsilon, \tag{A.3}$$

where $\lambda = \ln\left(\left[\mu_{\mathrm{T}}^{\mathrm{A}} + \mu_{\mathrm{C}}^{\mathrm{A}}\right]/\left[\mu_{\mathrm{T}}^{\mathrm{P}} + \mu_{\mathrm{C}}^{\mathrm{P}}\right]\right)$ with the population means of each group (μ), $\boldsymbol{\mu}$ a column vector of these population means ($\boldsymbol{\mu}' = [\mu_{\mathrm{T}}^{\mathrm{A}}, \mu_{\mathrm{C}}^{\mathrm{A}}, \mu_{\mathrm{T}}^{\mathrm{P}}, \mu_{\mathrm{C}}^{\mathrm{P}}]$), $\boldsymbol{x}$ a vector of the sample means $\boldsymbol{x}' = [\bar{X}_{\mathrm{T}}^{\mathrm{A}}, \bar{X}_{\mathrm{C}}^{\mathrm{A}}, \bar{X}_{\mathrm{T}}^{\mathrm{P}}, \bar{X}_{\mathrm{C}}^{\mathrm{P}}]$, the superscript $'$ indicates the transposition of a matrix, tr indicates the trace of a matrix, and ε the remainder (hereafter ignored, but indicates all the un-estimated higher-order expansions/corrections). Finally, this second-order expectation includes a Jacobian vector ($\mathbf{J}$) of the first-order partial derivatives of each μ in λ:

$$\mathbf{J}' = \left[\frac{1}{\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}}, \frac{1}{\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}}, \frac{-1}{\mu_{\mathrm{T}}^{\mathrm{P}}+\mu_{\mathrm{C}}^{\mathrm{P}}}, \frac{-1}{\mu_{\mathrm{T}}^{\mathrm{P}}+\mu_{\mathrm{C}}^{\mathrm{P}}}\right],$$

the correction uses a Hessian matrix ($\mathbf{H}$) with all the second partial derivatives of each μ in λ:

$$\mathbf{H} = \begin{bmatrix} \frac{-1}{\left(\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}\right)^2} & \frac{-1}{\left(\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}\right)^2} & 0 & 0 \\ \frac{-1}{\left(\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}\right)^2} & \frac{-1}{\left(\mu_{\mathrm{C}}^{\mathrm{A}}+\mu_{\mathrm{T}}^{\mathrm{A}}\right)^2} & 0 & 0 \\ 0 & 0 & \frac{1}{\left(\mu_{\mathrm{C}}^{\mathrm{P}}+\mu_{\mathrm{T}}^{\mathrm{P}}\right)^2} & \frac{1}{\left(\mu_{\mathrm{C}}^{\mathrm{P}}+\mu_{\mathrm{T}}^{\mathrm{P}}\right)^2} \\ 0 & 0 & \frac{1}{\left(\mu_{\mathrm{C}}^{\mathrm{P}}+\mu_{\mathrm{T}}^{\mathrm{P}}\right)^2} & \frac{1}{\left(\mu_{\mathrm{C}}^{\mathrm{P}}+\mu_{\mathrm{T}}^{\mathrm{P}}\right)^2} \end{bmatrix},$$

and where $\boldsymbol{\Sigma}$ is the variance–covariance matrix of all μ containing their large-sample variances (σ^2/N) and zero covariances as follows:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma^2(\mu_{\mathrm{T}}^{\mathrm{A}})/N_{\mathrm{T}}^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \sigma^2(\mu_{\mathrm{C}}^{\mathrm{A}})/N_{\mathrm{C}}^{\mathrm{A}} & 0 & 0 \\ 0 & 0 & \sigma^2(\mu_{\mathrm{T}}^{\mathrm{P}})/N_{\mathrm{T}}^{\mathrm{P}} & 0 \\ 0 & 0 & 0 & \sigma^2(\mu_{\mathrm{C}}^{\mathrm{P}})/N_{\mathrm{C}}^{\mathrm{P}} \end{bmatrix}.$$

Solving eq. A.3, while assuming that the expectation of $\bar{X} - \mu$ will asymptotically converge to zero at large sample sizes following the Law of Large Numbers (Stuart and Ord 1994), and swapping population means and variances for sample means and standard deviations, we get the second-order small sample corrected version (Δ) of $\ln RR^{\mathrm{O}}$ as follows:

$$\ln RR_{\Delta}^{\mathrm{O}} = \ln RR^{\mathrm{O}} + \frac{1}{2}\left(\frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}}\right]^2}{N_{\mathrm{C}}^{\mathrm{P}}\left[\bar{X}_{\mathrm{T}}^{\mathrm{P}}+\bar{X}_{\mathrm{C}}^{\mathrm{P}}\right]^2} + \frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}}\right]^2}{N_{\mathrm{T}}^{\mathrm{P}}\left[\bar{X}_{\mathrm{T}}^{\mathrm{P}}+\bar{X}_{\mathrm{C}}^{\mathrm{P}}\right]^2} - \frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}}\right]^2}{N_{\mathrm{C}}^{\mathrm{A}}\left[\bar{X}_{\mathrm{T}}^{\mathrm{A}}+\bar{X}_{\mathrm{C}}^{\mathrm{A}}\right]^2} - \frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}}\right]^2}{N_{\mathrm{T}}^{\mathrm{A}}\left[\bar{X}_{\mathrm{T}}^{\mathrm{A}}+\bar{X}_{\mathrm{C}}^{\mathrm{A}}\right]^2}\right). \tag{A.4}$$

The small sample corrected version of the variance of $\ln RR^{\mathrm{O}}$ approximated via the following second-order Taylor expansion of the variance expectation:

$$\sigma^2\left(\ln RR^{\mathrm{O}}\right) \approx \mathbf{J}'\boldsymbol{\Sigma}\mathbf{J} + \frac{1}{2}\mathrm{tr}[(\mathbf{H}\boldsymbol{\Sigma})^2] + \varepsilon, \tag{A.5}$$

and solving A.5 we get the corrected variance for $\ln RR_{\Delta}^{\mathrm{O}}$ as:

$$VAR(\ln RR_{\Delta}^{\mathrm{O}}) = VAR(\ln RR^{\mathrm{O}}) + \frac{1}{2}\left(\frac{[\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}}]^4}{[N_{\mathrm{C}}^{\mathrm{P}}]^2[\bar{X}_{\mathrm{T}}^{\mathrm{P}}+\bar{X}_{\mathrm{C}}^{\mathrm{P}}]^4} + \frac{[\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}}]^4}{[N_{\mathrm{T}}^{\mathrm{P}}]^2[\bar{X}_{\mathrm{T}}^{\mathrm{P}}+\bar{X}_{\mathrm{C}}^{\mathrm{P}}]^4} + \frac{[\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}}]^4}{[N_{\mathrm{C}}^{\mathrm{A}}]^2[\bar{X}_{\mathrm{T}}^{\mathrm{A}}+\bar{X}_{\mathrm{C}}^{\mathrm{A}}]^4} + \frac{[\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}}]^4}{[N_{\mathrm{T}}^{\mathrm{A}}]^2[\bar{X}_{\mathrm{T}}^{\mathrm{A}}+\bar{X}_{\mathrm{C}}^{\mathrm{A}}]^4}\right). \quad \text{(A.6)}$$

Derivation of the log response ratio for the interaction effect of a factorial experiment

Morris et al. (2007) described the first-order approximation of the interaction-effect log response ratio ($\ln RR^{\mathrm{I}}$) as:

$$\ln RR^{\mathrm{I}} = \ln\left(\frac{\bar{X}_{\mathrm{C}}^{\mathrm{A}}}{\bar{X}_{\mathrm{C}}^{\mathrm{P}}}\right) - \ln\left(\frac{\bar{X}_{\mathrm{T}}^{\mathrm{A}}}{\bar{X}_{\mathrm{T}}^{\mathrm{P}}}\right), \quad \text{(A.7)}$$

with a variance of:

$$\mathrm{VAR}(\ln RR^{\mathrm{I}}) = \frac{(\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}})^2}{N_{\mathrm{C}}^{\mathrm{A}}(\bar{X}_{\mathrm{C}}^{\mathrm{A}})^2} + \frac{(\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}})^2}{N_{\mathrm{T}}^{\mathrm{A}}(\bar{X}_{\mathrm{T}}^{\mathrm{A}})^2} + \frac{(\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}})^2}{N_{\mathrm{C}}^{\mathrm{P}}(\bar{X}_{\mathrm{C}}^{\mathrm{P}})^2} + \frac{(\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}})^2}{N_{\mathrm{T}}^{\mathrm{P}}(\bar{X}_{\mathrm{T}}^{\mathrm{P}})^2}. \quad \text{(A.8)}$$

Similar to $\ln RR_{\Delta}^{\mathrm{O}}$ and $VAR(\ln RR_{\Delta}^{\mathrm{O}})$, second-order corrections can be derived using the multivariate Delta method with the Tailor expansions of equations A.3 and A.5, but here assuming that $\lambda = \ln(\mu_{\mathrm{C}}^{\mathrm{A}}/\mu_{\mathrm{C}}^{\mathrm{P}}) - \ln(\mu_{\mathrm{T}}^{\mathrm{A}}/\mu_{\mathrm{T}}^{\mathrm{P}})$, $\boldsymbol{\mu}' = [\mu_{\mathrm{C}}^{\mathrm{A}}, \mu_{\mathrm{C}}^{\mathrm{P}}, \mu_{\mathrm{T}}^{\mathrm{A}}, \mu_{\mathrm{T}}^{\mathrm{P}}]$, $\boldsymbol{x}' = [\bar{X}_{\mathrm{C}}^{\mathrm{A}}, \bar{X}_{\mathrm{C}}^{\mathrm{P}}, \bar{X}_{\mathrm{T}}^{\mathrm{A}}, \bar{X}_{\mathrm{T}}^{\mathrm{P}}]$, with Jacobian vector equaling:

$$\mathbf{J}' = \left[\frac{1}{\mu_{\mathrm{C}}^{\mathrm{A}}}, \frac{-1}{\mu_{\mathrm{C}}^{\mathrm{P}}}, \frac{-1}{\mu_{\mathrm{T}}^{\mathrm{A}}}, \frac{1}{\mu_{\mathrm{T}}^{\mathrm{P}}}\right],$$

the Hessian matrix ($\mathbf{H}$) as:

$$\mathbf{H} = \begin{bmatrix} \frac{-1}{(\mu_{\mathrm{C}}^{\mathrm{A}})^2} & 0 & 0 & 0 \\ 0 & \frac{1}{(\mu_{\mathrm{C}}^{\mathrm{P}})^2} & 0 & 0 \\ 0 & 0 & \frac{1}{(\mu_{\mathrm{T}}^{\mathrm{A}})^2} & 0 \\ 0 & 0 & 0 & \frac{-1}{(\mu_{\mathrm{T}}^{\mathrm{P}})^2} \end{bmatrix},$$

and finally with a variance–covariance matrix of:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma^2(\mu_{\mathrm{C}}^{\mathrm{A}})/N_{\mathrm{C}}^{\mathrm{A}} & 0 & 0 & 0 \\ 0 & \sigma^2(\mu_{\mathrm{C}}^{\mathrm{P}})/N_{\mathrm{C}}^{\mathrm{P}} & 0 & 0 \\ 0 & 0 & \sigma^2(\mu_{\mathrm{T}}^{\mathrm{A}})/N_{\mathrm{T}}^{\mathrm{A}} & 0 \\ 0 & 0 & 0 & \sigma^2(\mu_{\mathrm{T}}^{\mathrm{P}})/N_{\mathrm{T}}^{\mathrm{P}} \end{bmatrix}.$$

Given these assumptions, the small sample corrected (Δ) version of $\ln RR^{\mathrm{I}}$ is as follows:

$$\ln RR_{\Delta}^{\mathrm{I}} = \ln RR^{\mathrm{I}} + \frac{1}{2}\left(\frac{[\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}}]^2}{N_{\mathrm{T}}^{\mathrm{A}}[\bar{X}_{\mathrm{T}}^{\mathrm{A}}]^2} + \frac{[\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}}]^2}{N_{\mathrm{C}}^{\mathrm{P}}[\bar{X}_{\mathrm{C}}^{\mathrm{P}}]^2} - \frac{[\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}}]^2}{N_{\mathrm{C}}^{\mathrm{A}}[\bar{X}_{\mathrm{C}}^{\mathrm{A}}]^2} - \frac{[\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}}]^2}{N_{\mathrm{T}}^{\mathrm{P}}[\bar{X}_{\mathrm{T}}^{\mathrm{P}}]^2}\right), \quad \text{(A.9)}$$

which as a variance of:

$$VAR\left(\ln RR_{\Delta}^{\mathrm{I}}\right) = VAR\left(\ln RR^{\mathrm{I}}\right) + \frac{1}{2}\left(\frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{A}}\right]^4}{\left[N_{\mathrm{T}}^{\mathrm{A}}\right]^2\left[\bar{X}_{\mathrm{T}}^{\mathrm{A}}\right]^4} + \frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{P}}\right]^4}{\left[N_{\mathrm{C}}^{\mathrm{P}}\right]^2\left[\bar{X}_{\mathrm{C}}^{\mathrm{P}}\right]^4} + \frac{\left[\mathrm{SD}_{\mathrm{C}}^{\mathrm{A}}\right]^4}{\left[N_{\mathrm{C}}^{\mathrm{A}}\right]^2\left[\bar{X}_{\mathrm{C}}^{\mathrm{A}}\right]^4} + \frac{\left[\mathrm{SD}_{\mathrm{T}}^{\mathrm{P}}\right]^4}{\left[N_{\mathrm{T}}^{\mathrm{P}}\right]^2\left[\bar{X}_{\mathrm{T}}^{\mathrm{P}}\right]^4}\right). \quad \text{(A.10)}$$

A.2 Supplemental figures and tables associated with unpaired analysis of overall and interactive effects of ocean acidification and warming

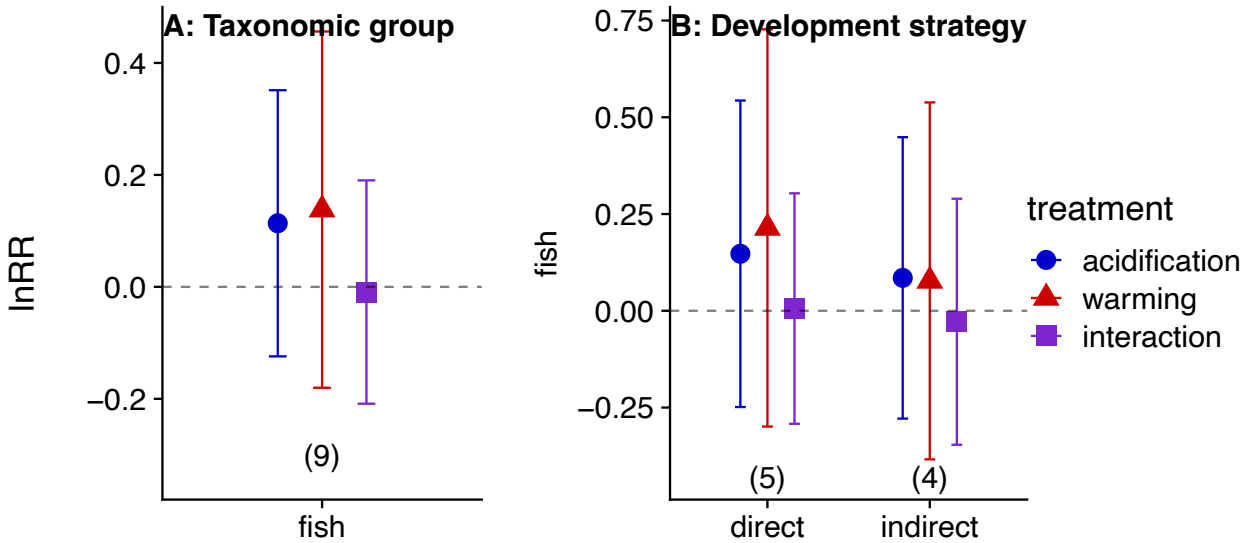

Fig A.1. The pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on aerobic scope** across categorical moderators based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 9 acidification, n = 9 warming, and n = 9 interaction effect sizes for fish aerobic scope).

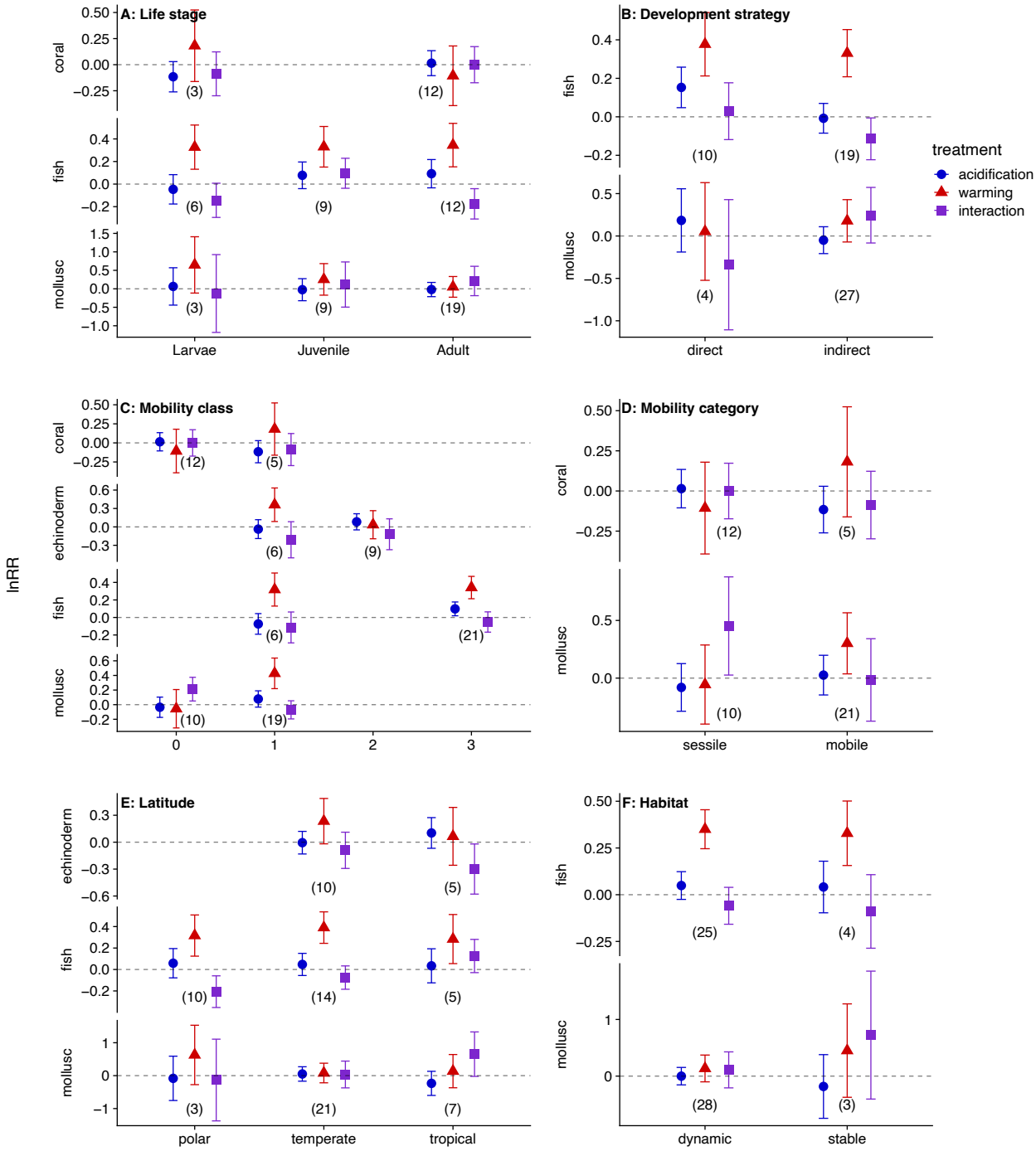

Figure A.2. The pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on metabolism** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 3 acidification, n = 3 warming, and n = 3 interaction effect sizes for larval coral metabolism).

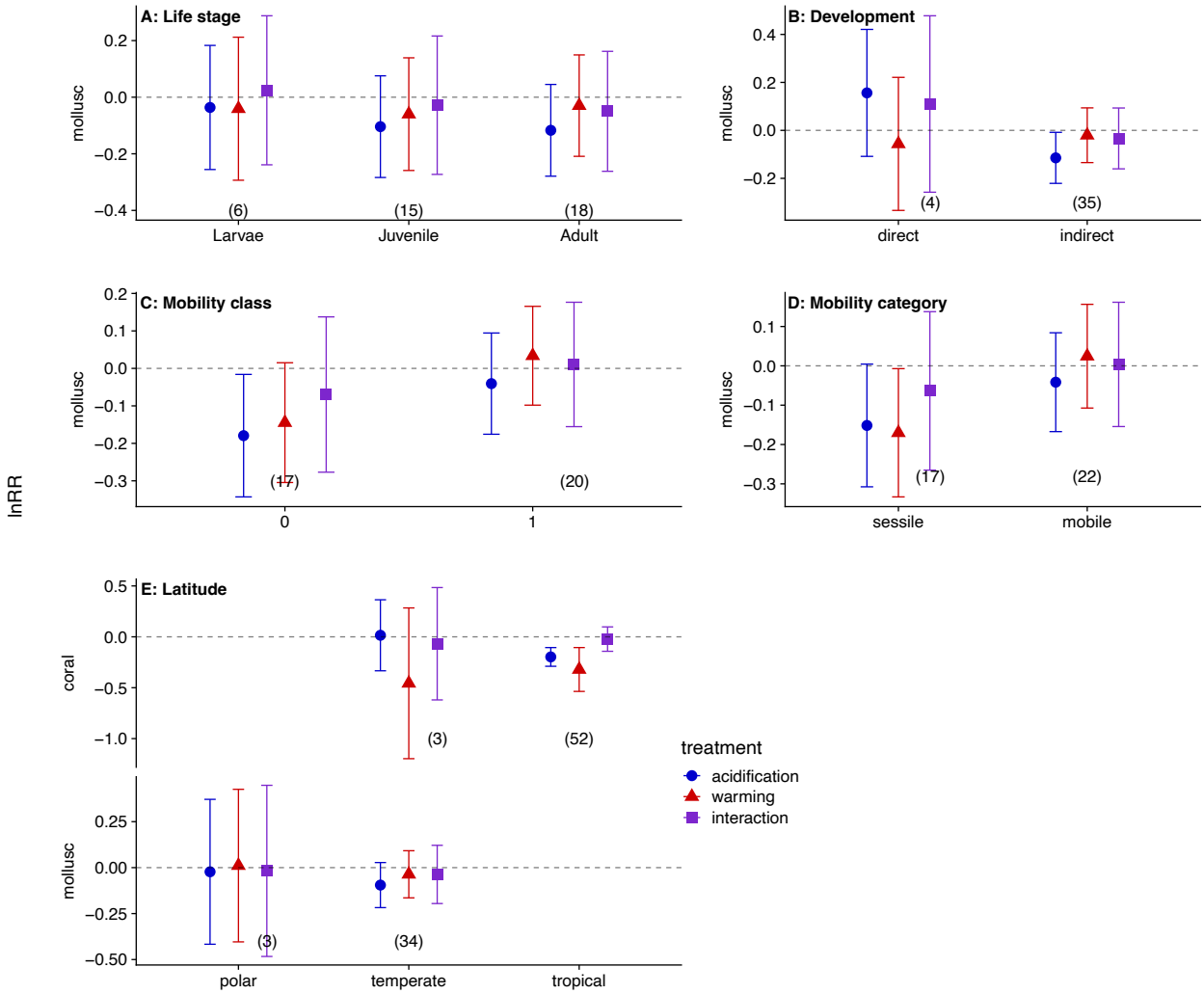

Figure A.3. The overall pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on calcification** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 6 acidification, n = 6 warming, and n = 6 interaction effect sizes for larval mollusc calcification).

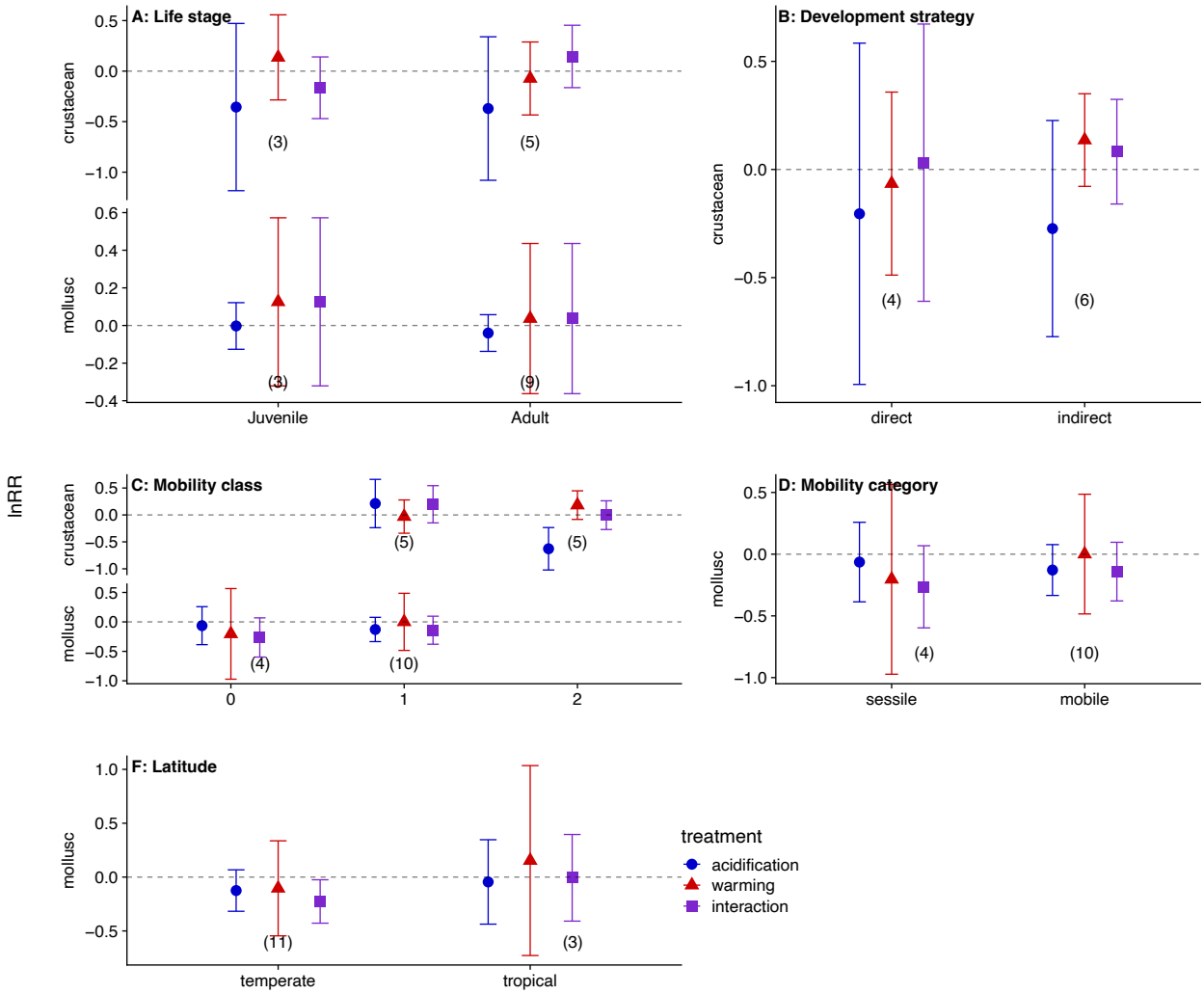

Figure A.4. The overall pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on feeding rate** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 3 acidification, n = 3 warming, and n = 3 interaction effect sizes for juvenile crustacean feeding rates).

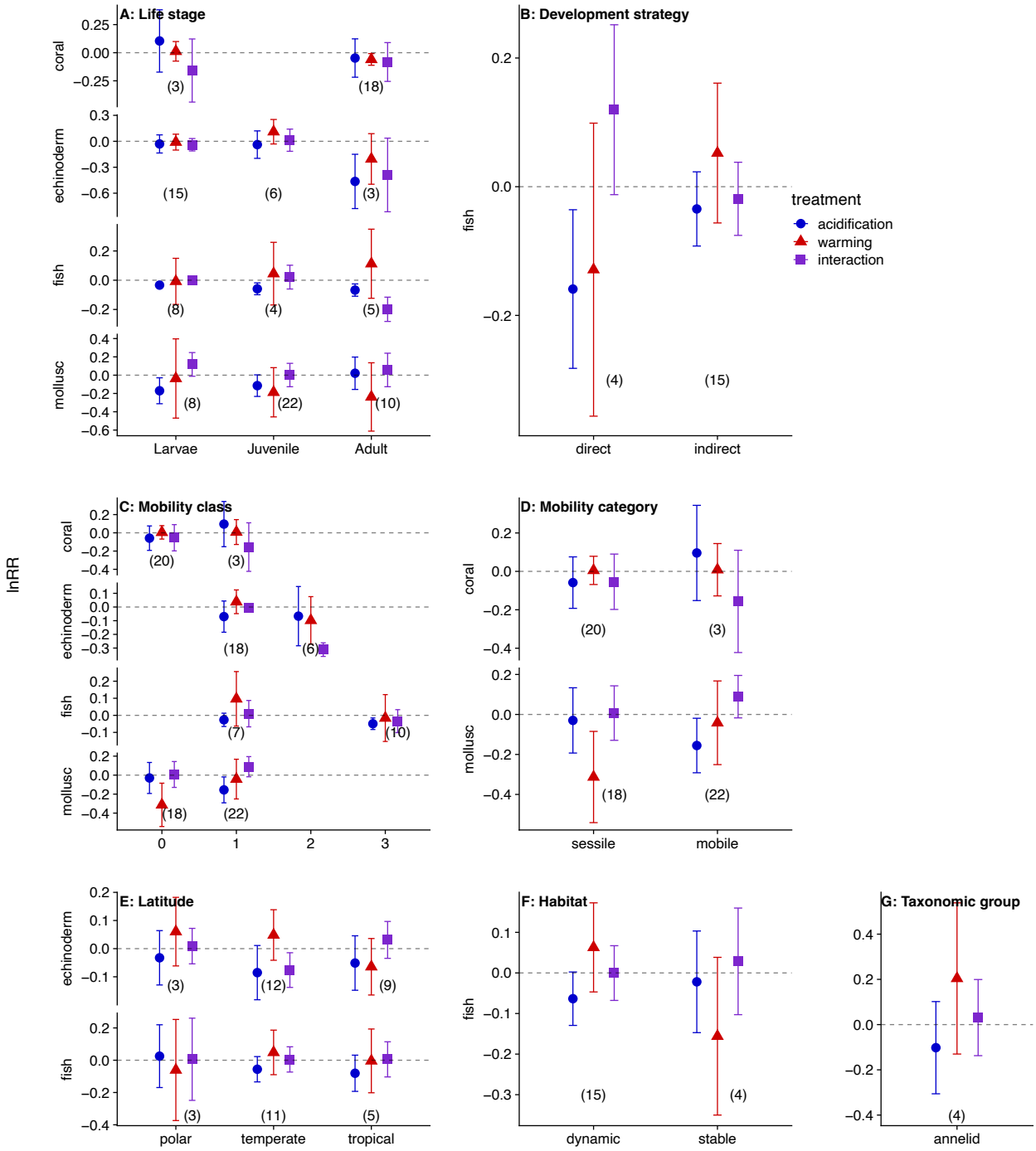

Figure A.5. The overall pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on growth** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 3 acidification, n = 3 warming, and n = 3 interaction effect sizes for larval coral growth).

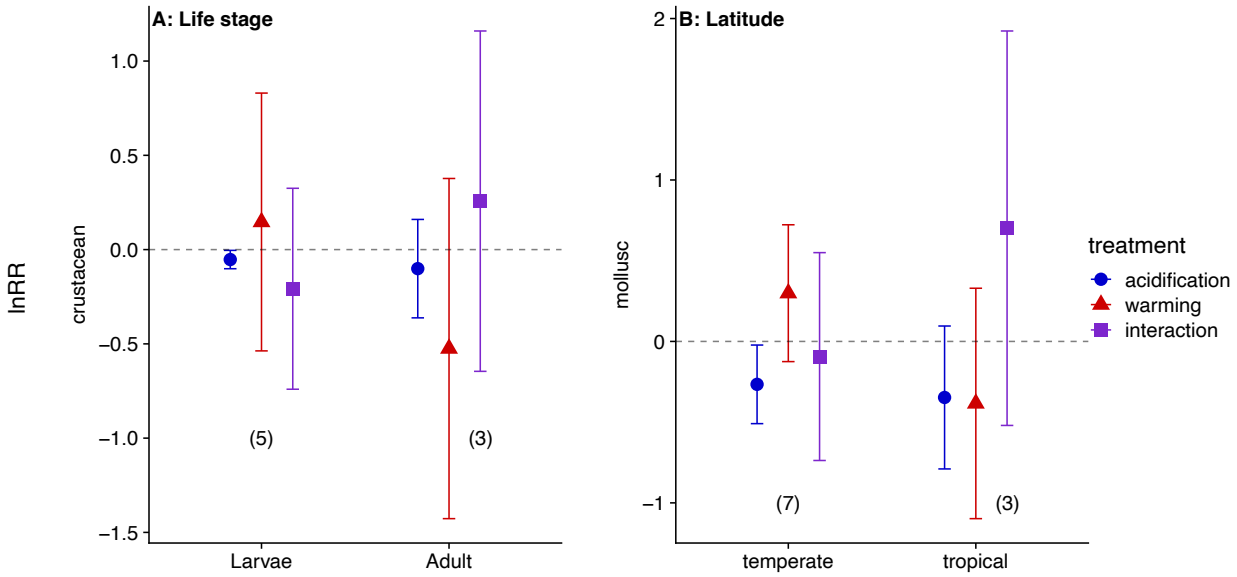

Figure A.6. The overall pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on development and reproduction** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 5 acidification, n = 5 warming, and n = 5 interaction effect sizes for larval crustacean development).

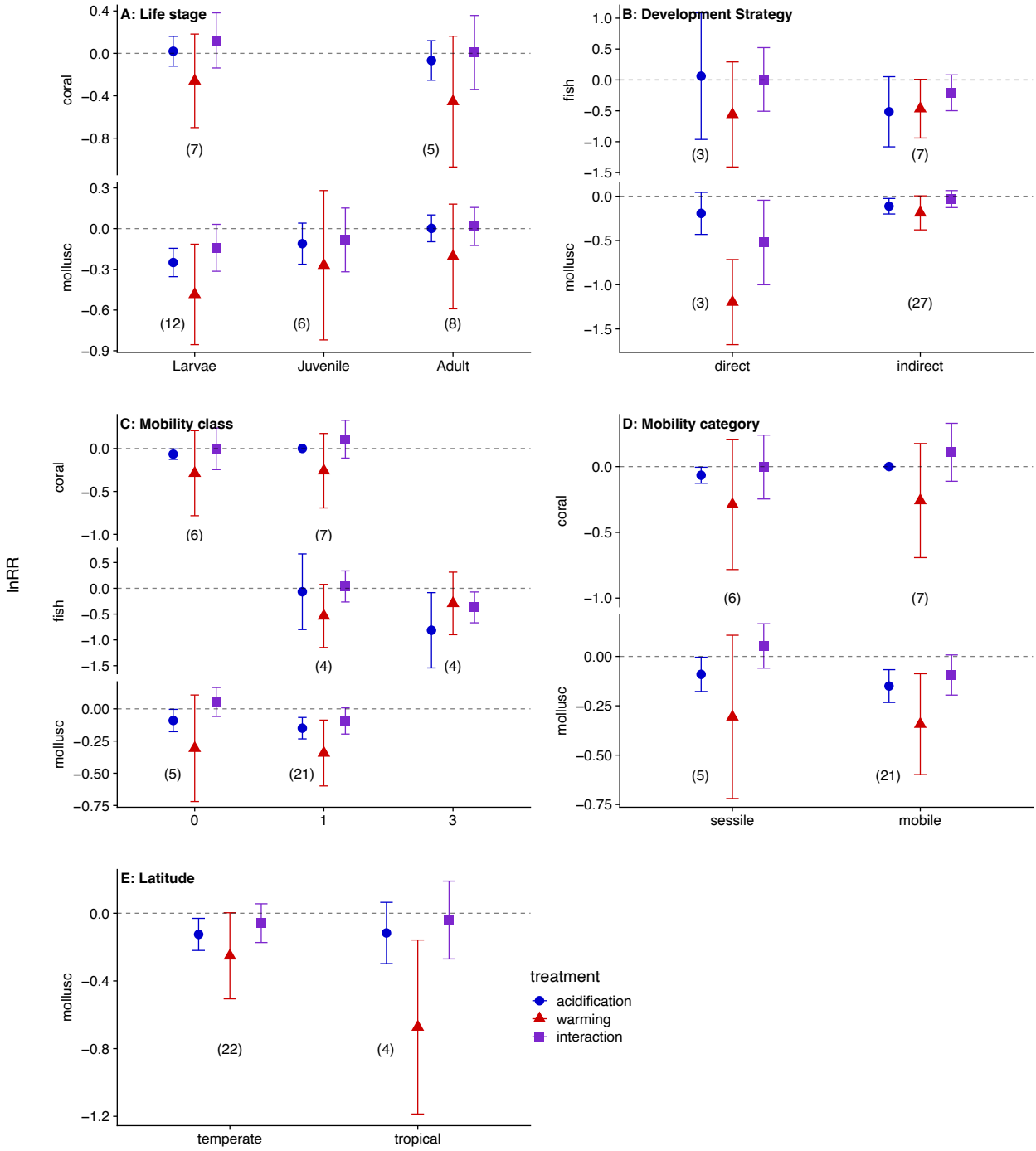

Figure A.7. The overall pooled effects of ocean acidification (blue circles), warming (red triangles), and their interaction (purple squares) **on survival** across categorical moderators and taxonomic groups based on a mixed-effect meta-analysis of bias-corrected log response ratios (lnRR) with 95% confidence intervals. The number of effect sizes within the three driver groups are provided in parentheses for each categorical moderator (e.g., there are n = 5 acidification, n = 5 warming, and n = 5 interaction effect sizes for larval crustacean development).

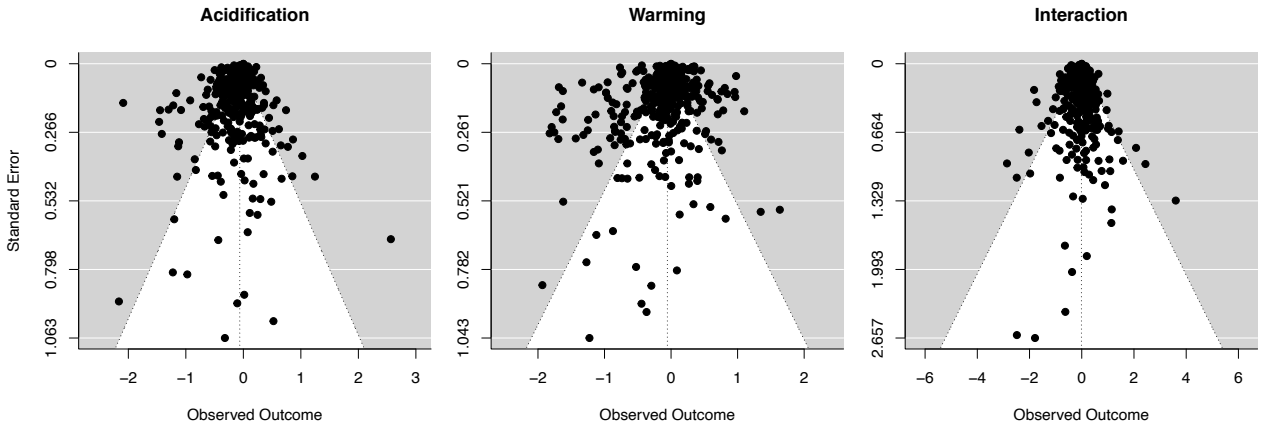

Figure A.8. Funnel plots of study effect sizes plotted against standard error for the overall effects of acidification and warming and the interaction effect sizes. The diagonal hashed lines indicate a confidence interval region (± 1.96 SE) around the vertical dashed line, which is the model estimate. Dots outside the diagonal lines (i.e., in the grey region) indicate significant effects at a given study variability.

Table A.1 A comprehensive list of the specific response variables that were measured and associated with each response variable category included in the dataset (i.e., aerobic scope, feeding rate, calcification, development and reproduction, growth, metabolism, and survival).

RV	Response specific
Aerobic scope	Aerobic scope, Aerobic Scope, Absolute aerobic scope (AAS), Metabolic scope, Absolute aerobic scope
Feeding Rate	Feeding rate, Mean clearance rate (CRmax), Ingestion rate, Relative consumption rates (RCR), Ingestion Rate Clearance rate, Mean consumption rate, Predation rates, Predation rate, Crab feeding, Whelk feeding Abalone feeding, Consumption, Total consumption Consumption rate, Daily feed consumption, Mean number of algal cells cleared/12 h (Clearance rate), Food Consumption, Mean predation rate, Absorption efficiency, Feeding, Feed intake, Change in fluorescence, Number of prey/larva, Number of Artemia eaten, Food Strikes
Calcification	Calcification rate, Mean net calcification, Dry shell weight, Shell length, Shell growth, Shell height, Calcification, Dry shell mass, Whole cuticle thickness, Shell size, Calcification all corals, Net calcification, Total procuticle thickness, Whelk shell growth, Percent increase in carapace length, Shell thickness, Roster-carinal diameter (RCD) change, Shell growth rate, Mean surface area-normalized net calcification (Gn) rates, Calcification rates, Mean shell-length, Change in buoyant wight, Net calcification rate, Net Calcification, Net calcification rate (NCR), Carapace length, Calcified Mass, Calcifed Mass/Soft Tissue Dry Mass, Test thickness, Length-corrected shell mass, Net calcification raate Microhardness, Shell dry weight, Shell increment rate, Larval shell area, SGR buoyant weight, Net Calcification Rate, Experiment shell

Development and Reproduction	Fertilization success, Total number of newborns Molt stage duration, Fecundity, Egg production Deformities, Days post hatch, Days to Hatching Percent malformed, Deformed larvae, Gastrulation, Fecudity, Proportion fecund, Metamorphosed, Mean percentage of eyed larvae, Hatching time, Nauplii production, Fertilization rates, Development, Mean normal development, Normal larvae, Normal Development time, Fertilisation, Development index, Normal echnioplutei, Fertilization, Mean developmental stage, Metamorphosis, Development to Early Gastrula, Normal Blastuae Final settlement, Mean cercariae, Settlement
Growth	Wet weight, Dry meat weight, Change in total biomass, Dry tissue weight, Length at hatch, Growth Rate, Larval size after 7 days, Larval length, Fulton condition index, Length, Lateral growth Dry weight (DW), Hatching size, Dry weight, Whelk tissue growth, Tissue growth, Overall length, Lateral Shell Width, Growth, Growth efficiency, Standard length, Fulton's Index, Juvenile developmental rate, Body length, Tissue production, Body weight change, Biomass, Total surface area, Juvenile growth, Corallite height, Specific growth rate, Gross productivity, Total body weight change, Size, Diameter, Weight loss, Change in wet weight, Scope for growth, Tube volume, Body length average, Wet body mass, Hatchling length, Body condition, Growth Rate in Wet Mass, Length:Width ratio, Post-settlement growth rate, Relative change in volume, Specific growth rate (SGR), Final size, Tissue biomass, Arm length, Test diameter, Growth increase, Larval Size, Egg fresh weight, Body dry weight, Shell growth (weight), Mid line body length (PO:MB), Total larval length, Mean dry weight, Weight, Mean length, Final weight, Change in Relative growth, Egg size, Hatch length, SGR wet mass, Change in Weight
Metabolism	Respiration, Mean dark respiration, SMR, Mean standard metabolic rate (SMR), Respiration data, Whole-embryo respiration (MO2), Resting oxygen uptake rates (MO2), Ventilation rate, Total energy, Respiration rate, Oxygen Uptake, Metabolic Rate, Respiration rate (O2 consumption), Mean oxygen consumption rates (MO2), Mass-specific oxygen consumption rate, Dark respiration, Oxygen Consumption (MO2), Metabolic rate, Standard metabolic rate, Routine metabolic rate (RMR), Mass-specific metabolic rate, Oxygen Consumption, Net O2 production, Mean oxygen uptake rate, Resting oxygen uptake (MO2rest), Oxygen consumption, Oxygen comsumption rates (OCR), Mean oxygen consumption rate, Oxygen consumption rates (OCRs), Standard metabolic rate (SMR), Day respiration, Metabolic rates, Mass-specific oxygen uptake (MO2), Oxygen consumption (standard), Oxygen consumption rate (OCR), Routine metabolic rates (RMR), Oxygen consumption rates, O2 consumption, RMR
Survival	Oxygen consumption (MO2), Oxygen consumption (MO2rest), Oxygen consumption rate, Survival, Mortality, Hatching success, Larval survival, Cumulative survival, Hathcing success, Cumulative mortality, Survival proportion, Hatching Success, Tissue, Dead larvae, Cumulative survival until hatch, Survival to sexual maturity, Settlement, Morality rates, Partial Mortality, Mean percentage mortality, Mean survival, Density, Eggs that survived to hatching, 30 Days Post-hach Survival, Developmental Stage, Survival rate, Hatching, Daily mortality rate, Cumulated mortality, Survivors, Survival rates, Survivorship, Mean embryonic mortality, Number of propagules, Mean mortality, Final survival, Mean survivorship

Table A.2 A comprehensive list of the papers that were included and excluded in the meta-analysis dataset based on the keyword search of "ocean acidification" and "temperature" between 2012-2019. Exclusion rationales are provided for any papers that did not align with the four inclusion criteria (studies had to be factorial, test a marine ectothermic animal, measure a lethal or sublethal response variable that was monotonically related to fitness, and report a mean response value, variance, and unit of replication). In sum, 1932 papers were excluded and 200 selected for inclusion in this dataset. Given the length of Table A.2 (over 200 pages long), please use this Dropbox link to access the file: https://www.dropbox.com/s/rd5a4728hbobc4j/Table_A2.xlsx?dl=0

Table A.3. The number of studies in this database that are partitioned by response variable and taxonomic group.

	Response Variable							
Taxonomic Group	Aerobic scope	Calcification	Development	Feeding Rate	Growth	Metabolism	Survival	Total
Annelid	0	0	2	0	4	0	1	7
Cnidarian (non-calcifying)	0	0	0	0	3	0	1	4
Coral	0	55	4	1	23	17	13	113
Crustacean	0	5	9	10	7	5	7	43
Echinoderm	0	4	12	2	24	15	8	65
Fish	9	0	5	7	19	29	10	79
Mollusc	1	39	11	14	40	31	26	162
Sponge	0	0	0	0	8	3	4	15
Trematode	0	0	1	0	0	0	0	1
Total	10	103	44	34	128	100	70	489

Table A.4. The number of studies in this database that are partitioned by taxonomic group and categorical moderator.

		Taxonomic group									
Categorical Moderator	**Moderator level**	Annelid	Cnidarian (non-calcifying)	Coral	Crustacean	Echinoderm	Fish	Mollusc	Sponge	Trematode	Total
Life stage	Adult	2	2	89	14	19	24	67	13	0	230
	Juvenile	4	0	5	12	13	19	55	2		108
	Larvae	1	2	18	17	32	25	40	0	1	138
	Embryo	0	0	1	0	1	11	0	0	0	13
Development	Direct	2	0	0	9	0	26	17	0	1	55
	Indirect	5	4	113	34	65	53	145	15	0	434
Mobility class	0	0	2	95	4	0	10	55	13	0	179

	1	7	2	18	27	44	21	103	2	1	225
	2	0	0	0	17	21	0	4	0	0	37
	3	0	0	0	0	0	48	0	0	0	48
Mobility category	Sessile	0	2	95	4	0	10	55	13	0	179
	Mobile	7	2	18	39	65	69	107	2	1	310
Latitude	Polar	0	0	0	0	5	16	8	0	0	29
	Temperate	6	4	7	37	40	47	132	0	0	273
	Tropical	1	0	106	6	20	16	22	15	1	187
Habitat type	Dynamic	7	4	113	42	65	75	156	15	1	468
	Stable	0	0	0	1	0	14	6	0	0	21

Table A.5. Heterogeneity in overall analysis (Q_T), residual heterogeneity (Q_E) and influence of response variables on the driver effects (Q_M). Statistical heterogeneity (significant Q_T values) indicates that there is variability in the observed driver effects that is larger than expected by random error. Residual heterogeneity (significant Q_E values) indicates that there may be other moderators that influence the variability in true effects. Significant Q_M values indicate that the effects of each driver are significantly different across levels of the categorical moderator (in this case response variable). Degrees of freedom (*df*) associated with Q_T reflect total dataset without metabolism studies, while those associated with Q_E and Q_M reflect the total dataset and number of response variable groupings -1. Table corresponds to Figure 2.1 and significant effects are bolded.

Driver	***Q*-type**	***Q*-value**	***df***	***p*-value**
Acidification	Q_T	6466.853	388	**<0.001**
	Q_E	6635.835	482	**<0.001**
	Q_M	14.583	6	**0.024**
Warming	Q_T	20209.490	388	**<0.001**
	Q_E	21887.106	482	**<0.001**
	Q_M	57.526	6	**<0.001**
Interaction	Q_T	2566.328	388	**<0.001**
	Q_E	3107.002	482	**<0.001**
	Q_M	6.365	6	0.384

Table A.6. Variation in the effects of drivers explained by categorical moderators (Q_M) and residual heterogeneity (Q_E) in the categorical meta-analysis. Table corresponds to Figure 2.2.

Categorical moderator	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Life stage	Acidification	Q_E	6072.964	385	**<0.001**
		Q_M	5.563	3	0.135
	Warming	Q_E	18448.972	385	**<0.001**
		Q_M	5.470	3	0.141
	Interaction	Q_E	2492.353	385	**<0.001**
		Q_M	5.263	3	0.154
Development strategy	Acidification	Q_E	6436.222	387	**<0.001**
		Q_M	0.423	1	0.515
	Warming	Q_E	20179.644	397	**<0.001**
		Q_M	0.568	1	0.451
	Interaction	Q_E	2552.838	387	**<0.001**
		Q_M	1.153	1	0.283

Mobility class	Acidification	Q_E	5749.926	385	**<0.001**
		Q_M	8.140	3	**0.043**
	Warming	Q_E	19393.260	385	**<0.001**
		Q_M	10.807	3	**0.013**
	Interaction	Q_E	2396.195	385	**<0.001**
		Q_M	9.178	3	**0.027**
Mobility category	Acidification	Q_E	5942.442	387	**<0.001**
		Q_M	3.945	1	**0.047**
	Warming	Q_E	19484.744	387	**<0.001**
		Q_M	9.182	1	**0.002**
	Interaction	Q_E	2543.074	387	**<0.001**
		Q_M	1.152	1	0.283
Latitude	Acidification	Q_E	6014.906	386	**<0.001**
		Q_M	82.407	2	**<0.001**
	Warming	Q_E	19952.204	386	**<0.001**
		Q_M	1.082	2	0.582
	Interaction	Q_E	2438.993	386	**<0.001**
		Q_M	3.834	2	0.147
Habitat	Acidification	Q_E	6454.472	387	**<0.001**
		Q_M	0.341	1	0.559
	Warming	Q_E	20103.139	387	**<0.001**
		Q_M	0.001	1	0.971
	Interaction	Q_E	2565.420	387	**<0.001**
		Q_M	0.024	1	0.877

Table A.7. Variation in the effects of drivers explained by taxonomic groups (Q_M) and residual heterogeneity (Q_E) in the categorical meta-analysis. Table corresponds to Figure 2.3.

Biological metric	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Metabolism	Acidification	Q_E	618.719	94	**<0.001**
		Q_M	3.641	5	0.602
	Warming	Q_E	1961.325	94	**<0.001**
		Q_M	5.605	5	0.357
	Interaction	Q_E	503.631	94	**<0.001**
		Q_M	6.103	5	0.296
Calcification	Acidification	Q_E	864.782	99	**<0.001**
		Q_M	2.176	3	0.537
	Warming	Q_E	1849.209	99	**<0.001**
		Q_M	13.089	3	**0.004**
	Interaction	Q_E	327.917	99	**<0.001**
		Q_M	1.563	3	0.668
Feeding rate	Acidification	Q_E	218.614	28	**<0.001**
		Q_M	0.804	2	0.669
	Warming	Q_E	452.314	28	**<0.001**
		Q_M	0.720	2	0.698
	Interaction	Q_E	74.474	28	**<0.001**
		Q_M	1.793	2	0.408
Growth	Acidification	Q_E	1612.878	120	**<0.001**
		Q_M	2.080	7	0.955
	Warming	Q_E	5681.032	120	**<0.001**
		Q_M	7.606	7	0.422
	Interaction	Q_E	605.338	120	**<0.001**
		Q_M	6.951	7	0.434
Development	Acidification	Q_E	379.447	36	**<0.001**

		Q_M	6.207	4	0.184
	Warming	Q_E	880.853	36	**<0.001**
		Q_M	3.556	4	0.469
	Interaction	Q_E	109.06	36	**<0.001**
		Q_M	1.298	4	0.862
Survival	Acidification	Q_E	1349.300	62	**<0.001**
		Q_M	5.267	5	0.384
	Warming	Q_E	7471.385	62	**<0.001**
		Q_M	4.164	5	0.526
	Interaction	Q_E	838.747	62	**<0.001**
		Q_M	5.888	5	0.317

Table A.8. Significant variation explained by categorical moderators across taxonomic group for **metabolism** measurements in the categorical random effects meta-analysis. Table corresponds to Appendix A: Figure A.2.

Biological metric Taxa	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Life stage					
Fish	Interaction	Q_E	38.830	24	**0.029**
		Q_M	9.238	2	**0.010**
Dev strategy					
Fish	Acidification	Q_E	86.035	27	**<0.001**
		Q_M	5.896	1	**0.015**
Mobility class					
Fish	Acidification	Q_E	82.451	25	**<0.001**
		Q_M	5.650	1	**0.018**
Mollusc	Warming	Q_E	609.048	27	**<0.001**
		Q_M	7.866	1	**0.0050**
	Interaction	Q_E	50.656	27	**<0.001**
		Q_M	7.228	1	**0.007**
Mobility category					
Mollusc	Interaction	Q_E	233.778	29	**<0.001**
		Q_M	4.252	1	**0.039**
Latitude					
Fish	Interaction	Q_E	40.307	26	0.036
		Q_M	9.391	2	**0.009**

Table A.9. Significant variation explained by categorical moderators across taxonomic group for **feeding rate** measurements in the categorical random effects meta-analysis. Table corresponds to Appendix A: Figure A.4.

Biological metric Taxa	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Mobility class					
Crustacean	Acidification	Q_E	62.831	8	**<0.001***
		Q_M	7.5997	1	**0.0058***

Table A.10. Significant variation explained by categorical moderators across taxonomic group for **growth** measurements in the categorical random effects meta-analysis. Table corresponds to Appendix A: Figure A.5.

Biological metric Taxa	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Life stage					
Echinoderm	Acidification	Q_E	694.541	21	**<0.001***

		Q_M	6.731	2	**0.0345***
Fish	Interaction	Q_E	8.029	14	0.888
		Q_M	21.479	2	**<0.001***
Mobility class					
Echinoderm	Interaction	Q_E	149.712	22	**<0.001***
		Q_M	139.375	1	**<0.001***
Mollusc	Warming	Q_E	1794.533	38	**<0.001***
		Q_M	5.554	1	**0.018**
Mobility category					
Mollusc	Warming	Q_E	1794.533	38	**<0.001***
		Q_M	5.554	1	**0.018**
Latitude					
Echinoderm	Acidification	Q_E	674.330	21	**<0.001**
		Q_M	80.807	2	**<0.001**
	Warming	Q_E	884.244	21	**<0.001**
		Q_M	6.567	2	**0.038**
	Interaction	Q_E	202.202	21	**<0.001**
		Q_M	63.132	2	**<0.001**
Habitat type					
Fish	Warming	Q_E	281.594	17	**<0.001***
		Q_M	4.216	1	**0.0400**

Table A.11. Significant variation explained by categorical moderators across taxonomic group for **survival** measurements in the categorical random effects meta-analysis. Table corresponds to Appendix A: Figure A.7.

Biological metric Taxa	**Driver**	***Q*-type**	***Q*-value**	***df***	***p*-value**
Life stage					
Mollusc	Acidification	Q_E	563.232	23	**<0.001**
		Q_M	11.753	2	**0.003**
Dev strategy					
Mollusc	Warming	Q_E	5872.320	24	**<0.001**
		Q_M	14.560	1	**0.001**
Mobility class					
Mollusc	Interaction	Q_E	420.185	24	**<0.001**
		Q_M	16.417	1	**<0.001**
Mobility category					
Coral	Acidification	Q_E	51.609	11	**<0.001**
		Q_M	4.464	1	**0.035**
Mollusc	Acidification	Q_E	420.185	24	**<0.001**
		Q_M	16.417	1	**<0.001**

Table A.12. Rosenthal's fail-safe numbers and 5N+10 criterion for each subset of data that generated a statistically significant mean effect size. Fail-safe numbers indicate the number of experiments with an effect size of 0 needed to make the confidence interval non-significant. High fail-safe numbers and those greater than the 5N+10 criterion (where N is the sample size within that dataset subset) indicate those findings are robust to sampling bias.

Driver	**Categorical moderator**	**Taxa or level**	**Rosenthal**	**Criterion**
temp	metabolism	overall	25864	510
temp	metabolism	fish	5721	155
temp	metabolism	mollusc	1972	165
interaction	metabolism	mollusc	96	165

acid	calcification	overall	7050	525
temp	calcification	overall	5990	525
acid	calcification	coral	2733	285
temp	calcification	coral	5801	285
acid	feeding	overall	131	180
interaction	feeding	overall	9	180
acid	feeding	crustacean	66	60
acid	growth	overall	11202	650
acid	growth	mollusc	502	210
temp	growth	mollusc	1615	210
acid	dev and reprod	overall	2109	230
acid	dev and reprod	echinoderm	245	70
acid	dev and reprod	mollusc	415	65
acid	survival	overall	6581	360
temp	survival	overall	17684	360
temp	survival	crustacean	470	45
acid	survival	fish	124	60
temp	survival	fish	573	60
acid	survival	mollusc	2675	140
temp	survival	mollusc	3240	140
acid	lifestage	adult	17563	865
temp	lifestage	adult	27678	865
interaction	lifestage	adult	1169	865
acid	dispersal	indirect	91932	1755
temp	dispersal	indirect	53460	1755
acid	mobility class	0	19409	770
temp	mobility class	0	28614	770
acid	mobility class	1	25413	940
acid	mobility class	2	37	130
interaction	mobility class	2	202	130
acid	mobility cat	sessile	19409	770
temp	mobility cat	sessile	28614	770
acid	mobility cat	mobile	34224	1195
acid	latitude	temperate	39704	1125
acid	latitude	tropical	13733	760
acid	habitat	dynamic	101316	1885
temp	habitat	dynamic	54421	1885
acid	overall	overall	105558	1955
temp	overall	overall	63129	1955

Appendix B Supplementary information for Chapter 3: Not just range limits: warming rate and thermal sensitivity shape climate change vulnerability in a species range centre

B.1 Supplementary experimental design, snail growth data analyses, and environmental parameters measured in mesocosm and reciprocal transplant experiments

Video B.1. Daily sea surface temperature data for the west coast of North America from June-August, 2016-2022, demonstrating that the Strait of Georgia is consistently one of the warmest regions between central California and Alaska. Data were recorded by multiple satellites and derived from Multiscale Ultrahigh Resolution (MUR) Level 4 (for more details see JPL MUR MEaSUREs Project. 2015). My study regions are indicated by triangles: blue for the Central Coast and orange for the Strait of Georgia. The yellow circle indicates the southern end of *N. lamellosa*'s range as per Sorte and Hofmann (2005). To access video, please use this Dropbox link: https://www.dropbox.com/s/4kep6pz6kyparcp/VideoS1_Beaty_Nucella.mp4?dl=0

Figure B.1. A representative sample of snails used in the reciprocal transplant from each region. The top white snails are from Cedar in the Strait of Georgia, whereas the bottom colourful snails are from Kwakshua channel on the Central Coast. Snails from each region demonstrate phenotypic divergence: Strait of Georgia snails tend to have thicker, smooth, and white shells, while Central Coast snails have frillier shells with greater colour variance.

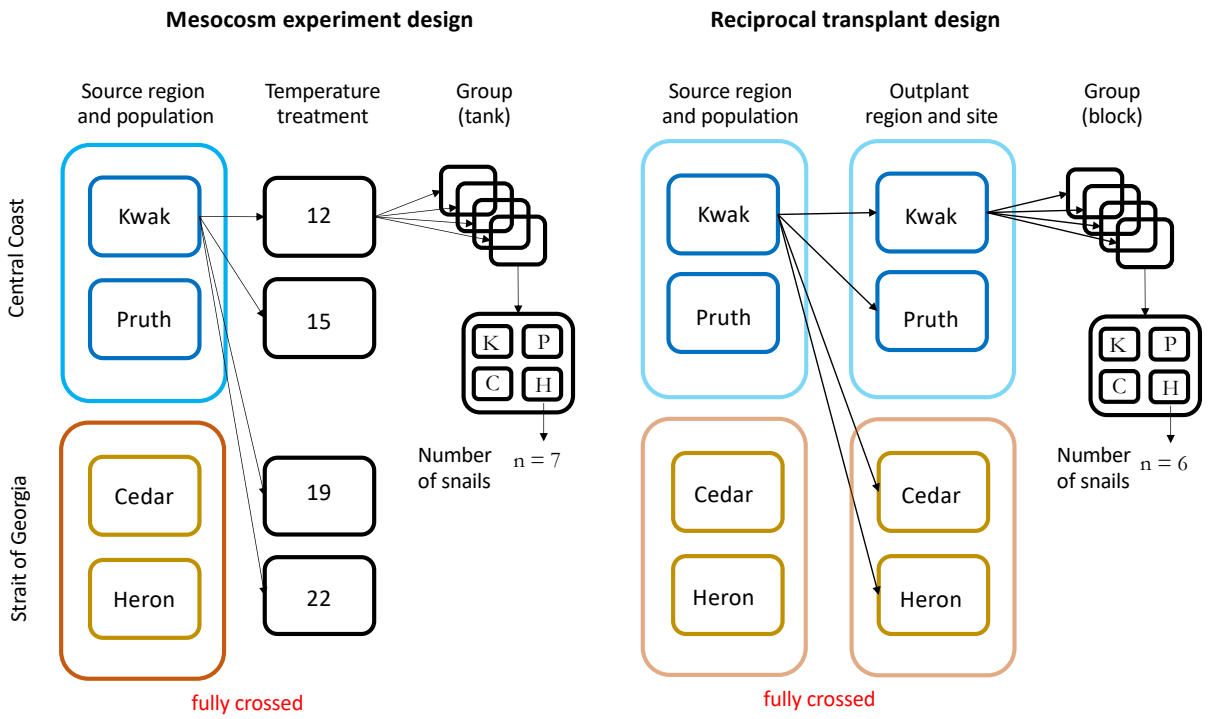

Figure B.2. The fully crossed reciprocal transplant and mesocosm experimental designs. The box colours indicate the source region, source population, outplant region and outplant sites (blue for Central Coast, orange for Strait of Georgia). Letters within the block and tank boxes indicate the source populations that were contained within separate plastic containers (mesocosm) and cages (reciprocal transplant) in each experiment.

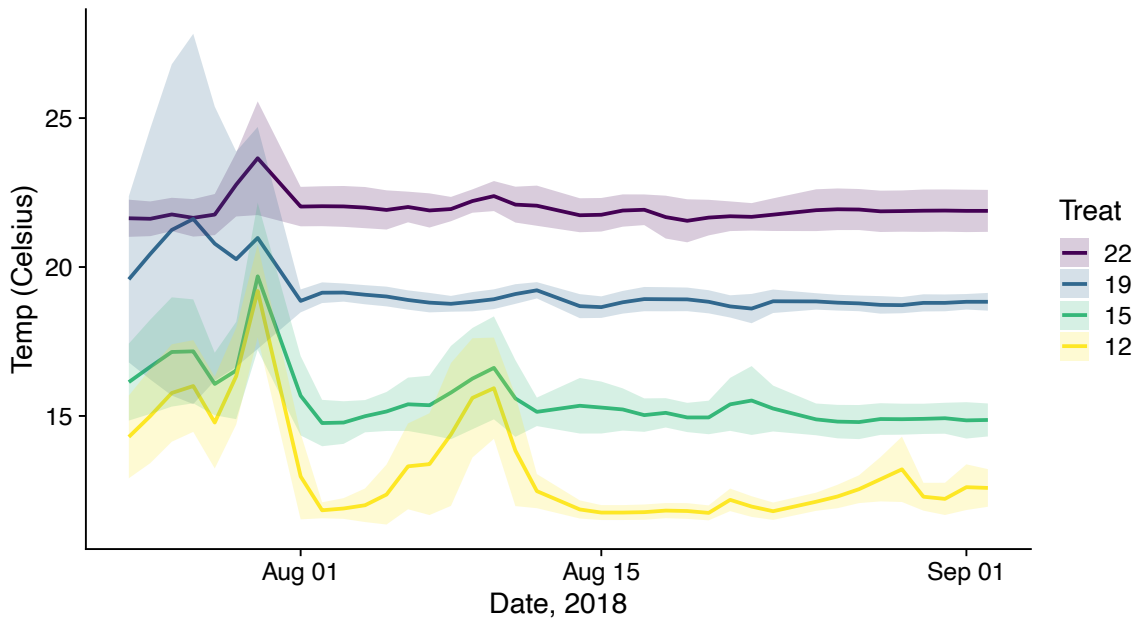

Figure B.3. The average temperature across temperature treatments in the mesocosm experiment. The heatwave within the first week of the experiment is visible. Another small thermal inconsistency occurred around August 10th in the 12°C treatments. Errors around the mean are ± SD.

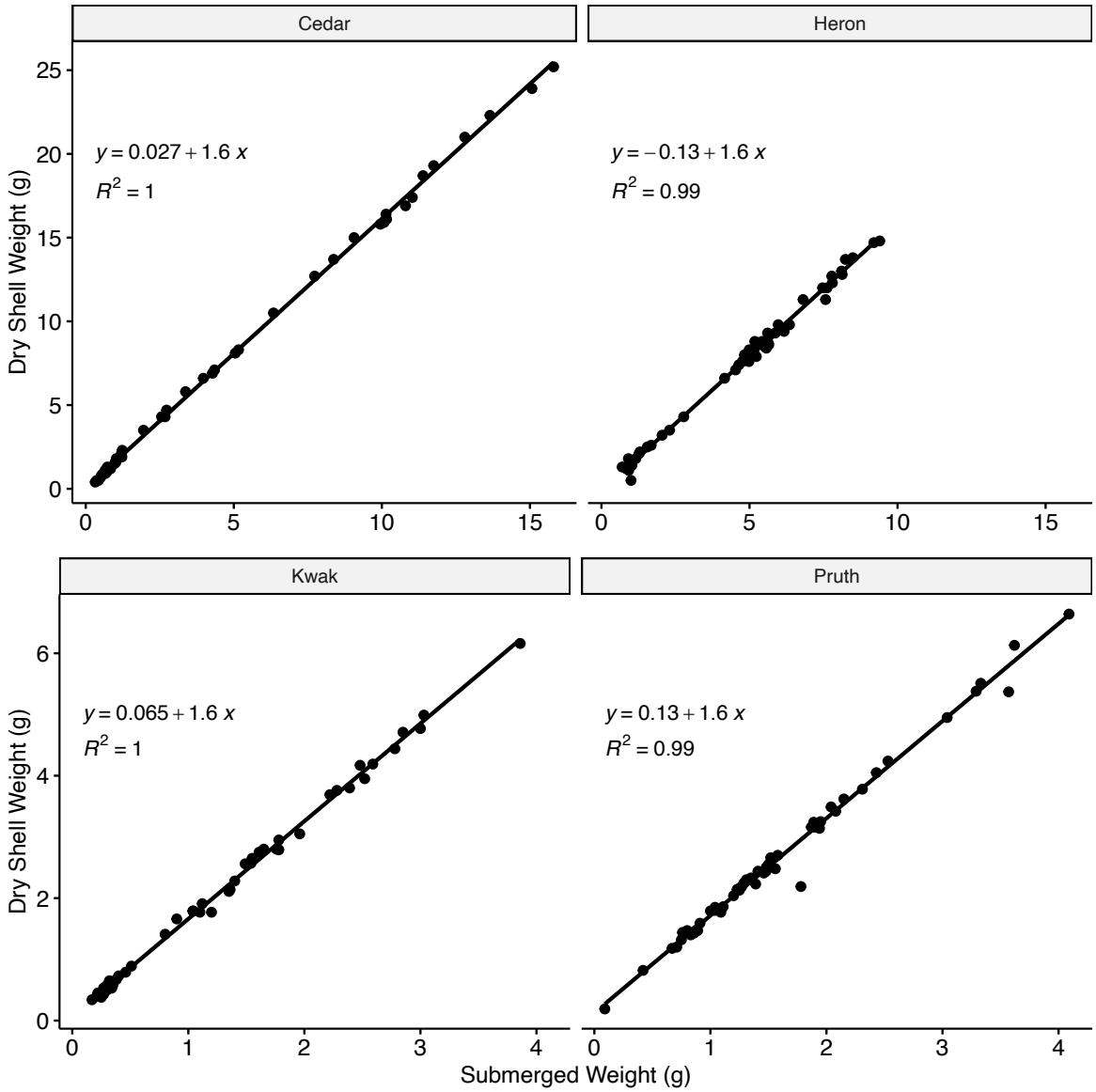

Figure B.4. Linear regressions between submerged weight (SW) and dry shell weight (DW) for each source population used in the reciprocal transplant and mesocosm experiments. These regressions were calculated following methods outlined in Palmer (1982). Regression equations were used to calculated shell weight for each snail in the reciprocal transplant and mesocosm experiments, which was then subtracted from total weight to estimate the tissue weight. n = 50 per source population.

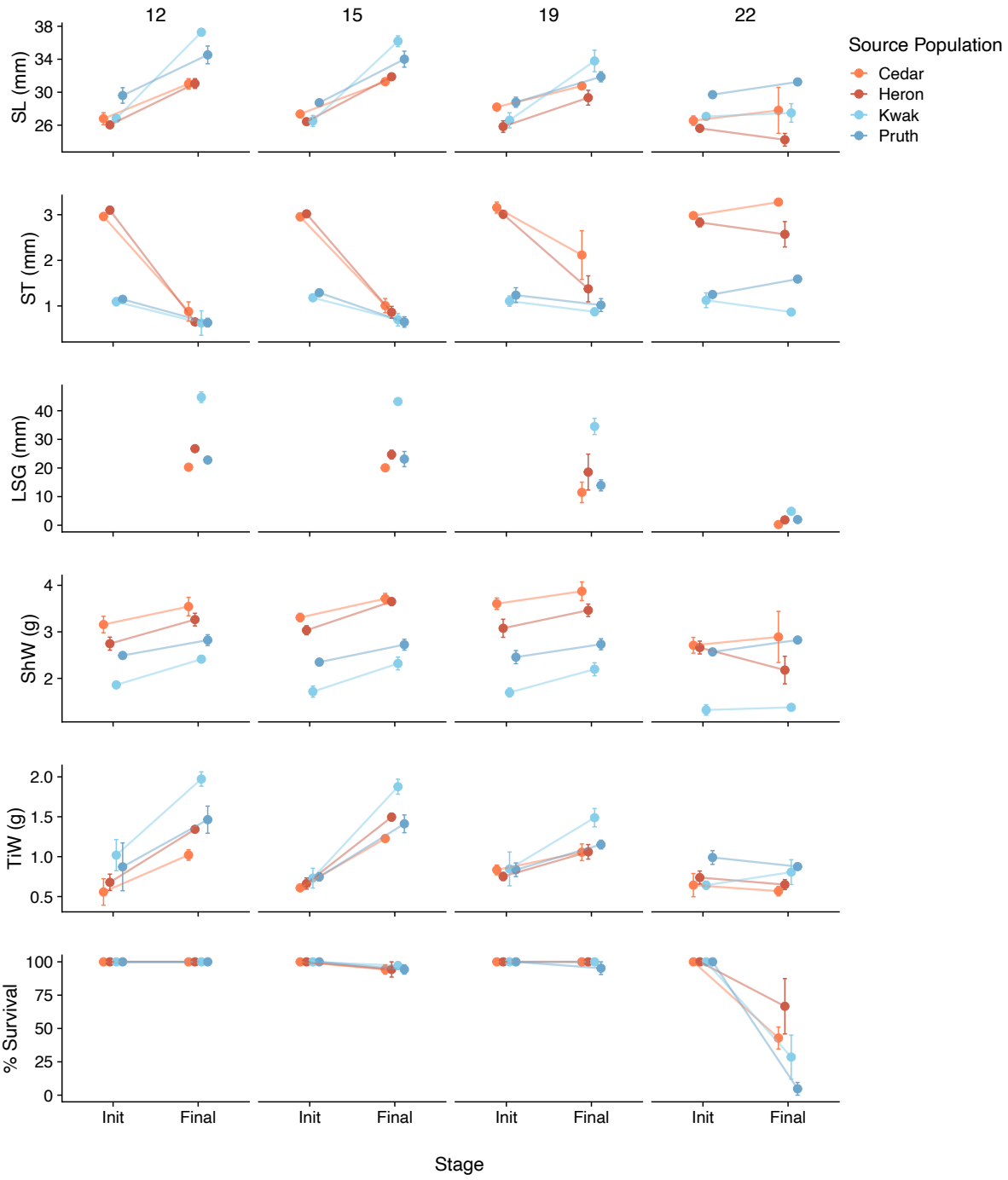

Figure B.5. Average growth, feeding rate, and survival metrics for each source population within each treatment across mesocosm treatments. Survival was measured on an ongoing basis, but here I visualize final cumulative survival. Colours correspond to the source region, with orange populations originating from the Strait of Georgia and blue from the Central Coast. Sample sizes were uneven across the temperatures due to equipment failure: 12 (n = 2), 15 (n = 5), 19 (n = 3), 22 (n = 3). Plots show mean ± SE. Acronyms are as follows: SL = shell length, ST = shell thickness, LSG = linear shell growth, ShW = shell weight, TiW = tissue weight.

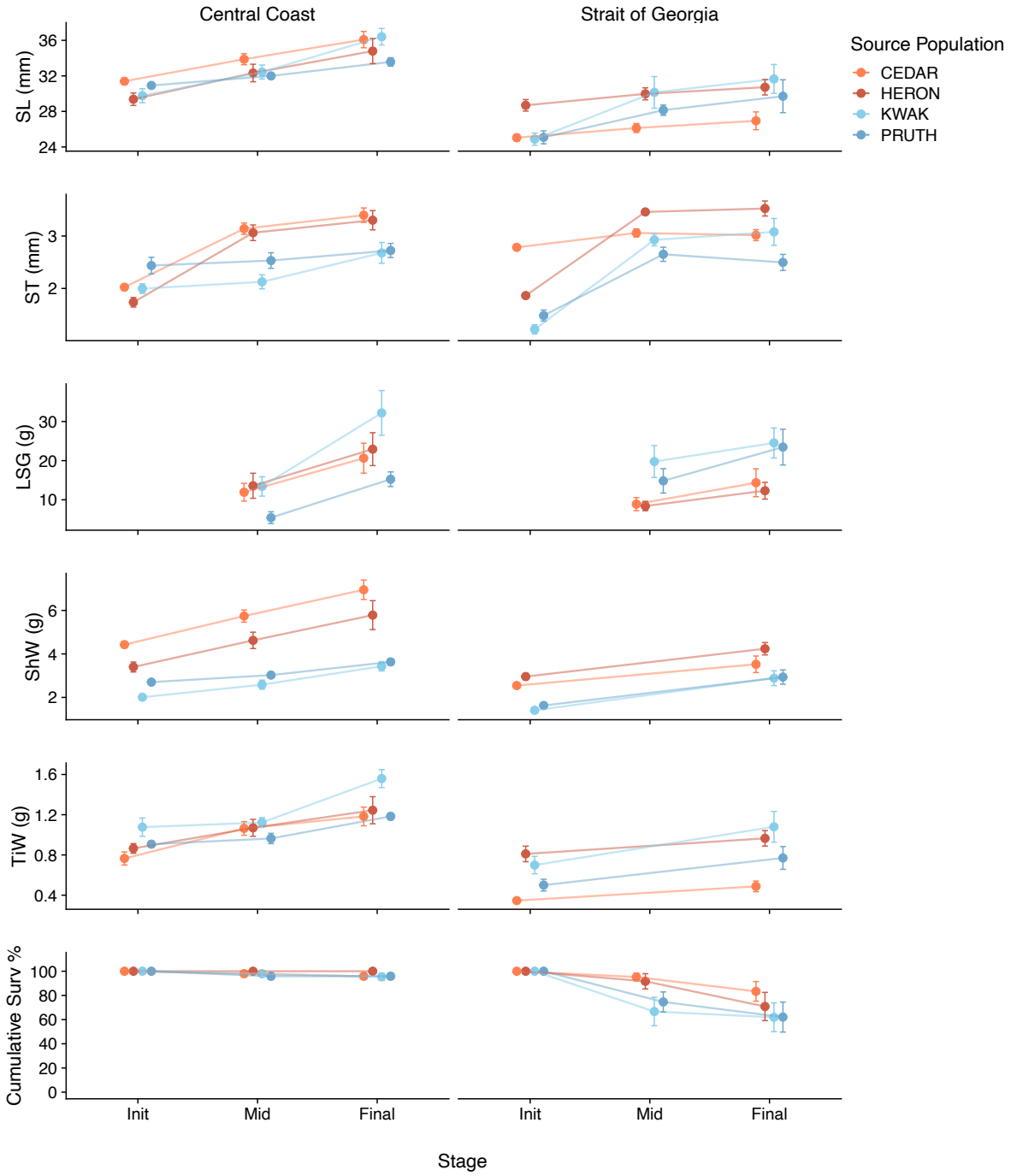

Figure B.6. Average growth and survival metrics for each source population within each outplant region at the beginning, middle, and end of the 2019 reciprocal transplant experiment. Colours correspond to the source region, with orange populations originating from the Strait of Georgia and blue from the Central Coast. n= 8. Plots show mean ± SE. Acronyms are as follows: SL = shell length, ST = shell thickness, LSG = linear shell growth, ShW = shell weight, TiW = tissue weight.

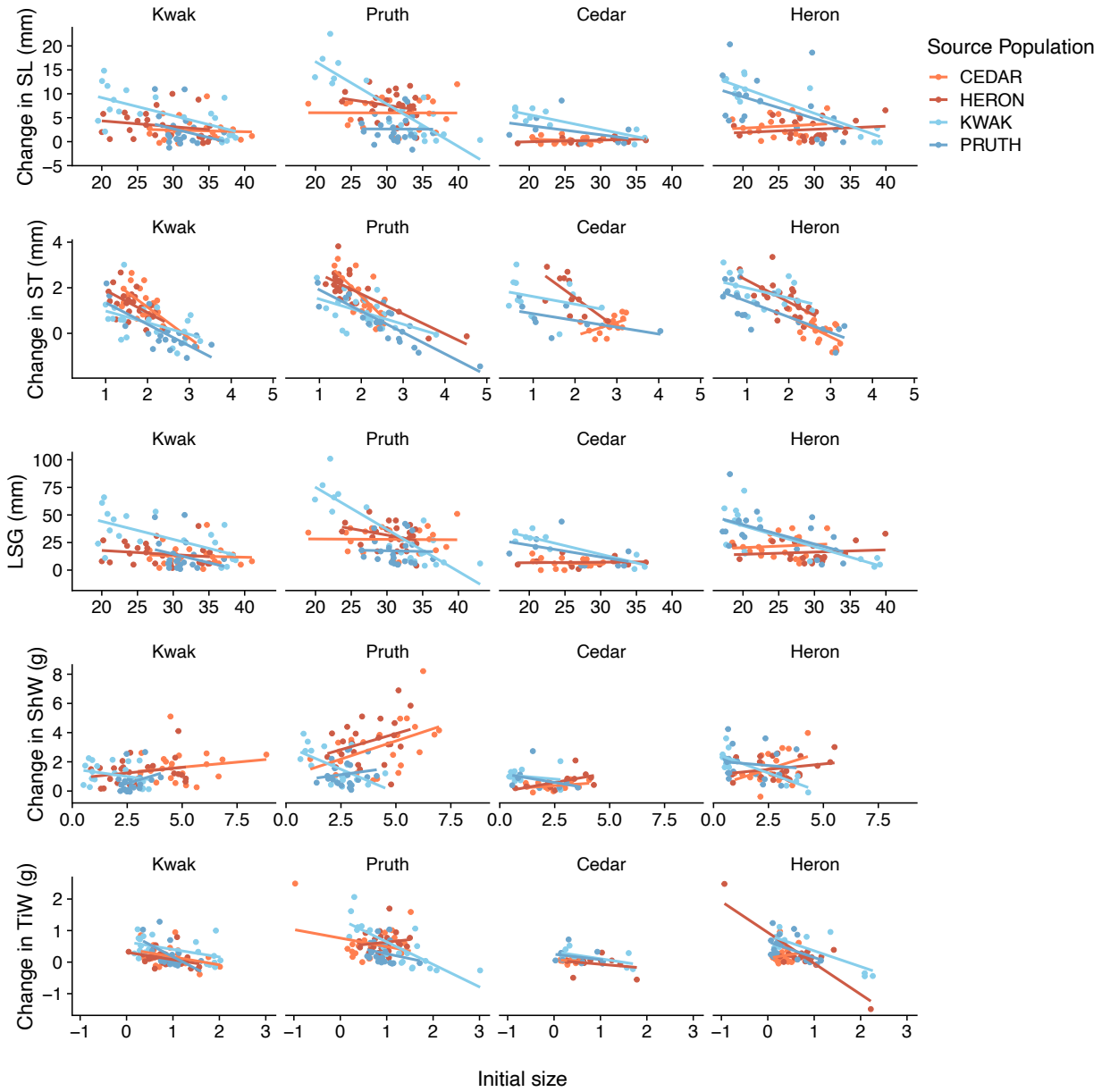

Figure B.7. Regressions between the initial size and change in growth metrics for each source population and outplant site from the 2019 reciprocal transplant experiment. Colours correspond to the source region, with orange populations originating from the Strait of Georgia and blue from the Central Coast. Sample sizes are as follows for each outplant site, ordered by Cedar, Heron, Kwakshua, and Pruth: Kwakshua (23, 24, 21, 19), Pruth (23, 24, 21, 22), Cedar (16, 12, 11, 9), Heron (19, 22, 15, 18).

Table B.1. Tank parameters across temperature treatments in the mesocosm experiment (July – Sept 2018) including iButton temperatures, and temperature, salinity, and pH measurements (mean ± SD). The iButton and Temperature data columns reflect the average tank conditions from after the heatwave until the end of the experiment (i.e., Aug 1 – Sept 2), whereas the other columns reflect average parameters during the full experiment (i.e., July 23 – Sept 2).

Treatment	Number of tanks	iButton (°C)	Temperature (°C)	Salinity (ppt)	pH
12	2	12.61±0.62	13.38±0.81	29.31±0.12	7.74±0.06
15	5	15.20±0.37	15.67±0.37	29.91±0.20	7.71±0.05
19	3	18.86±0.06	19.25±0.18	30.29±0.12	7.78±0.11
22	3	21.91±0.10	21.82±0.16	30.39±0.17	7.83±0.06

Table B.2. *In situ* measurements from spot samples recorded at each outplant site in 2019. The NAs indicate where pH and DIC measurements were not recorded.

Date	Site	Air temperature (°C)	Water temperature (°C)	Salinity	pH
March	Cedar	9.8	9.3	29.1	8.27
	Heron	16.1	10.4	29.5	8.49
	Kwakshua	9.0	7.7	31.7	7.87
	Pruth	8.0	7.8	25.5	7.81
April	Cedar	8.7	9.6	29.3	NA
	Heron	12.7	11.9	28.2	NA
June	Cedar	23.0	22.1	24.7	7.87
	Heron	19.9	16.8	24.4	7.80
	Kwakshua	11.1	11.0	29.4	7.97
	Pruth	12.6	11.7	28.7	7.97
August	Cedar	21.5	20.2	27.2	8.23
	Heron	21.2	17.5	27.1	8.18
	Kwakshua	18.1	14.0	25.6	7.81
	Pruth	15.1	14.8	27.8	7.89

Appendix C Supplementary information for Chapter 4 A local and Indigenous-led approach to knowledge creation transforms marine spatial planning tools and processes: a case study in the Salish Sea

C.1 Description of Átl'ka7tsem/Howe Sound

Beginning in the late eighteenth century, European colonization led to the extirpation of marine species (e.g., humpbacks, eulachon), relocation and disruption of Indigenous communities, and environmental pollution due to forestry and mining (Bodtker, 2017; Miller, 2020). Between 1905 and 2005, copper mining (and legacy effects) at Britannia Beach caused the worst point source metal contamination and seawater pollution in North America (O'Hara, 2007). Since the early 2000s, however, industrial remediation and community stewardship efforts have enabled the partial recovery of marine life. Present day, Átl'ka7tsem is globally renowned for supporting diverse marine ecosystems, including glass sponge reefs that were considered to have gone extinct in distant geologic eras. The revival of ocean health has inspired communities, organizations, and governments to collaboratively engage in regional conservation and planning and in 2021, Átl'ka7tsem was designated a UNESCO Biosphere Region. Given its proximity to high human density and industrial activities, life in and around Átl'ka7tsem experiences significant pressures. Development and tourism have grown rapidly over the past decade, several large industrial proposals (e.g., gravel mine, LNG port) have generated conflict within communities, and climate change has degraded coastal infrastructure through sea-level rise, storms, and flooding events (Bodtker, 2017; Miller, 2020).

Language and pronunciation resources for the Skwxwú7mesh sníchim (language)

- Átl'kat7sem: https://howesoundguide.ca/atlka7tsem-pronounciation-chief-ian-campbell-1/
- Skwxwú7mesh: https://youtu.be/yknmoz9PZRU
- Place names within the territory: http://squamishatlas.com/#

C.2 Átl'ka7tsem implementation of community-led MSP framework outlined in Figure 4.2.

1. Rightsholders and stakeholders in Átl'ka7tsem articulated their desire to improve the management of ocean health and community access through planning and the creation of holistic decision-support tools

a. 1996: Howe Sound Round Table identified need for a watershed-wide perspective for Howe Sound and coordinated governance and community management (AHSBRI, 2022)
b. 2014: Sk̲wx̲wú7mesh Úxwumixw established the goal of creating a Marine Use Plan (Skwxwú7mesh Úxwumixw, 2022)
c. 2017: A local research report identified the creation of an interactive map that collates knowledge about the marine environment as a priority action to protect ocean health and support holistic planning (Bodtker, 2017)
d. 2017: Átl'k̲a7tsem / Howe Sound Biosphere Region Initiative Society identified goal of creating a holistic land and marine use plan for the region

2. Rightsholders and stakeholders in Ál'k̲a7tsem formed collaborative partnerships and began pre-planning associated with creating an interactive map to support marine spatial planning
    a. 2017: Local governments, Sk̲wx̲wú7mesh Úxwumixw members, and non-profit organizations formed a task force to advance the creation of the interactive map
    b. 2018: The Átl'k̲a7tsem/Howe Sound Marine Stewardship Initiative (MSI, formerly known as the Marine Reference Guide) was established as a project on MakeWay's Shared Platform to create the interactive map
        i. The MSI formed a leadership committee with participation from Sk̲wx̲wú7mesh Úxwumixw councillors and the task force to ensure project develops in support of regional planning goals
        ii. The MSI formed a roundtable community advisory committee to shape project implementation with participation from local and Indigenous government staff, non-profit organizations, economic sectors, academia, and community organizations
    c. 2018: The MSI selected a study-area boundary that matched existing holistic planning boundaries, including the Provincial Government's Cumulative Effects Assessment boundary and the Átl'k̲a7tsem/Howe Sound Biosphere Region boundary. The boundary included the watersheds that flow into Átl'k̲a7tsem to reflect the holistic and interconnected dynamics across freshwater, terrestrial, and marine systems.

3. The MSI initiated data collation and map creation
    a. 2019-20: The MSI collated existing biophysical, administrative, and human-use data layers and began to build an interactive map using an ESRI platform
    b. 2019: The MSI identified data gaps associated with Átl'ka7tsem, including species and social data about human values

4. The MSI initiated a co-creation process to fill social data gaps
    a. 2019: MSI staff and researchers at the University of British Columbia formed research team
    b. 2019-21: The research team conducted an ethics approval process with the University of British Columbia and Skwxwú7mesh Úxwumixw council to form collaborative research agreement
    c. 2019-21: The research team and community advisory committee co-created and co-implemented research objectives and methods
    d. 2021-22: The research team conducted data analysis, solicited feedback from the community advisory team, and re-analyzed results to ensure community knowledge and needs were reflected in the research results
    e. 2022-23: Research team created and shared research results in myriad formats to enhance accessibility to different audiences, including an academic publication and dissertation chapter, written reports, story-maps, and uploading into the MSI interactive map

5. The MSI conducted training and evaluation workshops with end-users to build awareness, familiarity, and trust in research results and identify further data gaps / room for improvements
    a. 2021-2023: MSI staff conducted training workshops with planners from local, provincial, federal, and Indigenous governments and with community groups and stakeholders and gather feedback on further revisions

6. 2023: Rightsholders and stakeholders develop strategies and plans to protect ocean and community health using decision-support tools created via research process

C.3 Co-design process – survey and interviews

We employed the following co-creation process for our survey: 1) UBC research team members drafted the survey questions, some of which were informed by content shared during the interviews; 2) the draft was circulated amongst the community advisory team for feedback; 3) the revised survey questions were built into the Maptionnaire software and circulated amongst a pilot group, including both community advisory and research team members. We anticipated that some respondents would not complete the full non-spatial portion of the survey due to the relatively long survey design. Accordingly, we frontloaded demographic questions to enable as many semi-complete responses as possible for demographic analyses.

The interview design and recruitment processes were co-created with UBC research and community advisory team members. The semi-structured interview guide and table of values was first drafted by research team members and then iteratively revised by both the research and community advisory groups. Upon incorporating final feedback, several pilot interviews were conducted to test the participatory mapping software (MyMaps) and interview duration. For qualitative research that employs purposive sampling schemes, sample sizes are generally determined by saturation – which occurs when sampling additional data no longer provides new information or new thematic categories (Collins, 2010). The likelihood of reaching saturation at a given sample size changes based on whether your sample is heterogeneous or homogenous, where more heterogeneity requires larger sample sizes (Collins, 2010; Onwuegbuzie and Collins, 2007).

C.4 Correspondence analysis between gender, age, sector and frequency of mapped values

Ecological

The correspondence analyses visualize the relationship between age, gender, and sector with the fifteen mapped aquatic values (Figs C.7-C.9). Men and older participants (>46 years old) had a greater propensity to map intrinsic values, while younger participants had a greater propensity to map aesthetic values (Figs C.7-C.8). Respondents from the arts, culture, and media sectors mapped intrinsic values more than other sectors (Fig C.9).

Social

Women had a greater propensity to map spiritual, learning, and therapeutic values, and participants aged 36-45 mapped learning values the most frequently (Fig C.7, C.8). There was no strong association between professional sector and mapped social values (Fig C.9).

Cultural

In the correspondence analysis, participants aged 46-60 and those from the arts, culture, and media sector had a strong propensity to map Indigenous and non-Indigenous cultural values (Fig C.7, C.9).

Economic

In the gender correspondence analysis, women and men had a similar propensity to map shipping and transportation routes. Women were more closely associated with mapping tourism whereas men mapped natural resources, and commercial and recreational fishing more frequently (Fig C.8). Survey participants aged under 35 were similar in their propensity to map commercial fishing (Fig C.7) and there was a strong alignment between professional sectors and mapped economic values: industry participants had the greatest propensity to map commercial fishing; those from tourism and health had similar propensities to map recreational fishing; and folks from business were the most closely associated with mapping natural resources and development (Fig C.9). Education and government sectors were similarly associated with mapping tourism, while NGOs, academia, and community sectors were similar in their propensity to map shipping and transportation areas (Fig C.9).

C.5 Univariate tests of gender, age, and sector across individual values

Ecological

Analyses of the univariate effects of gender across each ecological value followed the same trend as the composite analysis, with women agreeing to a greater extent ($p < 0.05$; Fig C.10, Table C.5). Agreement toward biodiversity and conservation values differed across age, with the youngest participants strongly agreeing the most ($p <0.05$), while the perception of the importance of conservation varied significantly across sector ($p = 0.02$; Fig C.11- C.12, Table C.5).

Social

Agreement was high across all genders toward social values; however, men agreed to a lesser extent than women and non-binary folks that Átl'ka7tsem supports therapeutic, and learning education and research ($p < 0.03$, Fig C.10, Table C.5). As with ecological values, the youngest age category agreed the most that Átl'ka7tsem supports therapeutic and learning education and research values ($p < 0.04$; Fig C.11, Table C.5). The only social value in the univariate analyses where perspectives differed across sector was learning, education, and research ($p = 0.004$; Fig C.12, Table C.5).

Cultural

Perceptions about Indigenous cultural values varied across gender, with men agreeing to a lesser extent than women and non-binary folks ($p < 0.001$; Fig C.10, Table C.5). Age significantly affected perceptions that Átl'ka7tsem supports Indigenous cultural values, with younger participants [strongly] agreeing more than older ones ($p < 0.001$; Fig C.11, Table C.5). Agreement also significantly differed across sectors, with respondents from academia, arts cultural heritage and media, NGO, and governmental sectors expressing the most agreement ($p < 0.001$; Fig C.12, Table C.5). There was no significant effect of gender, age, or sector on non-Indigenous cultural values (Table C.5).

Economic

Agreement toward recreational fishing and development was higher in men than women and non-binary folks ($p < 0.01$; Fig C.10, Table C.5). Age also significantly affected the valuation of development and shipping and transportation, with respondents aged 26-45 disagreeing the most that Átl'ka7tsem supports these values ($p < 0.01$; Fig C.11, Table C.5). Finally, sectoral variation was significant in the univariate analyses of livelihoods, tourism, and natural resources, with strongest agreement from tourism or industry and strongest disagreement from the education sector ($p < 0.05$; Fig C.12, Table C.5).

C.6 Supplemental figures and tables associated with Chapter 4

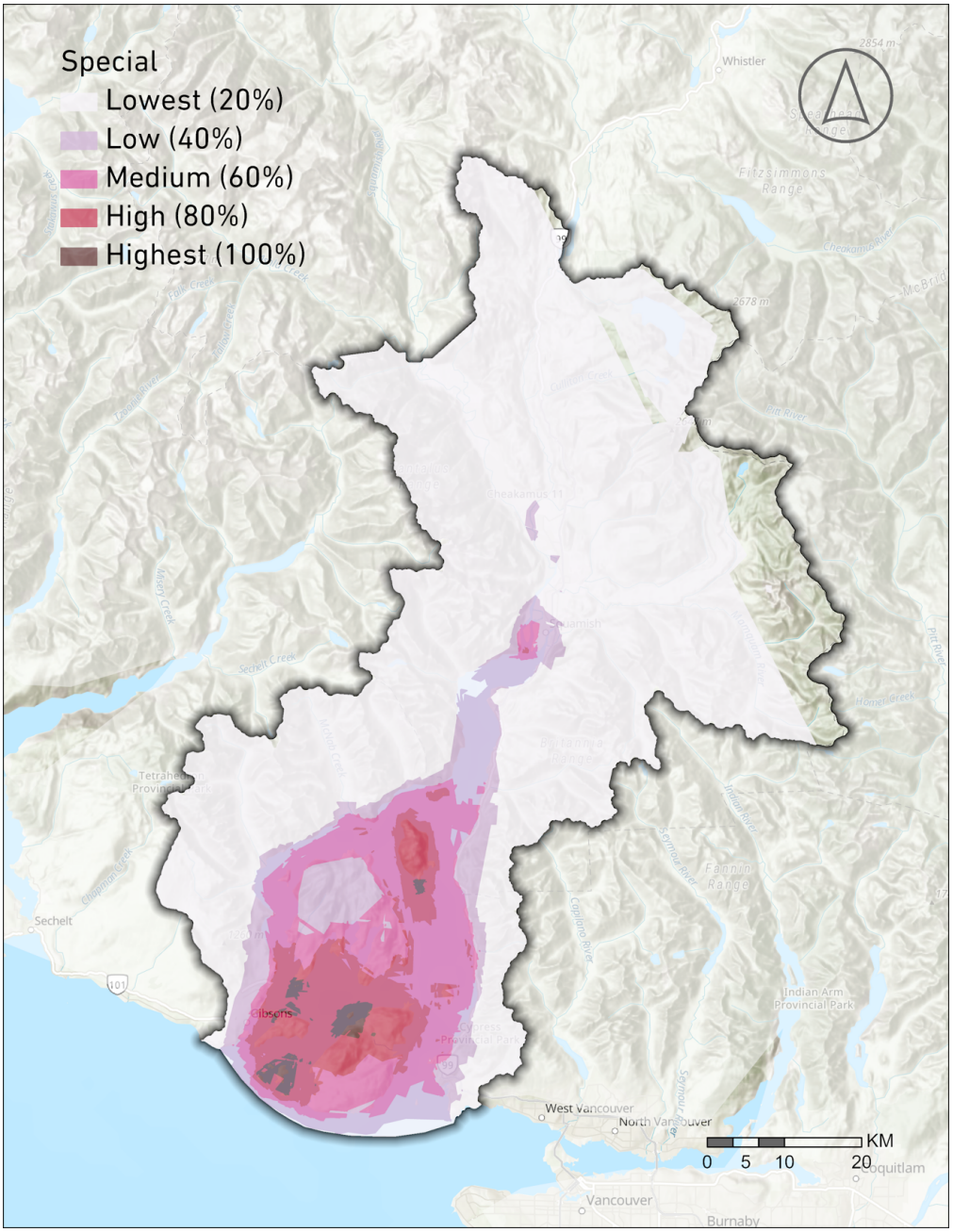

Figure C.1. Spatial distribution and concentration for special places identified by interview (n = 29) and survey (n = 124) participants, where darker indicates more polygons and lighter areas indicate fewer. See Table 4.2 for frequency metrics associated with polygon density.

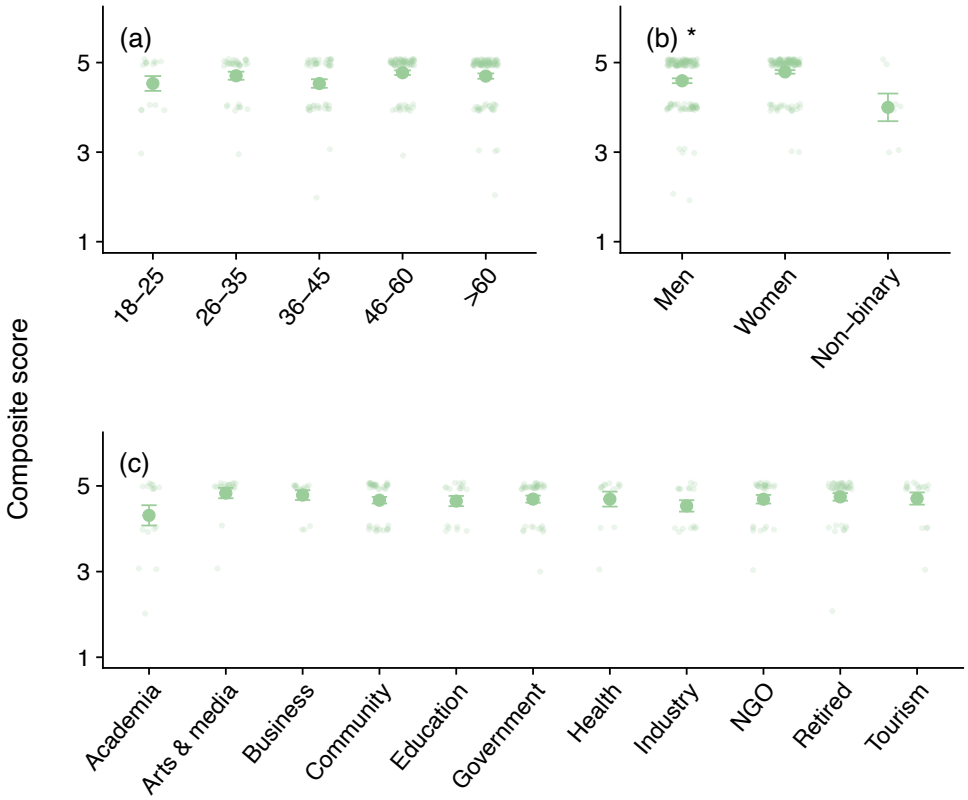

Figure C.2. Ecological composite scores across survey respondent ages (a), genders (b), and sectors (c). Points (jittered horizontally and vertically) represent individual survey respondents (n = 265-267) and plots show mean composite scores ± SE. Asterix denotes statistical significance.

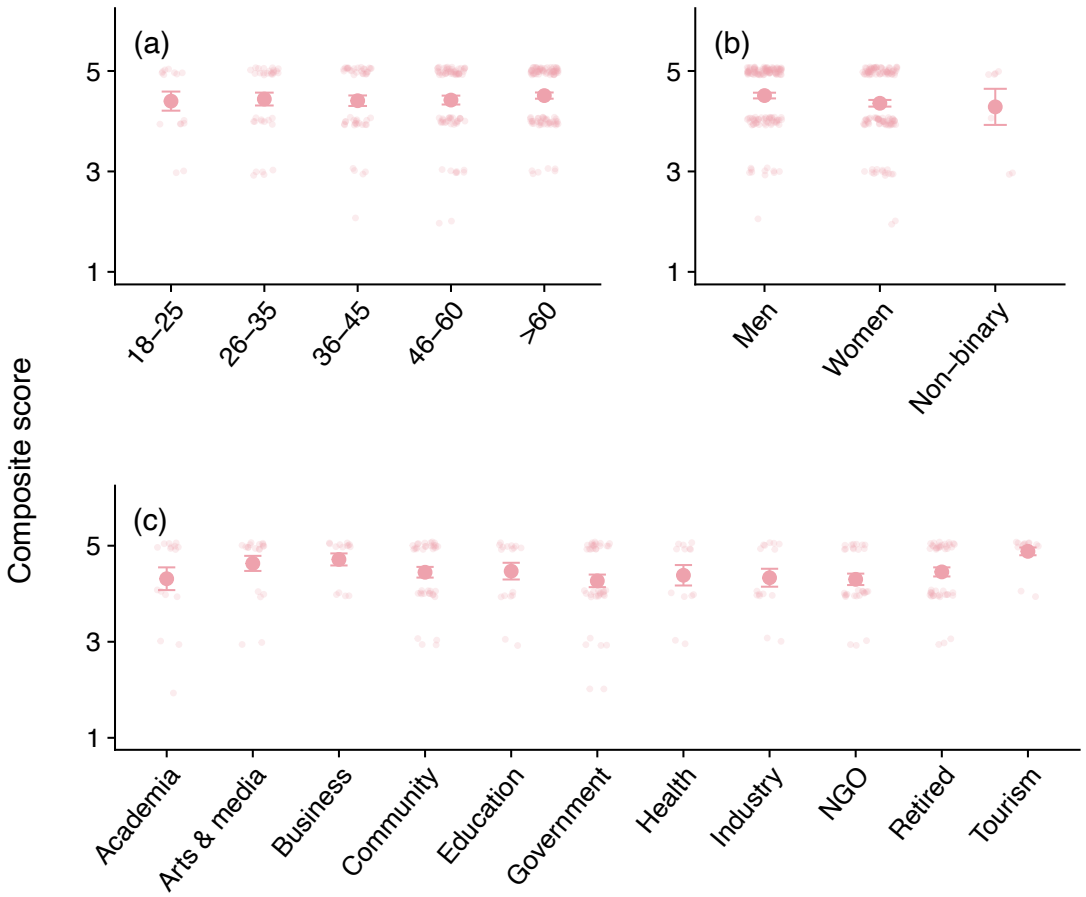

Figure C.3. Social composite scores across survey respondent ages (a), genders (b), and sectors (c). Points (jittered horizontally and vertically) represent individual survey respondents (n = 264-272) and plots show mean composite scores ± SE.

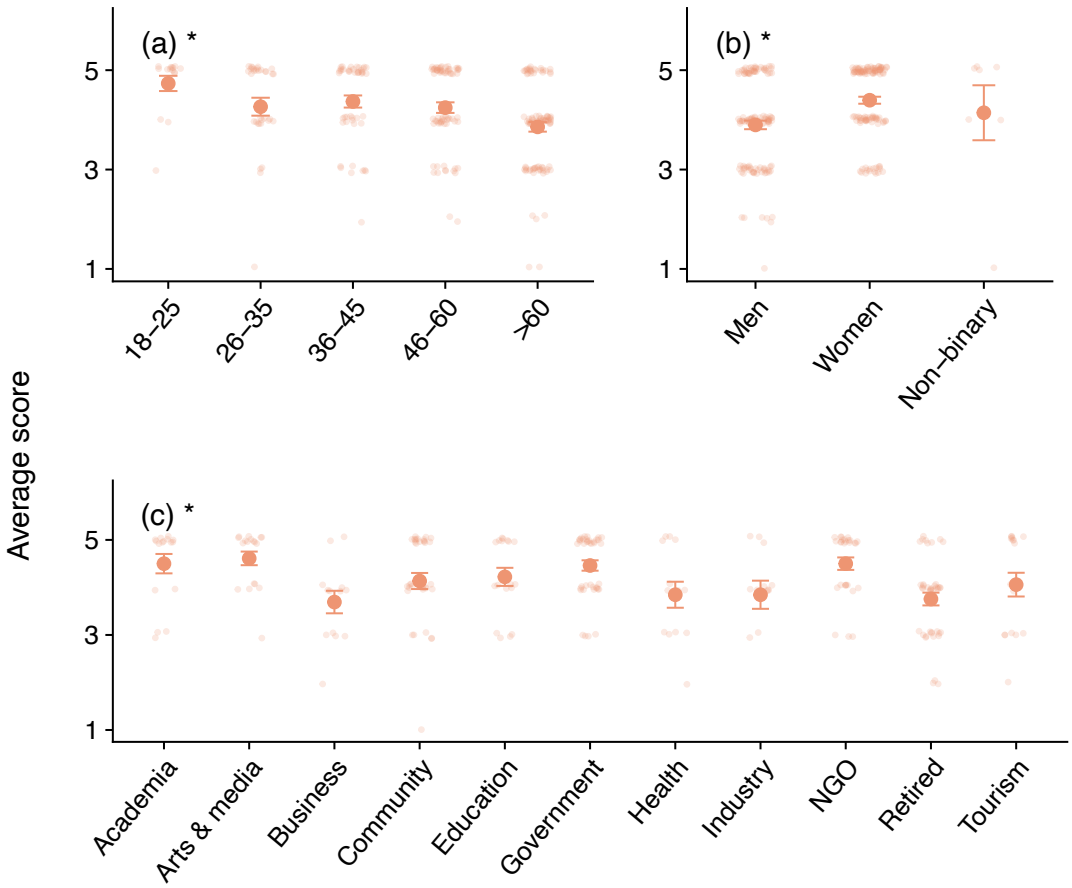

Figure C.4. Average scores for Indigenous cultural across survey respondent ages (a), genders (b), and sectors (c). Points (jittered horizontally and vertically) represent individual survey respondents (n = 253-260) and plots show mean composite scores ± SE. Asterisks denote statistical significance.

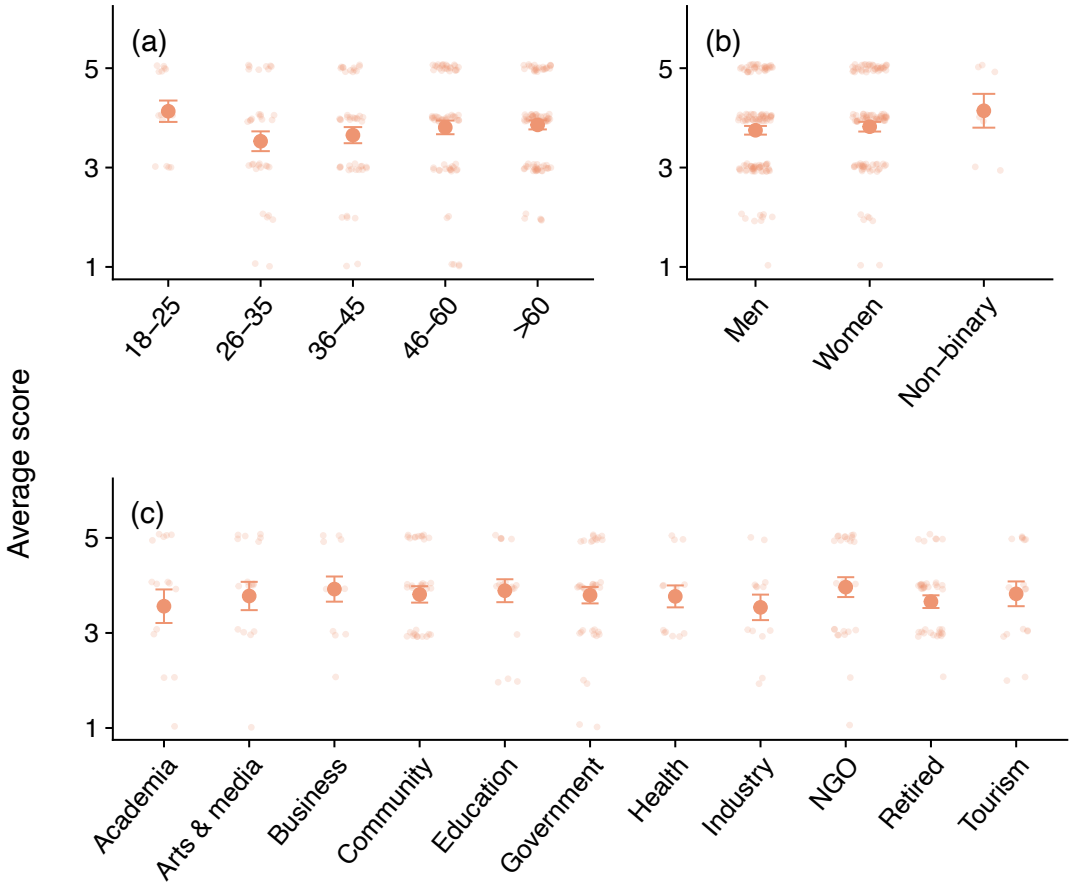

Figure C.5. Average scores for non-Indigenous cultural across survey respondent ages (a), genders (b), and sectors (c). Points (jittered horizontally and vertically) represent individual survey respondents (n = 253-260) and plots show mean composite scores ± SE.

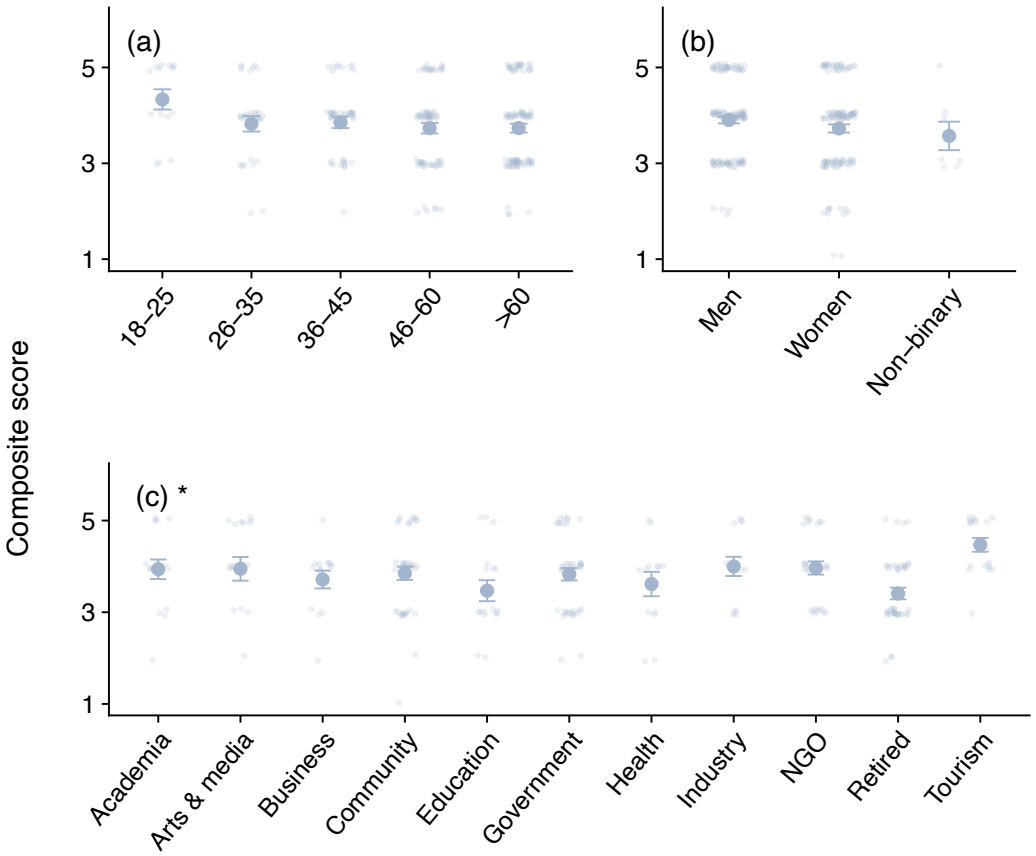

Figure C.6. Economic composite scores across survey respondent ages (a), genders (b), and sectors (c). Points (jittered horizontally and vertically) represent individual survey respondents (n = 264-270) and plots show mean composite scores ± SE. Asterix denotes statistical significance.

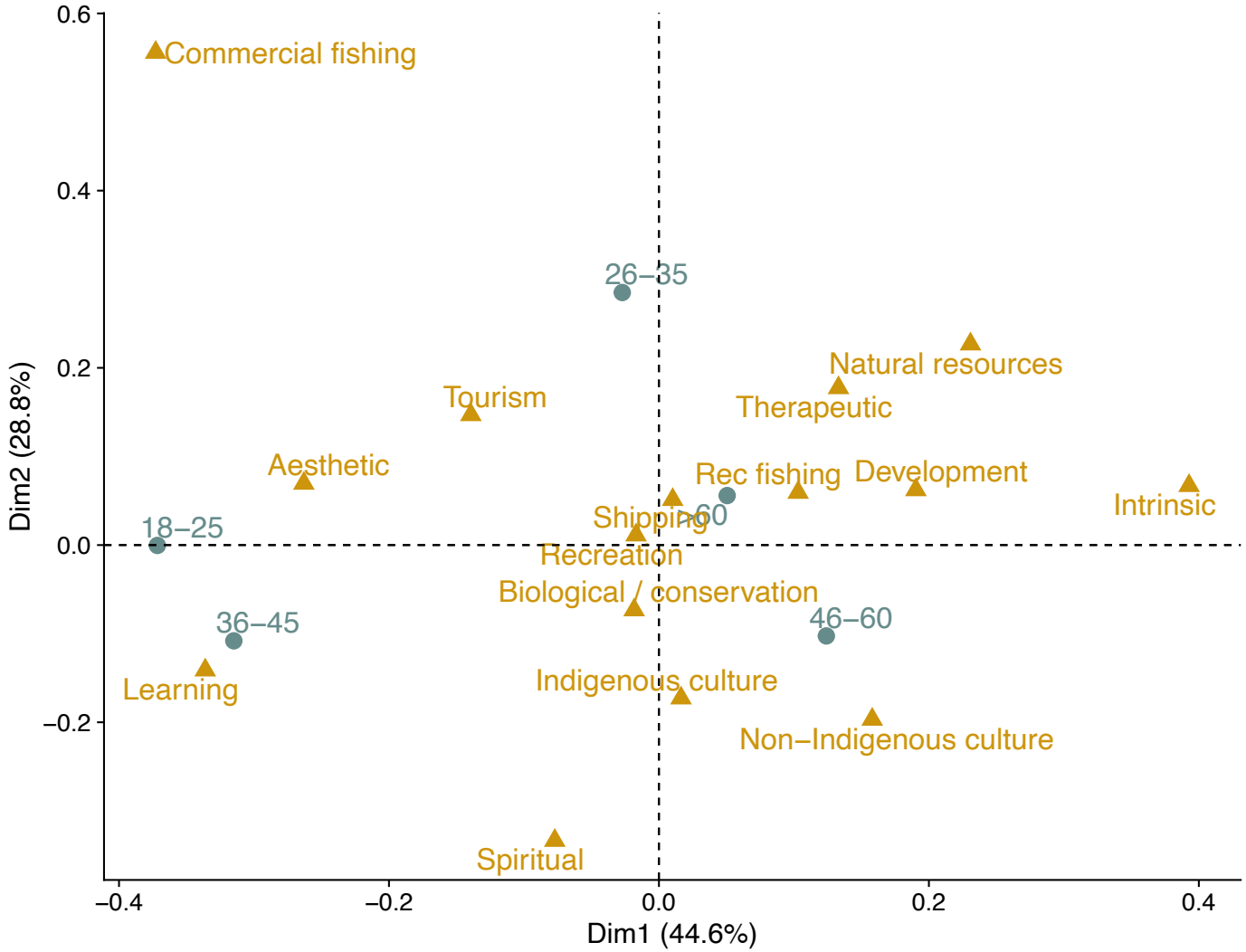

Figure C.7. Correspondence analysis of survey respondent age and mapped values.

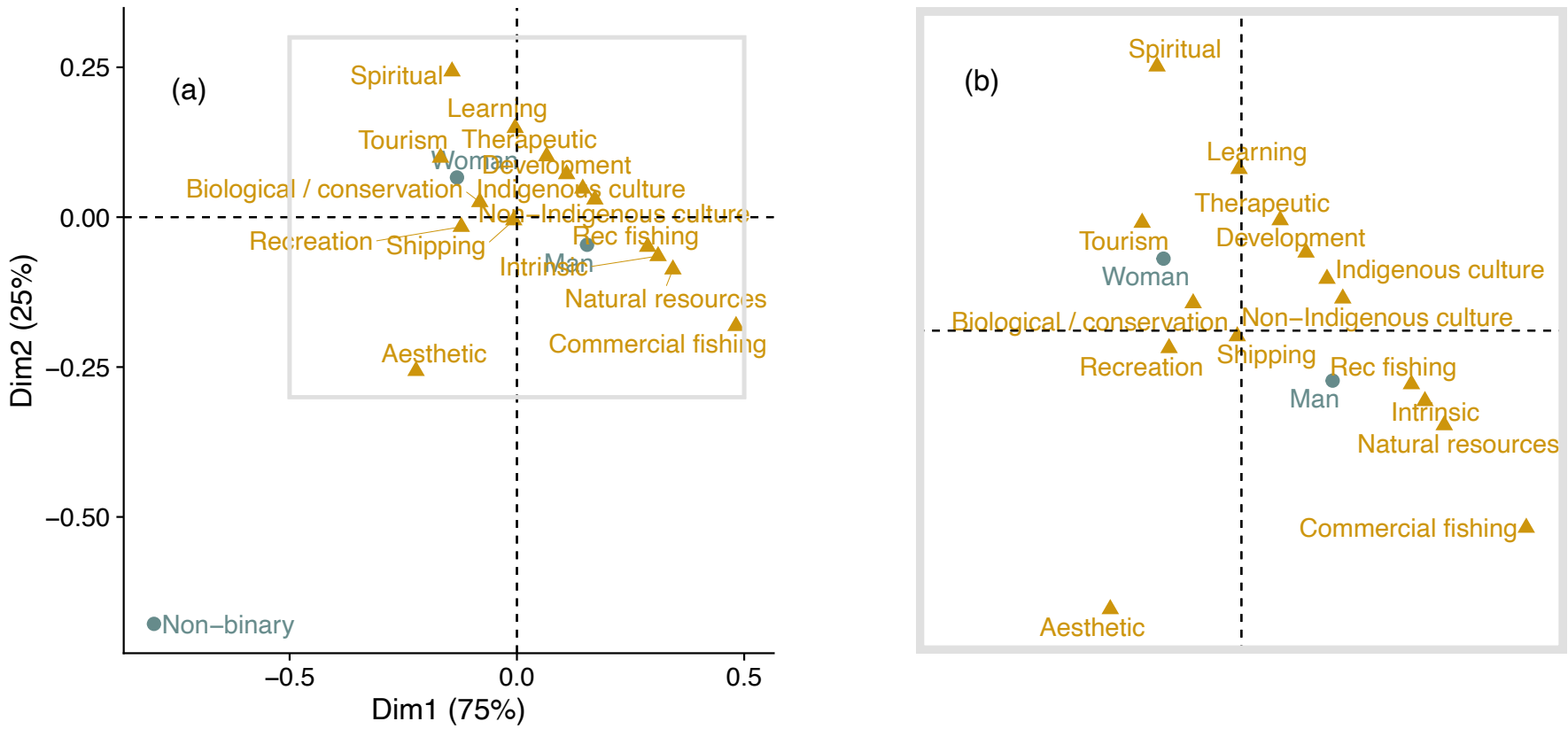

Figure C.8. Correspondence analysis of gender and mapped values. B) Zoomed-in subset of the full dataset visualized in A).

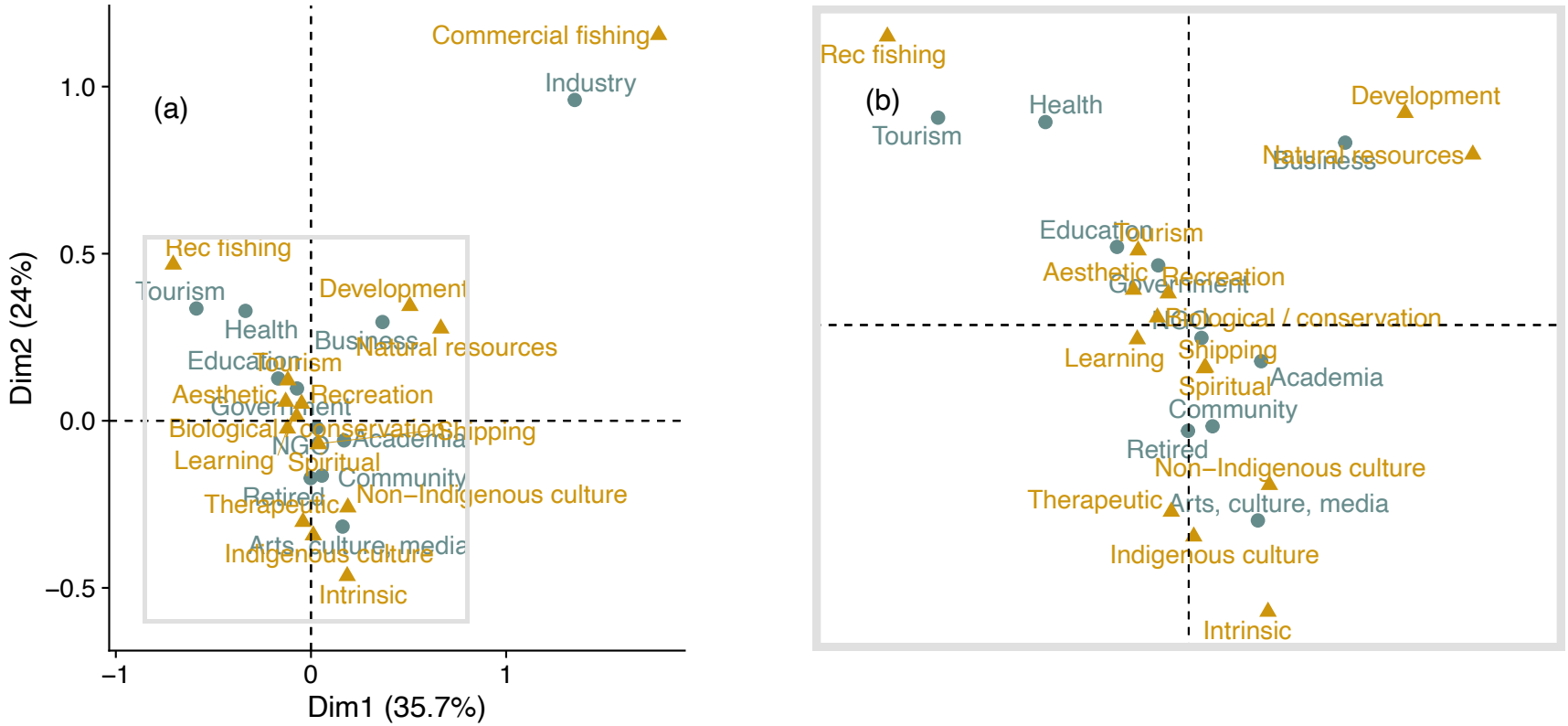

Figure C.9. Correspondence analysis of professional sector and mapped values. (b) Zoomed-in subset of the full dataset visualized in (a).

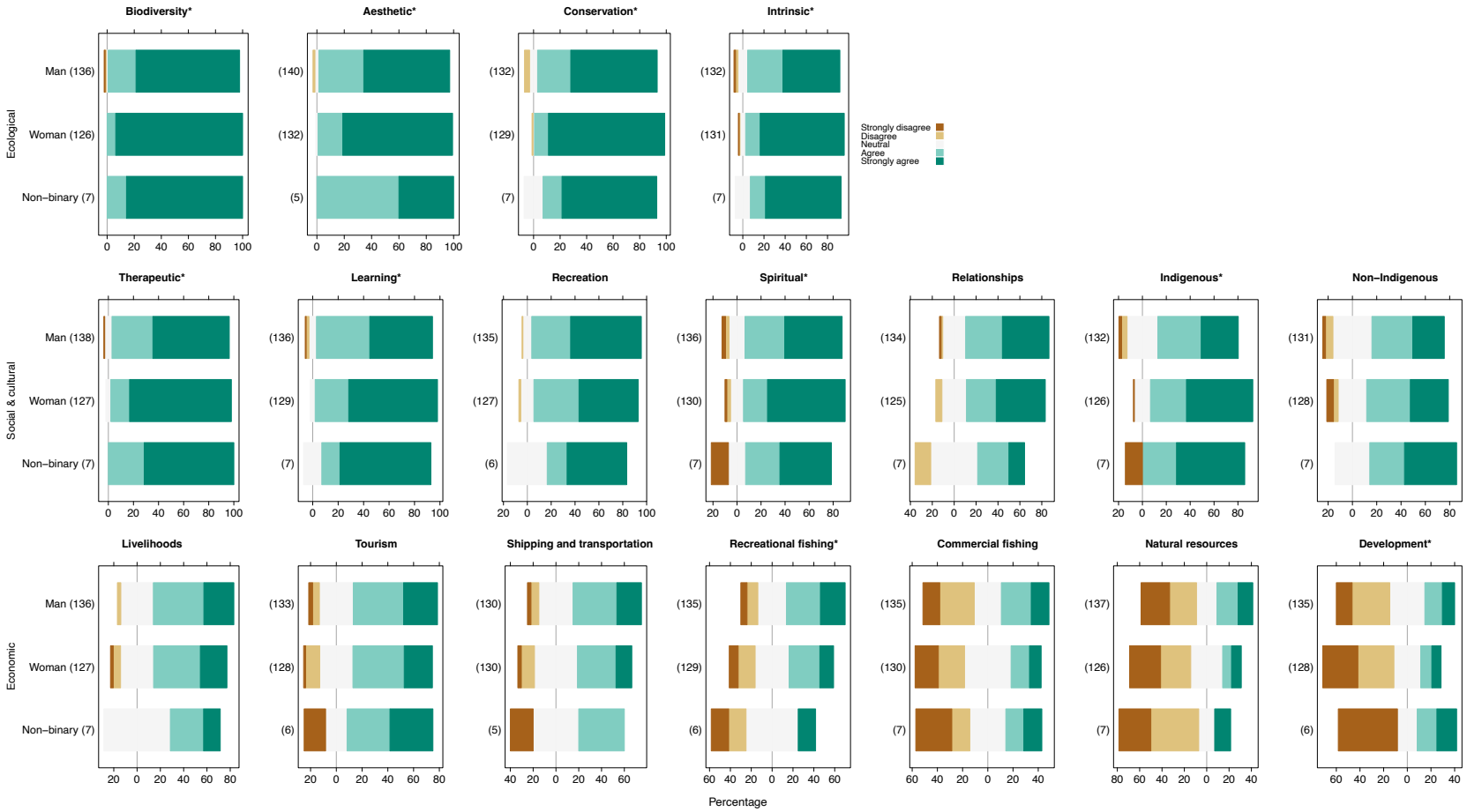

Figure C.10. Agreement toward the eighteen values across **gender**. The top row visualizes ecological values, the middle row shows social and cultural values, and the bottom row shows economic values. Dark red denotes strong disagreement and dark blue strong agreement. For the full value statements see Table C.3. Asterisks denote statistical significance of gender on agreement. Sample sizes are provided in parentheses for each demographic category.

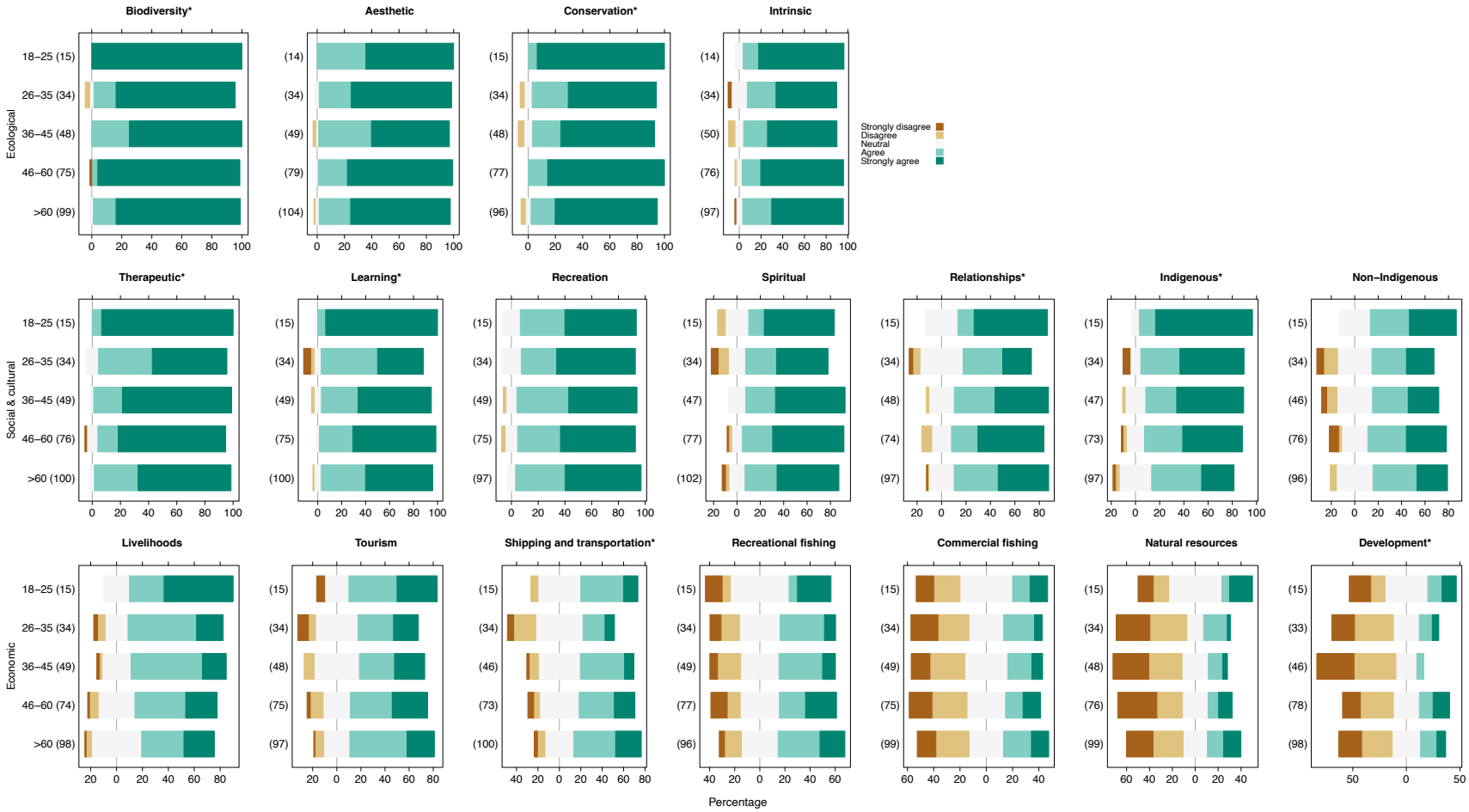

Figure C.11. Agreement toward the eighteen values across **age**. The top row visualizes ecological values, the middle row shows social and cultural values, and the bottom row shows economic values. Dark red denotes strong disagreement and dark blue strong agreement. For the full value statements see Table C.3. Asterisks denote statistical significance of age on agreement. Sample sizes are provided in parentheses for each demographic category.

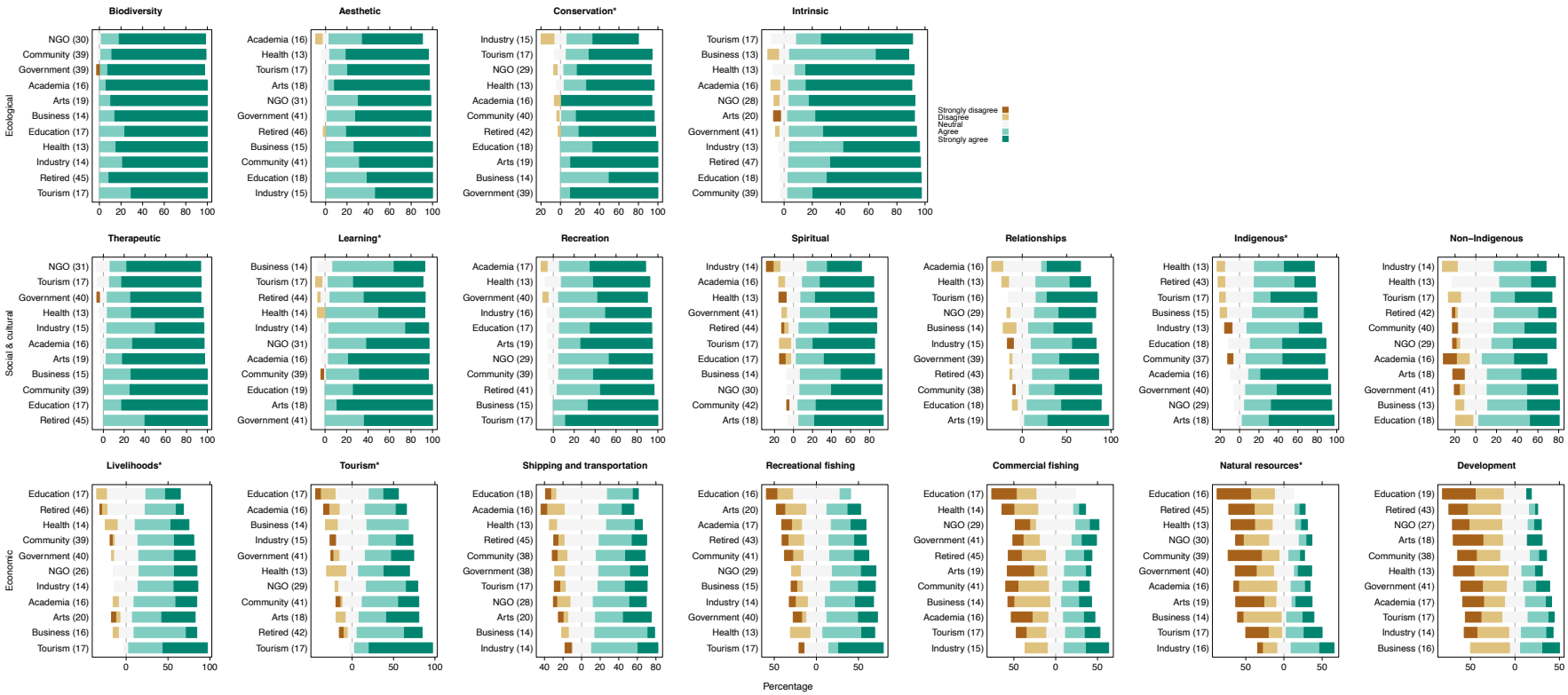

Figure C.12. Agreement toward the eighteen values across **sector**. The top row visualizes ecological values, the middle row shows social and cultural values, and the bottom row shows economic values. Dark red denotes strong disagreement and dark blue strong agreement. For the full value statements see Table C.3. Asterisks denote statistical significance of sector on agreement. Sample sizes are provided in parentheses for each demographic category.

Table C.1. Value statements used in the survey and interviews, and proportion of responses from the survey. Each value statement corresponds with a value category (Cat). Survey responses reflect the proportion of participants were asked to rate how strongly they agreed with the statements. Sample sizes are provided with the relative proportion in parentheses (N = 302).

Cat	Value	Statement	Survey responses Strongly disagree	Disagree	Neutral	Agree	Strongly agree	NA
Ecological	Aesthetic, physical, seascape	I value the Sound's water because of its aesthetic– what I can see, hear, and smell here	0 (0)	2 (0.70)	6 (2.11)	75 (26.3)	202 (70.9)	17
	Biodiversity[1]	I value the Sound's water because it supports a variety of species and life, such as marine mammals, birds, plants, fish, and invertebrates	1 (0.36)	1 (0.36)	3 (1.08)	37 (13.4)	235 (84.8)	25
	Conservation[1]	I value the Sound's water because it supports unique, iconic, and/or important species that should be or are protected	0 (0)	6 (2.17)	11 (3.98)	50 (18.1)	209 (75.7)	26
	Intrinsic/existence	I value the Sound's water and the life within for their own sake, no matter what I or others think about them	3 (1.08)	4 (1.44)	22 (7.91)	64 (23.0)	185 (66.5)	24
Cultural	Indigenous culture & food security	I value the Sound's water and the life within because they support Indigenous food security, cultural practices, and ways of life	6 (2.21)	6 (2.21)	53 (19.5)	89 (32.7)	118 (43.4)	30
	Non-Indigenous culture	I value the Sound's water and the life within because they reflect and support non-Indigenous heritage, traditions, and cultural activities	11 (4.01)	15 (5.47)	78 (28.5)	92 (33.6)	78 (28.5)	28
Social	Recreation	I value the Sound's water because it supports coastal recreational activities (e.g., camping, boating, fishing, diving, exploring, spending time with friends and family)	0 (0)	3 (1.09)	27 (9.78)	96 (34.8)	150 (54.3)	26
	Learning/ education/ research	I value the Sound's water because it provides opportunities to learn about nature and culture through experience, research, and observation	2 (0.71)	3 (1.07)	14 (5.00)	95 (33.9)	166 (59.3)	22

	Therapeutic/ health	I value the Sound's water because it makes me feel better mentally and/or physically	1 (0.36)	0 (0)	14 (5.00)	69 (24.6)	196 (70.0)	22
	Spiritual	I value the Sound's water because it allows for profound and/or spiritual experiences of nature	8 (2.85)	9 (3.20)	36 (12.8)	73 (26.0)	155 (55.2)	21
	Relational[2]	I value Howe Sound/ Átl'ka7tsem's water due to the relationships that I have formed because of it	3 (1.09)	10 (3.65)	61 (22.3)	82 (29.9)	118 (43.1)	28
Economic	Livelihoods[2]	I value Howe Sound/ Átl'ka7tsem's water because it supports livelihoods	4 (1.44)	12 (4.32)	80 (28.8)	115 (41.4)	67 (24.1)	24
	Natural resources	I value the Sound's water because it supports natural resource industries (e.g., forestry, mining) that rely on access to water	76 (27.4)	73 (26.3)	62 (22.3)	36 (12.9)	31 (11.2)	24
	Commercial fishing	I value the Sound's water because it provides fish and seafood that support commercial fisheries	44 (15.7)	69 (24.6)	81 (28.9)	53 (18.9)	33 (11.8)	22
	Recreational fishing	I value the Sound's water because it provides fish and seafood that support recreational fishing businesses	22 (7.91)	36 (12.9)	86 (30.9)	83 (29.9)	51 (18.3)	24
	Tourism	I value the Sound's water because it supports eco or nature-based tourism businesses	8 (2.91)	21 (7.64)	71 (25.8)	107 (38.9)	68 (24.7)	27
	Shipping and transportation	I value the Sound's water because it provides transportation and access routes for the movement of goods and people	10 (3.66)	24 (8.79)	95 (34.8)	97 (35.5)	47 (17.2)	29
	Development	I value the Sound's water because is supports existing and potential development opportunities	61 (22.0)	86 (31.0)	70 (25.3)	35 (12.6)	25 (9.03)	25
	Special places	These places hold special value based on my personal experience of Howe Sound/Átl'ka7tsem						

[1] These values were combined in the interviews as 'biological/conservation'
[2] These values were only included in the surveys

Table C.2. Demographic survey questions and breakdown of possible answers. Sample sizes are provided with the relative proportion in parentheses (N = 331).

Theme	Question	Responses	n (%)
Connection to region	What category best represents your connection to the region?	Full time resident currently or in the past	193 (59.6)
		Indigenous ancestral connection/territory	1 (0.31)
		Full or part-time worker	26 (8.02)
		Part-time/temporary resident	46 (14.2)
		Regular visitor/tourist	51 (15.7)
		Occasional visitor/tourist	7 (2.16)
		Unanswered	2
Associated region	If you are a resident or worker, please identify where you reside or wok. Otherwise, please identify the area you visit most frequently.	Bowen Island/Nexwlélexwem	43 (13.5)
		Gambier Island/Chá7elkwnech	28 (8.80)
		Gibsons/Ch'kw'elhp/Scheṅk	8 (2.52)
		Lions Bay/Ch'ich'iyúy	23 (7.23)
		Metro Vancouver electoral Area A	20 (6.30)
		Other islands within study area	28 (8.81)
		Squamish	81 (25.5)
		Squamish-Lillooet Regional District	12 (3.77)
		Sunshine Coast Regional District	20 (6.29)
		West Vancouver	25 (7.86)
		Whole region	30 (9.43)
		Unanswered	13
Length of time in region	How long have you lived in and/or visited the region (years)?	0-5	37 (11.3)
		6-10	42 (12.9)
		11-20	73 (22.4)
		21-40	83 (25.5)
		>40	91 (27.9)
Age	What age category do you fall within?	18-25	15 (4.73)
		26-35	39 (12.3)
		36-45	56 (17.7)
		46-60	87 (27.4)
		>60	120 (37.9)
		Unanswered	9
Associated sector	Please identify the main sector that you associated yourself with	Academia and research	19 (6.13)
		Arts, cultural heritage, media	23 (7.42)
		Business	20 (6.45)
		Community	45 (14.5)
		Education	22 (7.01)
		Government (local, provincial, federal, First Nations)	42 (13.5)
		Health	15 (4.84)
		Industry	18 (5.81)
		NGO	31 (10.0)
		Retired	54 (17.4)
		Tourism	21 (6.77)
		Unanswered	16
Race	How do you describe your race or ethnicity? Select all that apply	Asian	11 (3.61)
		Black	0
		Hispanic, Latinx, or Spanish origin	1 (0.33)
		First Nations, Inuit, or Métis	3 (0.98)
		Middle Eastern	1 (0.33)
		Mixed race	10 (3.28)

		White	273 (89.5)
		White & Hispanic	1 (0.33)
		White & Indigenous	4 (1.31)
		White & South Asian	1 (0.33)
		Unanswered	21
Gender	How do you currently describe your gender identity?	Woman	148 (46.8)
		Man	161 (50.9)
		Non-binary	7 (2.22)
		I prefer not to answer	10

Table C.3. Total number of references within each value code based on (n = 30) semi-structured interviews.

Value category	Value	Number of references
Ecological	Biological/conservation	276
	Aesthetic, scenic, physical seascape	113
	Intrinsic, existence	42
	Total (average)	431 (144)
Social	Recreation	262
	Learning, education, research	90
	Spiritual	43
	Therapeutic, health	20
	Total (average)	415 (104)
Economic	Natural resources	107
	Eco or nature-based tourism	84
	Development	50
	Shipping and transportation	46
	Fishing – recreational	42
	Fishing – commercial	22
	Total (average)	351 (59)
Cultural	Non-Indigenous, settler culture, heritage, history	83
	Indigenous culture, heritage, history	146
	Total (average)	229 (115)
In vivo	Access	59
	Livelihoods	22
	Safety	19

Table C.4. Representative quotes selected from semi-structured interviews.

Values	Quote
Intrinsic – Biodiversity – Spiritual	"I guess for me a spot that I really love is in the river. It's… my happy place and it's a spot I've gotten to know. There're bears and loads of fish. It's just really pretty. It's kind of a spot not a lot of people go… [it's] one of those places you go and you feel like you're in this, like, wilderness haven. There're lots of tracks from animals, yes, it's a magical place."
Intrinsic – access	"That's the thing that kind of hurts about our territory, is it's so easy for people to get everywhere now for most of it. And it makes the specialness of it lower in my mind sometimes because you can just hike there easily in the daylight, or you can drive there in half an hour. And some of these things are lost on us because of the level of access that we have now has changed how we experience these things and in our own lives."
Aesthetic – Conservation	"You know, people have become now more accustomed to seeing cetacean action in Howe Sound, and they know that the reason they live here is because they love the natural beauty of this place. And so, if something comes in and threatens that, people are very vocal about it."
Aesthetic – whole region	"You know, it's hard it's hard to differentiate when the whole place is so goddamn pretty"
Biodiversity changes through time	"What I like about Howe Sound is the diversity. I mean, I have seen bears swimming across the waters in Howe Sound, I've seen wolves swimming across the waters in Howe Sound. Deer are a common thing. You know the plethora of marine life there is unbelievable. And, you know, the birdlife and everything else. And the colonies of eagles that I've gotten to know up there for the last fifteen odd years… It's a really, really a neat spot and to think we've got that so close to downtown Vancouver is pretty amazing." "People are definitely inspired and amazed by whales and seals and all of the marine life that thrive in these coastal regions. So I see the area as a whole. Is this very, very important place in terms of ecological biodiversity" "There's so much life here, and what I love about being a local is that you can go into these sites and see the changes and you sort of fall into the rhythms of the ocean. So I know that in February, you know, it's lingcod egg mass season and then, you know, the plankton bloom brings certain animals going to see dogfish and maybe, you know, a six gill, if we're lucky, in the summer months. So it's really cool to fall into the rhythms of the ocean." "It wasn't until about six or seven years ago that we started seeing a lot of whales here. And that was amazing because no one had seen them in this area for, what, 100 years or something like that. And I was feeling so fortunate to actually witness that personally… It's really quite inspiring to see that… No matter where you are mentally, you cannot help but respond to such a magnificent creature" "McNab Creek - we don't find a lot of fish there anymore. We used to fish the month of August and you would find 40 pounders there all day long for two or three weeks. Yeah. You don't you don't see that anymore."

	"I said, well you guys only arrived here and Captain Vancouver was in Howe Sound here in 1792, June 15th. Since then, ooligan has gone extinct in our territory, herring just recently returned, and pink salmon was extinct, but that's back in small abundance. We have ethnobotany medicinal plants extinct that we can't find anymore because they can only grow in certain areas of canopies of old growth areas and watersheds. And that's all gone."
Biological – Indigenous culture	"It feels like the land's health is going down, but the water's health is getting better. Like, when I was really young, I never, ever seen any porpoises - never seen any porpoises ever before, but all of a sudden, one day they just came back and same as the seals, the sea lions and the seals. And I remember the day that they we seen all these porpoises coming into the water because they're chasing the herring, I think, and there's like, killer whales out in the sea. It was like beautiful… there's killer whales are coming back because the water is just becoming out healthier. The other week we went to go eat some or the other a couple of weeks to go and we're eating sea urchins from the ocean, like so beautiful. Name the stories they talk about that, how the old people that eat sea urchins and they dove down and get sea urchins and stuff, but I never thought I'd be able to do that." "I think the main message, again, just to let everybody know that, as we talked about, that the sound is healing, the life is coming back, you know. Sealife is taking their place where they should be. It's not a barren place where you just dump stuff again, you know, it's no longer that. It's slowly returning back to what it once was and just to share and acknowledge the history about it. And I think it's important for all of us to know. It's good stuff for our people to know, because I'm sure a lot of people may not know, you know, the names that we use, you know, creating awareness of the language, the names, place names. Prior to the Olympics, you know, driving the Sea to Sky Highway, we never had no footprints showing people like you're on Skwxwú7mesh-ulh Temíx̱w, you know. And after that, people are seeing stuff like, oh, Squamish, oh, OK, you know. Being more visible in our in our own territory, these things, these conversations and dialogs allow us to be seen more."
	"I always remember my late mother and every day, every morning, walking out the door to go to elementary school to catch a bus, she would stand by the door. There are 10 of us kids in the house and we're all standing there and all got a tablespoon of oil before we went out the door to catch a bus to go to school. Ooligan oil, my mother used to make it really good and not smelly or anything. And I said, 'Mom, how come we're doing this? How come you always give us a big tablespoon ooligan oil?' She said it's brain food, brain food."
Biodiversity – Natural resources – Learning	"Well, you know, in the olden days, you go in there, the whole water was white, and you think it was pollution but it's herring spawn going off. And then it died off because, you know, we had all the mill activity and problems with Britannia Beach, with the copper leaching and things like that. But it's coming back and with the with the [spawning] nets that they're putting in… And as a result, everything's coming back into that area and we're starting to see the humpbacks coming back. So much [that] humpbacks are becoming a bit of a

	nuisance because they're everywhere now. And the killer whales, you know, I mean, we'll see killer whales right in downtown Horseshoe Bay. Right at the ferry terminal now, where they've had to stop the ferries, so the killer whales move away and that kind of thing… It's all a result of how we're helping to ensure that the whole biosphere goes back to a sustainable level where the ocean capacities can work and be in balance with each other. And so, you know, I take my hat off to the people that have, you know, I don't usually have a lot of time for tree huggers, but, you know, a lot of this came about because of the tree huggers and things like that. And, you know, I take my hat off to them, they did a great job and continue to do a great job as watchdogs for the area. But until we get it, that's the only way we're going to bring in, you know, great is this awareness." "The return of the whales… everyone can look at and go, wow, this is significant... And then when new industries formed around it, people can say, well, look, we can protect this and have a livelihood. Then it eliminates that natural conflict that occurs between the idea that it has to be A or B"
Biodiversity – Natural resources	"I definitely hear from people who were born and raised in Squamish that they used to just be able to stick their hand in the water and grab a salmon. And that's not the case anymore. There's a lot of impacts to the salmon run and to fish in general. You know, the sediment from the wood lots, the wood sorts have created sort of an impenetrable barrier for anything to grow as a result of these many, many layers of woodchips. The pulp mills, of course, were reportedly responsible for poisoning the water. Woodfibre as well."
Biodiversity – Recreation	"A lot of people camping up there and stuff. I know up in the Elaho Valley or the Elaho stock we just released, like sixty thousand or something, fifty thousand spring salmon, skikimelú7, into the water there because they blew up the big rock that was blocking the way for the spring to go up. So, we went and did a first salmon ceremony, first time that's been done in a long time. Just up the river from where that ceremony is happening, we're like 'oh spring will be happy here, you know, not many, not much disturbances'. But now there's like people getting stuck and partying and shooting guns off the whole time. Me and my kids are there and my kids and my wife like this crazy. Never seen it that busy there in my life." "There's that shift of temporary marine recreationalists that are there to rip around and buzz and do all their water skiing and jet skiing and stuff, because it is a great place to do it. And then as whales come back into the Sound, I mean last summer I was out in the boat and there was some orcas and they were three or four hundred meters off and I just cut the engine and sat and watched. Beautiful. And then got ripped past by a whale watching boat and he was just way too close to these whales, and just chased them up the Sound. And, you know, these whales were just chilling and they were just swimming in the water and then all of a sudden they got this big rippin thing that's chasing them."
Spiritual – Indigenous culture	"There is such a spiritual connection to the land and the language in the culture. They say once you learn about one of these things, you start to learn about the others, too, because they're so connected. You know, you learn the culture, you learn a bit of the language. When you learn the language, you learn a bit of the culture. The same goes for the land because it's so connected, it's all interconnected. And so, when our

	people talk, a lot of our directional stuff, as you know, is really connected to the water. You know, we don't have a word – our words for up and down and stuff like that are so different, they're connected to where the water is. And so, when you're getting out of a canoe, for example, we don't have a word for getting out of the canoe, but it's a word for going ashore because you're just going to shore. And our elders used that for cars too, when they'd be dropping you off in a car, in a parking lot, they say go to shore in the language, which means get out of the car, go to shore." "When you start learning the language, your view of the way the world works can start to change a little bit. And you start to see how our ancestors thought of the world around them. And so many words that connect to the water, there's so many water words that speak about how our ancestors viewed the way that the water works. And the history that's in each word and each place name that goes behind it, it's vast. It's amazing to see the kind of history that we have here that we're connected to here and as Squamish people. You know, there's words that talk about the spirit of the water because in our language, you know, the old people would say that everything around you has the spirit. And that's where our powers come from. That's where our knowledge comes from." "There's words that talk about the spirit of the water because in our language, the old people would say that everything around you has the spirit. And that's where our powers come from. That's where our knowledge comes from"
Therapeutic / health – Indigenous culture	"So, you know, [we're seeing through climate change that] the health of Howe Sound is connected to the health of the world. Sk̲wx̲wú7meshulh syatshen, the country of our people, is being affected by what everybody else in the world is doing. And, you know, this often overused thing that we're all one, it's becoming painfully clear in a way that we never imagined how much one we really are. Like Thailand and Australia and Peru are all one with Howe Sound. And all these things are part of the health of Howe Sound now, and how we imagine our life as people in our own territory is no longer possible to be separate from that." "I would like for our people to have that, you know, to have that that experience of living on the land in Howe Sound. Become part of our life cycle and reimagine it for modern age, whatever that is. Because I think, you know, that for our spiritual, mental, physical, emotional health, whatever, we need it. I think our people need it. When I see people who managed to get back on the land and the changes it brings to them. And for that to become a part of the life of all the community as much as possible would be wonderful somehow."
Learning, education, research – localized sites	"The estuary's significant for so many reasons, educational value to. I remember when I first looked at the estuary, I was like, well, this is kind of like a barren, weird place with all sorts of driftwood. I had no idea what an estuary was, I had to look up the word 20 years ago, I didn't know what brackish water was. I didn't know what I was looking at at all yet. And I still don't know enough. But I know a lot more. And I think you can't underestimate this value of this. And fortunately, there were citizens back in the 80s who understood that

	value and stopped. There was a coal port that was destined for this spot right here. Yeah. And essentially, I think that was sort of the beginning of Squamish's environmentalism, if you want to call it that, were citizens basically stood up and said, no, you can't you can't fill in the estuary and put a coal port here. You are crazy." "There's so much to be learnt about how Britannia was remediated not just from a scientific or technical point of view, but from a community process standpoint, it was really probably revolutionary in its day how and [brought] all the parties together, government, business, community together to figure out how to start this massive, very expensive remediation project that happened at Britannia" "All the kids camps are amazing. There's so many in Howe Sound. Right. And they're so educational to the youth of today. A lot of them are stuck in the classroom too much. They need to be outdoors a bit more." "If you're teaching about government, you've got the interplay of what's happening in Mannion Bay with you've kind of got federal responsibility for the ocean, the provincial responsibility for the intertidal zone and municipal responsibility for kind of just up from that… I remember being down here four years ago with kids and you've got the Provincial crown corporation B.C. Ferry coming in, there happened to be a Coast Guard vessel that happened to be docked on the public dock, and then you've kind of got the municipal running of the government and the federal government dock as well. And then you've also got a little sign here that says Islands Trust. It's kind of like this mishmash of four levels of government operating, all in kind of one tiny little space. And only when you're near the ocean do you get that. Well, I imagine that this happens in other places, but it seems like for kids, it's a very relatable and understandable. I understand it's an area of interaction of governments. And I don't know that because it's tangible, because there's like water. Sometimes water will always land like this kind of relatable for kids that they can see who's got responsibility for what? And yet there's these issues that are still interconnected despite the very clear distinction. Right. So I actually find from teaching social studies, government, [the beach is a] pretty effective area."
Learning, education, research – Culture	"The area is loaded with history. One of the things that I found is that Sewells Marina runs their sea safari boats and things, and they'll poke around here and talking to the guests afterwards that have come off of it. And these are people who have been in the area, have lived in the area all their lives, and they might be out with their visitors that are in from out of town, pre Covid world and everything else are just amazed when they get a sort of a tour of Howe Sound as to the history behind it."
Learning, education, research – Indigenous culture	"I met a lot of people that have been sailing in the Howe Sound their whole lives, they've been diving in the Howe Sound their whole lives, or they've been fishing in the Howe Sound their whole lives, but they've never heard anything about the Squamish side, where we've been Squamish, we've been living here in the Howe Sound our whole lives. And I feel like it's a one way to kind of like connect people is to have some sort of gathering or conference or something. To go out like I mean, it'd be nice if covid would go away so we could go do it at like on a in the Howe Sound somewhere to like go to a camp, like Tsítsusm, and like get everybody together. That would be sweet, and it'd be really awesome to start the conversation and network and be able to talk about how can we join together. You know, help each other fight against the people who want to destroy the land and the water. And then from a stewardship side of things, the language, the land and the culture are all connected. And you can't talk, like I said earlier, you can't learn about one without learning

	about the other. And I feel like, I don't know how yet, but there's the stewardship of the language and the names and our history that comes from the land. It could we could use this knowledge in a way that could really help empower all the other work that's been going on here. So, in the stewardship part that's what I'd want people to know."
Recreation – Conservation	"Watching the resurgence of whales, watching people wrap pilings to make it better for herring, I mean, people are deeply connected to Howe Sound, and zooming out a little bit and looking at it from a sort of a greater Metro Vancouver perspective, I feel that that Howe Sound is really the recreational area for the whole of the lower mainland. And so, if you live here, I think it comes with an aspect of the public trust that it will continue to be productive, biodiverse. I think there's going to be an increasing amount of sense of protectiveness of it, because we realise what we have here, and we want to make sure that that's always here for future generations." "And in my experience, they're more aware. And wanting to preserve the natural values. This is why they're here, because they could live anywhere really. I mean, our neighbours across the street, if you look at their driveway, they have kayaks, they have bicycle's, they enjoy that environment. And every chance they get, they're out experiencing it. And it's you know, if we didn't have this natural environment here, they would they would be somewhere else. So it's a treasure that's very important to people." "It's really cool because if you dive in Bachelor Bay, which is not a marine protected area, even though it's so close to Whytecliff Park, you can see the drastic difference that one protected area can do for wildlife." "I've gone on sea kayaking trips to Minaty Bay. That's a special place and it's a shame that it's private access only. I've only access to it by accident from the water and then stumbled into it and gone oh my gosh, like this should be a park".
Recreation	"[The geography] welcomes people on to the water and on to the Sound. It's tamer and calmer than a big ocean. It's kind of like a little like an ocean playground in a way".
Recreation – Tourism	"There's a balancing act between commercial development, economic development, forestry and recreational values. Both, I think you could argue, have a place in the Squamish basin. How the two coexist, yeah, I wouldn't want to be faced with that decision."
Recreation – Development	"Now that it's becoming so developed, those beach opportunities or river, stream, opportunities that do exist are becoming quite busy. And so there's very few natural spaces left to be in nature without being around a bunch of people. And so that's why anything north of Langdale up to Port Mellon Highway. I think is becoming a little bit more important. It's where people that want to be in nature and not be on a trendy beach with a bunch of people are starting to use."
Indigenous culture	"I've heard from other people in _____, the things that are powers for dancers are remembering things that are no longer seen by us or else they're very rare. So, they remembered we might call them prehistoric

	things, they remember the landscape and so when people go and bathe in Deeks Creek, they're getting that power from remembering those things and the supernatural help from our ancestors." "One of the elders kind of looked up the mountain up the watershed we're at and said, 'See that glacier over there on the west? And you see that glacier way up there on the North. So that's the riparian zone to be protected.' That is our holistic traditional knowledge." "K̲'ik̲'élx̲n, that's funny, it means little fence. But it's not it's not how we would say it at Squamish, I think it's how you would say it in the shíshálh language. And something that I don't think people are comfortable with or understand enough yet is what I've learned about their place names are everywhere. You know, this is bordering with our territory, the territory of our neighbors and our friends, the shíshálh. It was common to have overlapping terminology in there, so there would be names from both people. So, it wasn't like a straight line where you're Squamish here, all the names are Squamish over your only shíshálh. There's overlapping names in that way. It was a much more friendly way to have a border between people. But it was acknowledged, shared, because the people were not just Squamish. It was never the probably the truth anywhere that at some point in history, all Squamish people were only Squamish. It's not true today, it wasn't true in the past. And that's how they acknowledged it. That's the wisdom of our ancestors to have place names that were of both languages because it was people that were really of both people. And it's true today… So that was also true back then, right? And it's always been true on the borders. And that's how people manage the borders of our territory in the past. So, I wanted to acknowledge that name, too, as a way of thinking about politics and I think a wiser way of doing it.
Indigenous culture – Shipping and transportation	"The ocean was the highway for Indigenous people and then also for the early settlers. The ocean was the connector and it's only recently that we are defining everything by land connections like by road connections. And this leaves Howe Sound in the in the weird position of instead of being one kind of coherent region all connected. It's instead chopped up into all kinds of jurisdictions."
Indigenous culture – Learning	"Tsítsusm, Potlatch Creek, it'd be awesome to bring our people there again. That camp, you know, they're starting to really want to learn more about our history and stuff. But for years, like we never had any, as far as I know, the Squamish youth and stuff, had never really been a part of that. But it's like literally in the heart of our territory, like there's so many places like that in the sound that. Nex̲wlélex̲wem there's like a whole community there. I've never been there in my life, but I'd love to go there. I'd love to talk about and teach and learn about how our people used to use that area. Super awesome deer hunting back in the day, apparently. And to be able to do some of this stuff, that's kind of my dream is I'd like to see more cultural inclusivity. Yes, that's right, word, but just more opportunity for our youth and our people in general just to utilize the Howe Sound the way that we've been able to back in the day. And, you know, I think things like this, like the project you're doing, is going to help open people's eyes to like to that how much we used to use it like. So many stories about our people hunting and fishing and the supernatural beings that used to live on the islands, all that. One of my biggest dreams is to be able to go to some of these places without having to figure out, like, am I supposed to be here or like is this private land? I don't know. But it'd be nice to go and use these islands like our ancestors used to."

	"I feel like with everybody starting to learn more about their culture, their teachings, and the language, they start having more of a connection to place and that makes them, as I said, more connected. They want to do something to take care of it. So, I think it's a big part of both [the health of our environment and our culture and language]. But it's the main reason why our people and other people are starting to do stuff to make the ocean go back to what it once was." "I feel like the language is such an important piece that's missing… When you learn the language, the connection to that thing, to the water and the land and stuff, it feels like it's just gone tenfold over the years. And every time I learn more language or every year, the stronger connection I feel I have to the land that we're in." "I think there needs to be a better job done at integrating the Indigenous aspects of [this region]. You know, that history, that awareness of again how special this place is not just from a historical context, but also what this region can offer [going forward]."
Non-Indigenous culture – Natural resources – Learning	"The historical things are tied with industry like Woodfibre, Nexen… I think there's a lot of opportunities for figuring out better ways moving forward and educational opportunities to start having these conversations and going recognising that, okay, this is our history and this is what we did and this is how Howe Sound was exploited. How can we do better moving forward now that we know so much more. I mean, there's history everywhere. And there's the scars of history everywhere, like humans always have an impact". "I think Britannia is one of those really interesting components of history, actually, because on the one hand, it's sort of a negative history from the perspective of the impacts that it had environmentally. Obviously, it was a huge, important economy. But I also think an important part of that story [is] the environmental impact that was addressed eventually. We can all criticize till we're blue in the face and look at the negatives of industry, but I think there's also the positive of how eventually something was done."
Development	"I was shocked at how much residential development there is. I mean, not shocked in a bad way. I just didn't know there was that much going on in Squamish. It's such a growing community, right, home-based businesses too." "I personally hate the idea of putting these little pods of residential pods all along Howe Sound. I think you just end up creating commuter's and exclusive neighbourhoods. And I think Porteau should have never been approved as a subdivision. I think Furry Creek should not be developed any further. That's just my opinion. I think Britannia and Squamish should have the opportunity to grow. But these other areas, they really are not a good idea to just keep putting these little satellite neighbourhoods that just get further and further away from it. And it will just put tons more traffic on the highway and not concentrate our infrastructure and resources and that kind of thing."
Development – Natural resources	"What happens in Howe Sound I mean, if you think about it, is the landowners down there on the industrial side that invest capital in their plant, whatever you want to call it, physical plant, you know, it requires considerable investment to make this work and so they do it. And I think what happens or what they're fearful of happening, and well founded a lot of cases, is that there begins to be encroachment in that area by both recreational users and people that start coming to live in the area. And then people who would be seen by

	long term industrial tenants and in the area, landowners in the area, as sort of Johnny-come-lately come and say 'Hey, wait a minute, what's this you know, they're leaving the lights on at night at that big plant and they're keeping me awake'. And so I think it's fairly easy for the people in the industry with big investment to be wary, you know, they're wary about what is the agenda of this group or that group."
Development – cultural shift	"As we made that argument, that this is a great place and we need to preserve it because it's such a great recreational [spot]. And I think that was intentional is to say how do we develop a recreational economy as opposed to an industrial economy. But the downside of that is the traffic, the boats, the construction, the people buying properties and taking trees and affecting the tree cover and impacting marine values of the area. That's the part that I see as being the most problematic" "People move to Squamish because of the quote on quote, lifestyle. You get away from the city. You can live in a place where you can basically go out your door and get into that wilderness… it has a lot if you want to live an outdoor lifestyle. That's what it's sold on" "I guess the new waterfront development [in Horseshoe Bay] is not keeping with the Sound. I'm not sure what it is. It's almost there's an encroachment of high density, sort of metropolitan area sort of encroaching into the Sound is sort of the feeling I get when I see what's happening in Horseshoe Bay. So you're sort of you know, you're you know, you're losing the you're losing the natural features of the interface between sort of the water and the land."
Commercial fishing	"Fishing as an occupation is way down. And even fish guiding, which was a big business back in the day, I think that's way down to"
Commercial fishing – Conservation	"We've got a few fisheries left in Howe Sound. In my opinion, they're sustainable fisheries, they're well researched, they've got good stock assessment, they're stable, and they're very productive here in Howe Sound. And we're right next to an urban center where there's a really rare opportunity for farm to plate, but boat to plate whatever you want… We've got an awesome fishery here. So, I'm all for protecting glass sponge reef, but if we go too far, if we get to the point where we're not thinking about this from a balanced perspective, there's always another country that's willing to do it for us and they'll do it worse… I think Howe Sound represents a really cool opportunity to work with fishermen and to celebrate the natural marine resources that we have here in BC"
Commercial fishing – Shipping & Transportation	"I think there's five [commercial] boats in the harbour. Something like that. That's important for the harbour authority because it allows them to leverage federal money."
Recreational fishing - livelihoods	"Your expectations are that you can catch a salmon, even in the winter. So, this fishery up [in Howe Sound] provides a lot of the charter guys a little bit more of a year-round venture because of the winter fishery here. And that doesn't happen everywhere"
Recreational fishing – Intrinsic/existence – Biodiversity/conservation	"You know, I've spent time as a young person fishing with my dad and to be able to go out and respect nature and to show a family or young people about what they can bring out of the ocean and how the ocean, for subsistence and everything else, can be beneficial. And respect for it, I think has just an incredible value. I have no patience for the kill mentality, but in terms of access and sustainability, I think it's important that we

	have something like that. And when you look at the urban population of the Vancouver area, [Howe Sound] is an area that is highly accessible in some regard."
Shipping / transportation – Access – Recreation	"When you have a boat access only place like McNab Creek or Passage Island, you learn to respect the ocean. It's just been wonderful to be out, be able to spend a lot of time on the water. Get into and from one place to another. It's been mainly for transportation, but it's spawned to recreation, and it's been very spiritual too."
Natural resources – Biodiversity	"Anytime I've been on Howe Sound on a boat, McNabb Creek just seems like one of the most amazing, big, broad valleys. Like, it's such an amazing entity, and to think they want to actually have a gravel pit there just breaks my heart. It just seems like the worst place in the world. It's just such a unique valley. It's so broad and wide and from just a geological point of view, it's so impressive, I just always loved it".
	"The access to the tide water, that's really important, to be able to transport logs and load logs, both into and out of the water… Anywhere that logs are or were put into the water now and in the past is important economically, and the access to these areas needs to be maintained. Forestry access doesn't have to mean destroying the area, just making sure that the barges and equipment can be brought to carry the logs away."
	"This whole area is probably the commercial or the industrial heart of Howe Sound now. It's where the pulp mill is, where all the log sorts are. It's where a number of other industries and booming grounds are. I'm guessing their practises are more environmentally sound than they used to be. I know, for example, the pulp mill is much more environmentally sound than it was 25 years ago, but if any area remains economically important, it would be that area."
Natural resources – localized	"Since the Thornbrough area is industrialized. OK, that's great. So maybe then you shouldn't be considering housing developments on the east side of Gambier Islands that's going to stare at it"
Tourism – Biodiversity, conservation	"The only way that we're going to preserve these areas is to get people out looking and using these areas. We can sit back and discuss all the beauty of it and everything else. But unless people support the idea and can get behind what the goals are, it's just not I can't see it happening. So, I can really support, to some degree, the economics of the eco and nature-based tourism, I think it's so necessary for the layman to be able to see the passion or understand the passion of why people are interested in preserving these areas. I do have a bit of a challenge when it comes to making an eco-based tourism sort of operation and sort of clouding it with the financial priority that a lot of them have, and what I mean by that is, you know, we get a lot of whale watching boats up in this area. We do have some resident killer whales that come through occasionally. Most of them are transients. But people are definitely, in the eco-tourism world, are more interested in getting a wild experience, a YouTubeable experience for their guests, more so than respecting what we're what we've got to offer. So, you know, I would like to see that aspect of it tightened up a bit."
	"Tourism is the economic driver now. I mean, I can remember years ago there was no kayak rental company, now there's several. The Howe Sound is an amazing spot, you know, just a few minutes out of Vancouver, you're here in this pristine environment. There's going to be a lot, lot of pressure on the Sound in the future with that activity from people wanting to experience the water area"

Tourism – Culture	“I mean, the entire area. As you know, has you know, it has had so many so much potential for recreation and cultural values that I mean, this is well known and well documented. I would just, you know, add my voice to that. I think the main as far as economic opportunities, I think from my perspective, it’s more cultural and recreational values that those are the and how they’re related to the preservation of nature that has really, really strong value economically. And it’s a total shift from the thinking of 50 years ago or one hundred years ago.”

Table C.5. Statistics from Kruskall-Wallis tests of univariate relationships between age, sector, and gender across individual values.

Value category	Value	Demographic trait	chi.squared	*df*	*p*-value	sig
Ecology	Biodiversity	Age	12.8503	4	0.012	*
		Sector	8.1512	10	0.6141	
		Gender	15.1947	2	5.00E-04	**
	Aesthetic	Age	6.5737	4	0.1602	
		Sector	8.9018	10	0.5414	
		Gender	12.2689	2	0.0022	*
	Conservation	Age	11.362	4	0.0228	*
		Sector	24.454	10	0.0065	*
		Gender	18.9234	2	1.00E-04	***
	Intrinsic	Age	6.51	4	0.1642	
		Sector	13.9841	10	0.1737	
		Gender	17.9728	2	1.00E-04	**
Social	Therapeutic	Age	11.4834	4	0.0216	*
		Sector	7.9528	10	0.6334	
		Gender	12.4665	2	0.002	*
	Learning, education, research	Age	18.4638	4	0.001	*
		Sector	25.7837	10	0.004	*
		Gender	12.1289	2	0.0023	*
	Recreation	Age	0.7136	4	0.9496	
		Sector	13.9648	10	0.1746	
		Gender	3.2446	2	0.1974	
	Spiritual	Age	5.1286	4	0.2744	
		Sector	10.6476	10	0.3856	
		Gender	6.7313	2	0.0345	*
	Relationships	Age	9.8866	4	0.0424	*
		Sector	14.9955	10	0.1322	
		Gender	3.823	2	0.1479	
Cultural	Indigenous	Age	22.3944	4	2.00E-04	**
		Sector	32.8835	10	3.00E-04	**
		Gender	19.8441	2	0	***
	Non-Indigenous	Age	4.5242	4	0.3397	
		Sector	4.0198	10	0.9465	
		Gender	1.8794	2	0.3907	
Economic	Livelihoods	Age	6.5699	4	0.1604	
		Sector	25.3407	10	0.0047	*
		Gender	2.5117	2	0.2848	

Tourism	Age	3.7568	4	0.4399	
	Sector	30.2404	10	8.00E-04	**
	Gender	0.9451	2	0.6234	
Shipping and transportation	Age	13.4331	4	0.0093	*
	Sector	7.4703	10	0.6804	
	Gender	5.6351	2	0.0598	
Recreational fishing	Age	2.7084	4	0.6077	
	Sector	17.7574	10	0.0592	
	Gender	8.1363	2	0.0171	*
Commercial fishing	Age	1.2554	4	0.8689	
	Sector	12.2583	10	0.2681	
	Gender	1.971	2	0.3733	
Natural resources	Age	6.97	4	0.1375	
	Sector	21.2319	10	0.0195	*
	Gender	2.6139	2	0.2706	
Development	Age	13.8865	4	0.0077	*
	Sector	10.3492	10	0.4104	
	Gender	8.999	2	0.0111	*