Fisheries New Zealand
Tini a Tangaroa

Climate vulnerability and risk assessments in marine ecosystems, with a special focus on fisheries in Aotearoa (New Zealand)

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PLAIN LANGUAGE SUMMARY

- This report examines the approaches to evaluating the impact of climate change on fish and marine ecosystems, particularly in New Zealand.
- Climate change is already altering where fish live and the productivity of our oceans, and it could intensify.
- We reviewed 75 studies from around the world to understand how scientists assess the risks that climate change poses to fisheries.
- We reviewed various methods for assessing climate risk, including expert opinion, trait-based methods, computer models, and combinations of these approaches.
- Five case studies show how these tools can be used to understand which fish species and fishing communities are most at risk.
- The best approaches consider not only the biology of fish but also factors such as fishing infrastructure and community resilience.
- These assessments enable managers and governments to determine how to protect the ocean and plan for its future.
- Doing this work now will help make our fisheries more sustainable and better prepared for a changing climate.

EXECUTIVE SUMMARY

Boyce, D.G.; Tittensor, D.P.; Schleit, K.E.; Fuller, S. (2025). Climate vulnerability and risk assessments in marine ecosystems, with a special focus on fisheries in Aotearoa (New Zealand).

New Zealand Aquatic Environment and Biodiversity Report No. 367. **49 p.**

This report provides a comprehensive review of climate vulnerability and risk assessments (CVAs) in marine ecosystems, with a particular emphasis on fisheries and their relevance to Aotearoa (New Zealand). Climate change is exerting profound and increasingly significant effects on marine ecosystems worldwide, impacting the distribution, productivity, and recovery potential of marine species and fisheries. These impacts pose serious risks to food security, livelihoods, and the sustainability of marine resources. Despite this, climate change considerations are not yet routinely incorporated into fisheries management strategies globally or in New Zealand.

This report provides an overview of the history and development of CVAs in marine systems and synthesizes 75 CVA studies, assessing their methods, data, and outcomes. It summarises the spatiotemporal distribution of climate vulnerability studies and categorises their methodologies into expert assessments, trait-based approaches, correlative methods (e.g.*,* species distribution models), and combined frameworks. While each method has strengths and limitations, combined approaches are increasingly common, offering more robust and spatially explicit assessments. Most CVAs have focused on the Northern Hemisphere; few have been applied to the Southern Hemisphere, and only two have been specifically applied to New Zealand, highlighting a significant geographic gap. The two New Zealand-focused CVAs are expert assessments of climate vulnerability, primarily using species traits for a subset of harvested species.

Five international case studies illustrate the diversity of CVA frameworks. These include expert assessments, trait-based fuzzy logic models, integrated ecological-socioeconomic assessments, fleet and community risk evaluations, and the flexible Climate Risk Index for Biodiversity. These examples highlight the diversity of CVA approaches, the importance of considering objectives when developing CVAs, and the necessity of integrating biological, environmental, socioeconomic, and governance information for comprehensive climate risk assessment.

Considering these 75 studies collectively, this report outlines the steps in CVA development and describes best practices for CVA development, including the use of spatially explicit and standardized outputs, integration of ecological and socioeconomic dimensions, transparency and reproducibility, and co-production with indigenous and local knowledge holders. It emphasizes the importance of matching the CVA framework to specific management goals and available data.

For New Zealand, CVAs present a critical opportunity to identify climate-vulnerable species, regions, and fisheries, prioritize research and monitoring, and inform climate-adaptive fisheries management. Frameworks such as CRIB or trait-based assessments could be adapted using New Zealand-specific data. Implementing national-scale CVAs could enhance the resilience and sustainability of Aotearoa's marine ecosystems in a changing climate by supporting empirically based proactive management.

1 Introduction

Climate change is a pervasive driver of change in marine ecosystems (Scheffers et al. 2016), affecting species through a complex web of pathways with critical consequences for ecosystem services (Free et al. 2019) and human well-being (Boyce et al. 2020). In particular, climate change has significantly affected, and is projected to continue affecting, the distribution, yield, and productivity of marine fisheries (Bryndum-Buchholz et al. 2018; Free et al. 2019; Lotze et al. 2019; Boyce et al. 2020; Tittensor et al. 2021) as well as delaying the timelines of recovery for collapsed or depleted populations (Britten et al. 2017; Cheung et al. 2022). Fisheries contribute significantly to the employment and income of marine economies (Ganter et al. 2021) and are disproportionately crucial to the cultures, economies, food production, and prosperity of many coastal regions worldwide. Therefore, ongoing climate impacts on marine fisheries critically threaten their sustainability and the well-being of individuals, communities, and nations that depend on them (Free et al. 2019; Lotze et al. 2021).

Despite its overarching impacts, climate change is not yet routinely considered in the conservation and management of marine living resources, including fisheries (Bryndum-Buchholz et al. 2021; e.g. Boyce et al. 2021; O'Regan et al. 2021; Mason et al. 2023). The limited incorporation of climate change considerations into fisheries management strategies could compromise their efficacy, leading to poor management outcomes, possible conflicts over fishing resources (Østhagen et al. 2020), the loss of livelihoods, and outmigration (Hutchings & Rangeley 2011). Delaying the implementation of climate-adaptive fisheries management actions could impair the long-term sustainability of vulnerable species and result in missed opportunities (Brown et al. 2012). There is an increased urgency to understand how fisheries are impacted by both long-term secular climate changes and shorter-term climate variability to support climate-adaptive management (Pinsky & Mantua 2014; Gattuso et al. 2015; Busch et al. 2016) and adaptation strategies (Melvin et al. 2016) to support productive and sustainable fisheries.

While there is broad agreement that climate change must be considered when managing marine fisheries, a consensus approach has not been established. However, at a fundamental level, understanding climate change and its impacts on marine life species, ecosystems, and fisheries living resources is a crucial prerequisite for developing effective management and adaptation strategies. Climate Vulnerability Assessments (CVAs) and Climate Risk Assessments (CRAs), hereafter both referred to as CVAs, are crucial for identifying species, regions, and communities that are most vulnerable to climate change and have been promoted as a vital component of marine management under climate change, particularly in protected areas (Tittensor et al. 2019; Bryndum-Buchholz et al. 2022) and fisheries management (Hobday & Pecl 2014; Busch et al. 2016; Hare et al. 2016; FAO 2018; Greenan et al. 2019; Boyce et al. 2023, 2024).

The IPCC was among the first to formally define climate vulnerability as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes(IPCC 2001, 2007)." It defined vulnerability as the intersection of climate sensitivity, exposure, and adaptive capacity. Later, the IPCC modified its focus from vulnerability to risk, where risk is defined as "potential for adverse consequences for human or ecological systems resulting from climate-related hazards, exposure, and vulnerability," where vulnerability is the intersection of sensitivity and adaptive capacity(IPCC 2014, 2022). Among other things, it was thought that shifting towards risk could help prioritize trade-offs, making it more operationally useful to policymakers. Scientific uptake of the various IPCC definitions of vulnerability and risk has been mixed.

A review by Estoque et al. (2023) found that among about 460 vulnerability studies published between 2017 and 2020, about half employed vulnerability concepts outside of the IPCC definition, 43% used the older definition of vulnerability, and only 3% explicitly adopted the newer risk-based definitions. The original components of vulnerability—sensitivity, exposure, and adaptivity—align well with core concepts of ecological stability such as resistance, resilience, and reactivity(May 1973;

Holling 1973; Britten et al. 2014), which may explain why ecological studies seem to prefer the original definition. To date, over 800 peer-reviewed studies have evaluated the climate vulnerability or risk of species, ecosystems, or fisheries, encapsulating a broad spectrum of approaches, methods, data, and outputs, each possessing its own advantages and disadvantages (Pacifici et al. 2015; de los Ríos et al. 2018; Foden et al. 2019; Li et al. 2023).

This review is part of an Fisheries New Zealand project (ZBD2024-04) to develop a climate vulnerability assessment tool to guide the management of New Zealand's fisheries. The work builds on the information summarised in ZBD2014-09 (Cummings et al. 2021) and provides a next step to work currently underway in project ZBD2022-02A (The impacts of marine heatwaves on fisheries in New Zealand) as well as prior work investigating the impacts of climate change on fished populations (ZBD2018-03). The specific objectives of the project include:

1. To review available international approaches to climate change vulnerability assessments for fisheries and identify existing frameworks that could be adapted for use in New Zealand.
2. To develop a climate vulnerability assessment for New Zealand's fisheries that can be applied to any fishery or region, and a user guide.
3. To apply the vulnerability assessment to a priority fishery or region.

This review focuses on the first objective and synthesizes the methods, data, approaches, and findings from 75 global and regional CVA studies, focusing on marine systems and fisheries (Appendix Supplementary Information Table S1). It highlights the strengths and limitations of various approaches, identifies best practices, and outlines a pathway for their application to New Zealand's marine fisheries. Consideration is given to studies that integrate ecological and socioeconomic indicators, including a case study by Payne et al. (2021) on European fisheries and a proposed framework by Boyce et al. (2023) from Atlantic Canada. Recommendations are provided for implementing a national climate risk framework for fisheries in New Zealand.

2 Climate vulnerability assessments: an overview

Climate change vulnerability and risk assessments emerged as a field of research in the 1990s in response to the impacts of climate change, including changes in the frequency of natural hazards, disaster planning, and the endangerment of species. Early research was predominantly focused on the vulnerability and risk of terrestrial systems, and primarily humans, human infrastructure and economies. For instance, in its first report in 1990, the Intergovernmental Panel on Climate Change (IPCC) briefly discussed the potential impacts of climate change on terrestrial biodiversity and speculated on the most vulnerable ecosystems (IPCC 1990). From this humble beginning, the field has expanded, and CVAs are now widely viewed as a critical component of quantifying climate change impacts and climate-smart management of species, ecosystems, and fisheries (Busch et al. 2016; Hare et al. 2016; FAO 2018; Boyce et al. 2024).

Fundamentally, CVAs seek to understand the susceptibility of people, species, ecosystems, fisheries, infrastructure, nations, economies, or other entities to climate change (IPCC 2021). However, they can also provide more detailed and nuanced information about how, why, and when vulnerability manifests, which is crucial for managing risk and developing effective adaptation strategies. They can also identify vital gaps in data and information that require addressing to better understand climate change impacts.

Well over 800 CVA studies of species have been published using a tremendously broad range of approaches, data and methods (Pacifici et al. 2015; de los Ríos et al. 2018; Foden et al. 2019). Yet, despite the tremendous variability in how these studies evaluate vulnerability or risk, there is broad agreement on how vulnerability is defined. Following the definition set out in the IPCC Fourth Assessment Report (IPCC 2007) and subsequently adopted (Foden et al. 2013, 2019; Pacifici et al. 2015; Comte & Olden 2017; de los Ríos et al. 2018; Albouy et al. 2020), species' climate vulnerability is defined by their sensitivity, exposure, and adaptivity (adaptive capacity) to climate change. *Exposure* refers to the degree (e.g., extent and magnitude) of climate change that a species, ecosystem, or fishery experiences, such as changes in temperature, dissolved oxygen, or ocean pH. *Sensitivity* refers to the inherent characteristics of a species, ecosystem, or fishery that dictate their response to hazardous climate exposure, including, for instance, life history traits and habitat specificity. *Adaptivity* refers to a species' potential to adjust or adapt to adverse exposure to climate change, encompassing, for instance, genetic diversity or behavioural plasticity. These dimensions have close analogies in other disciplines, including community ecology and dynamic complex systems theory (Scheffer & Carpenter 2003; Scheffer et al. 2009, 2012). For example, sensitivity is analogous to the ecological concept of resistance, exposure to reactivity, and adaptivity to resilience (May 1973; Holling 1973; Britten et al. 2014).

The fifth IPCC report subsequently updated its measure of concern from vulnerability to risk, with risk being defined by the intersection of exposure, vulnerability, and hazard, and vulnerability instead being defined by sensitivity and adaptive capacity (IPCC 2014). Yet despite this updating, the ecological community has continued to favour the definition of vulnerability outlined in the original report (i.e. sensitivity, adaptive capacity, and exposure); (Foden et al. 2019), possibly because hazard is less easily defined in an ecological setting. This evolving IPCC definition has led to somewhat differing interpretations of what the most appropriate measure of concern for climate impact research is (e.g., vulnerability or risk) and how, precisely, vulnerability should be quantified.

3 Assessing vulnerability: rationale, data and approaches

This review focused on peer-reviewed studies and gray literature that assessed the vulnerability or risk of marine species or fisheries in a quantitative or semi-quantitative manner, or that reviewed such studies. Such climate vulnerability and/or risk studies were identified by searching the Web of Science, SCOPUS, and Google Scholar for key search terms including: (“fish” or “fisheries” or “species”) and (“marine” or “ocean” or “sea”). From the initial list of returned publications, those that met the criteria for inclusion were retained. The references from this initial list of publications were searched to identify any additional relevant studies. Peer-reviewed as well as gray literature reports were also included. Our inclusion criteria meant that studies that focused on specific climate impact pathways, for instance, marine heatwaves (e.g. Cook et al. 2025), or that evaluated climate vulnerability at scales that didn’t explicitly involve species or fisheries (e.g. Ministry for the Environment 2020) were excluded.

We identified 75 studies that evaluated climate vulnerability and/or risk for marine species, communities, or fisheries. Because fisheries are coupled socio-ecological systems, these studies were diverse, with some focussing primarily on the vulnerability of the fisheries living resources (e.g., species, stocks, and populations), others on the vulnerability of social and economic fisheries components (e.g., national markets, communities, and fleets), and others on fisheries decision-making structures (e.g., management systems and quota allocation systems). Due to this complexity, and the challenge of integrating the breadth of ecological, socioeconomic and management information, only one study addressed all three aspects (Boyce et al. 2023).

After removing global studies (12) and reviews, syntheses, perspectives, and frameworks that did not produce vulnerability outputs (9), most (83%) of the remaining 53 studies were conducted in the Northern Hemisphere (Figure 1). Most studies were conducted in the North Atlantic Ocean, particularly in the northwest Atlantic, along the US eastern seaboard, and in Atlantic Canada. No studies were identified in Australia and New Zealand, only three in the Indian Ocean, and only four studies were conducted in waters around Central and South America. Vulnerability studies were conducted at a range of spatial scales, including 12 global studies, 13 at the basin scale (1000–10 000 km), 17 at the ecoregion scale (100–1000 km), 18 at the subregion scale (10–100 km), and three at the local scale (<10 km).

Most studies focused on fisheries living resources evaluated vulnerability at the species level, with few evaluating how vulnerability varies across species ranges in a spatially-explicit manner (Boyce et al. 2022, 2024). In contrast, studies of fisheries socioeconomic vulnerability tended to evaluate it at the community or port level, allowing for vulnerability to be explored spatially. Studies focused on decision-making structures focused largely at the stock scale.

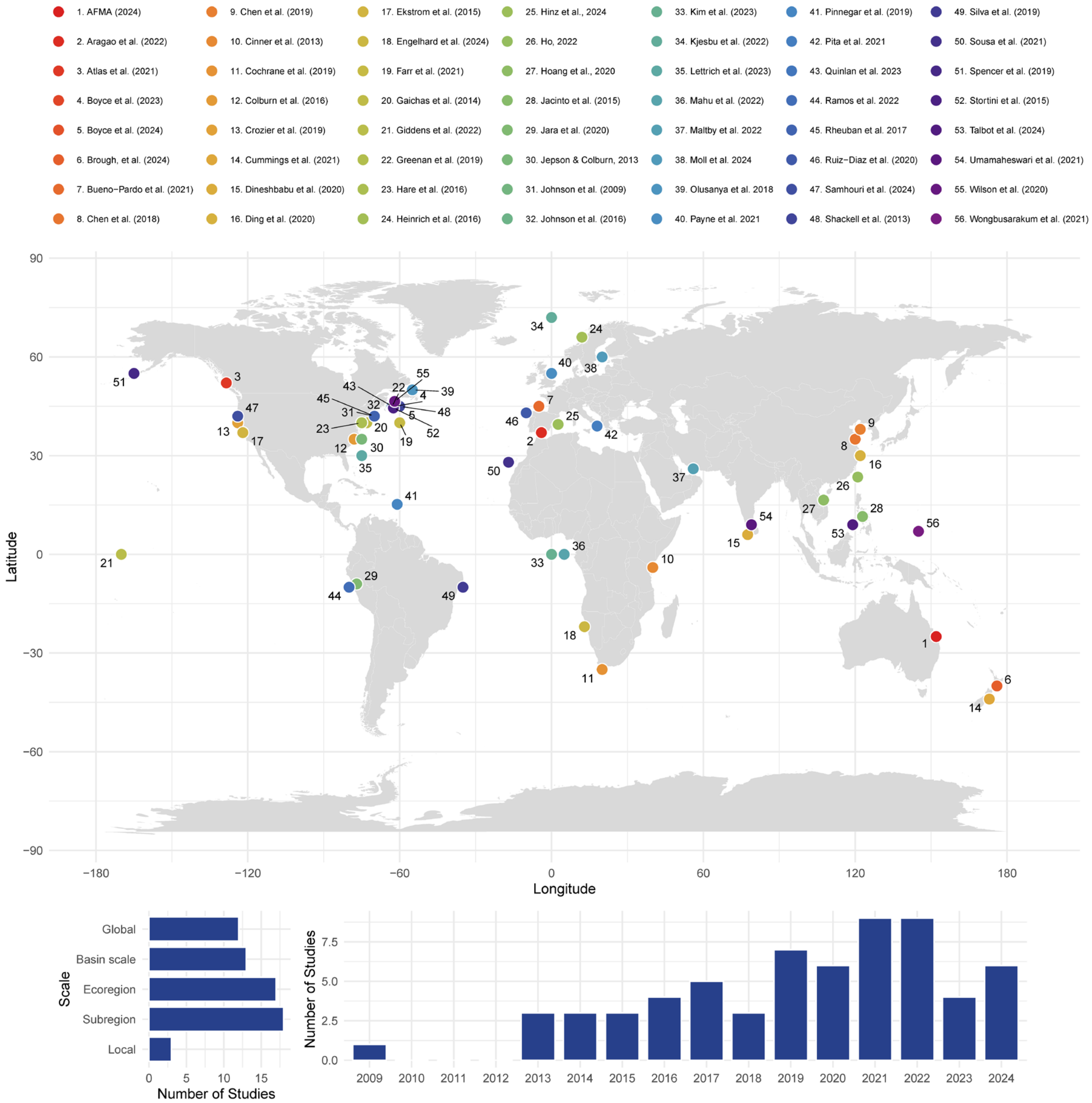

Figure 1: | Spatial and temporal distribution of the reviewed climate vulnerability studies.

The CVA frameworks that assemble and synthesize the information used to calculate, quantify and define climate vulnerability or risk are varied. Yet, when considered together, these varied frameworks can broadly be grouped into the following methods (e.g. Foden et al. 2019); (Figure 2):

a) **Expert assessment:** One of the earliest approaches, expert assessment examines the range of probable climate impact pathways on species, ecosystems, or fisheries, with the goal of categorizing, prioritizing, and/or ranking them according to their impacts, typically in a non-statistical manner. Through this approach, experts or panels of experts can score species on their perceived vulnerability or risk to climate hazards (e.g., warming, acidification). Expert assessment can be based on, for instance, experience, personal knowledge of the climate impact literature, visual comparison of species distributions in relation to projected climate changes, or assessments of species traits. Vulnerabilities are often categorized on semi-quantitative ordinal scales (e.g.*,* low, moderate, high) and/or numeric scales (e.g.*,* 1 to 5). For instance, Hare et al. (2016) conducted a **climate vulnerability assessment** for 82 fish and invertebrate species on the Northeast U.S. Continental Shelf using an **expert assessment framework**. Three of the reviewed CVA studies (4%) used expert assessment as a sole means of evaluating vulnerability (Figure *2*).

- *Advantages*: Can often incorporate a greater level of bespoke detail (e.g.*,* life stage analysis) and capture a granular level of information that is challenging to incorporate into fully data-driven frameworks; flexible to design and implement; can be applicable in data-limited situations; captures specialist knowledge.

- *Disadvantages*: Qualitative or semi-quantitative; subject to biases in expert assessment; not inherently spatialized; difficult and time-consuming to reproduce consistently, especially for a large number of species and/or areas.

b) **Trait-based**: Trait-based approaches rely on the associations between specific biological traits and climate change impacts; they utilize species-specific biological and ecological traits to assess sensitivity and adaptive capacity (Murray & Conner 2009; Chessman 2013; Pearson et al. 2014; Jones & Cheung 2018). Traits may be qualitative, categorical or quantitative. For example, life history traits such as fecundity, population doubling time, reproductive rates, or maximum lifespan are often used as proxies for species adaptivity or resilience to climate impacts (Hare et al. 2016; Jones & Cheung 2018). Six of the reviewed studies (9%) used trait-based methods to assess vulnerability. However, trait-based methods are often combined with expert assessment to determine how traits translate to vulnerability. For instance, when using quantitative traits, such as body size, thresholds must be defined to categorize species by vulnerability. Trait-based CVAs require ecological knowledge but little statistical expertise and enable rapid vulnerability assessments for many species. For instance, Spencer et al. (2019) applied a trait-based assessment to fish and invertebrate stocks in the eastern Bering Sea, incorporating climate projections and biological traits to evaluate vulnerability.

- *Advantages*: Traits are increasingly available through public databases for use in data-limited situations; relatively rapid assessments for many species; requires little statistical or modeling expertise.

- *Disadvantages*: Traits may be challenging to find for some species; high uncertainty about the relationship between traits and climate impacts; quantifying thresholds for high/low vulnerability is often arbitrary; approaches for combining trait scores are challenging and often produce categorical outputs; may oversimplify complex ecological interactions; not inherently spatialized.

c) **Correlative**: Correlative methods analyse historical or present-day data to identify statistical relationships between climate variables and species abundance or presence. Correlative methods in CVA can be diverse, but species distribution models (SDMs) are perhaps the most common correlative approach. Using georeferenced species occurrences and co-occurring environmental data, SDMs apply statistical models to represent the realized niche of a species in response to climate variation to infer how species distribution and/or abundance will be impacted by climate change. Such SDMs are often used to project changes in suitable habitat or occurrence with climate change, and are widely used to evaluate species vulnerability to climate change (e.g. Shackell et al. 2014; Stortini et al. 2015; Kaschner et al. 2019). Because occurrence data are publicly available for many species, SDMs are relatively rapid and cost-effective to develop for a large number of taxa and are widely used in vulnerability assessment. Nine of the studies (13%) used correlative methods as the primary CVA assessment method.

- *Advantages*: Can reveal existing climate-biology relationships; rapid and cost-effective for many species; inherently spatialized; forward-looking.

- *Disadvantages*: Increased uncertainty when projecting beyond the conditions within the range of observed data; assumes that species distributions are in equilibrium with prevailing climate; does not consider non-environmental effects on species distributions (e.g., fishing); infeasible for species with few occurrence records; choice of model technique can lead to uncertainty (but this can be mitigated through ensemble modeling).

d) **Combined Approaches:** Incorporate the strengths of individual methods (a-c) and can thus draw on the advantages of different approaches while mitigating some of the disadvantages. Almost three-quarters of the reviewed studies (74%) blended two of the three approaches described above, with most (54%) combining expert assessment with trait-based methods.

- *Advantages*: Draw on the strengths of individual approaches to increase information while mitigating uncertainty; often a more complete synthesis of climate impacts; by combining approaches, can often be spatially explicit.
- *Disadvantages*: Can be data-intensive, requiring greater computational resources.

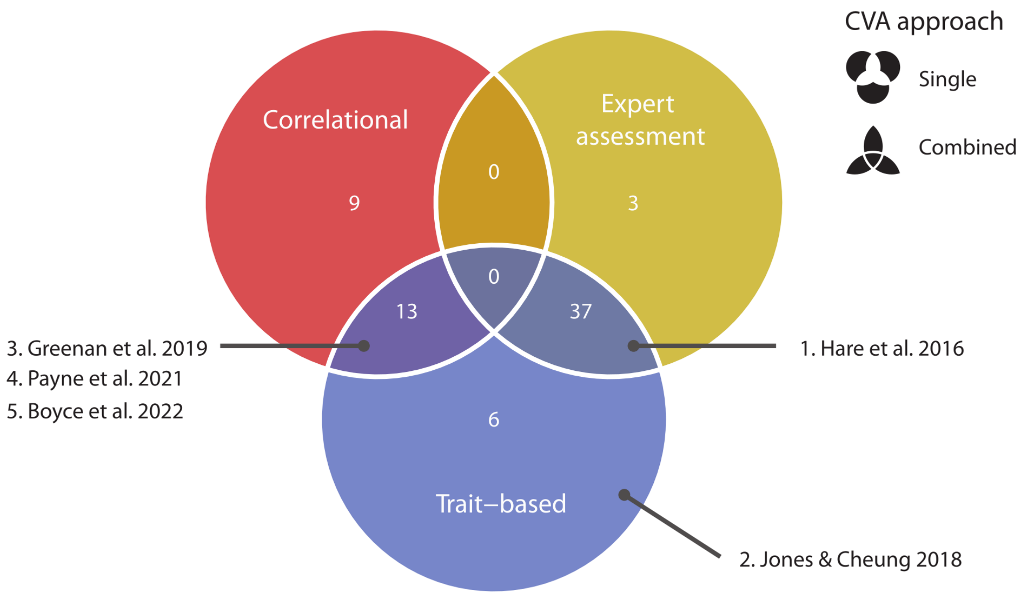

Figure 2 | General CVA frameworks. Red, blue and yellow depict the categories of CVA assessment of species or fisheries to climate; purple, orange, green and black depict combined methods. The case studies presented in this report are annotated.

The above CVA frameworks are most common, yet there are other approaches to evaluating climate vulnerability that don't readily fit within the IPCC-established CVA or CRA frameworks and definitions (IPCC 2007, 2014). Such approaches evaluate climate vulnerabilities, but may neglect to evaluate them in a structured manner (e.g., evaluating sensitivity, adaptive capacity, and exposure), or provide outputs that facilitate vulnerability rankings across species, ecosystems, or fisheries. While such approaches don't fit within the established CVA or CRA frameworks, they nonetheless can capture vital climate impacts on species, ecosystems, and/or fisheries. For instance, **mechanistic** models simulate biological processes and interactions within ecosystems to predict responses to climate change. By explicitly representing the underlying processes that drive how species and populations behave, mechanistic models use scientific understanding of cause-and-effect relationships to recreate how systems should work internally and theoretically. Examples include mechanistic niche and demographic models. For instance, the Apex Predators ECOSystem Model (APECOSM) is a size-structured, spatially explicit ecosystem model developed by the Institut de Recherche pour le Developpement (IRD) designed to simulate the biomass, distribution, and size-spectrum of marine communities under varying climate and fishing pressures (Maury 2010). APECOSM is forced by physical-biogeochemical Earth System Models (e.g., temperature, oxygen, currents, and primary production) to evaluate the impacts of changing marine climate on marine species and communities. Such mechanistic models require detailed data and are more easily applied in data-rich systems, but can be difficult to calibrate, computationally expensive, can require extensive validation to build confidence in projections, and are often taxonomically constrained or indeed not species-based but functional group- or size-based, so are less frequently used to evaluate or rank species by their climate vulnerability. Likewise, while **laboratory experiments** enable the evaluation of detailed cause-and-effect climate impacts on marine species or communities, they are less suited to CVA methodologies, which often assess climate impacts on multiple species simultaneously.

Within the primary CVA approaches considered here (e.g., expert assessment, trait-based, correlative, and combined), methods vary in terms of the data they use, how quantitative they are, their spatial consideration and resolution, how past- or forward-looking they are, their flexibility and reproducibility, and how their outputs are communicated – all features that can make them less or more useful depending on their intended audience and use.

Data sources for these different CVA assessment types are diverse but can broadly be grouped as climatic, biological, and socioeconomic. Observational climate data can be obtained from observational or remote sampling platforms, while projections can be produced by global climate (GCM) or Earth System Model (ESM) models and downscaled regional models, providing spatially resolved past or future spatial data and/or time series of environmental variables. Biological data can include environmental niche or life history traits, population dynamics, or species distributions, often obtained from fisheries surveys, ecological studies, databases such as FishGLOB (Maureaud et al. 2024) or OBIS (OBIS 2025), the scientific literature, or estimated, using for instance, imputation. Socioeconomic data can include a broad suite of social and economic information on fishing communities, economic dependencies, and management frameworks.

The methods employed in CVAs range from qualitative or semi-quantitative expert assessment systems where users categorize vulnerability into subjective categories of ‘low’ to ‘high’ to fully quantitative, data-driven approaches that integrate and synthesize empirical data to produce numeric outputs. Each offers advantages and disadvantages. Fully data-driven approaches can be rapidly implemented for many species across large areas, can often be synoptic and spatialized, are often more transparent, flexible, and easily reproducible, and are less subject to observer biases – a particularly important feature for consistency when reproducing or updating them. However, semi-quantitative (e.g., expert assessment) approaches can often incorporate a greater level of bespoke detail (e.g., life stage analysis) and capture a level of information that is challenging to incorporate into fully data-driven frameworks, while being flexible to design and implement.

Many CVAs derive a single vulnerability score for each species and do not explicitly consider geographic variation in climate vulnerability across their distributions. This approach makes summarizing climate vulnerability across a large number of species straightforward and could be more suitable for certain applications, such as ranking or triaging species from high to low vulnerability. However, other approaches are spatially explicit, decomposing climate vulnerability and/or its components across the geographic distribution of species to evaluate it and provide different vulnerability or risk values at various locations. Spatialized approaches convey far more information but can be more challenging to communicate in a more straightforward manner, yet they are far more relevant to supporting conservation and management objectives such as species conservation, fisheries management, or marine spatial planning at the local to regional scales at which such processes are implemented.

Many approaches calculate vulnerability or risk using historical or present-day information. However, some are forward-looking, using climate models to explore how projected climate hazards could contribute to vulnerability. Such approaches can evaluate how climate vulnerability or risk varies under alternative future pathways or time horizons, or provide information on the timelines until the onset of harmful climate risk (e.g. Trisos et al. 2020). Under such approaches, decisions are sometimes required regarding the appropriate future time horizon over which vulnerability or risk is to be considered.

Lastly, some approaches are inherently more scalable and reproducible. That is, they are conducted in such a way that it is feasible to re-calculate them in the future or in a different location rapidly, so that vulnerability could, for instance, be tracked over time, or the vulnerability of species in one location could be compared on the same scale as those in another. For instance, expert assessment approaches are challenging to reproduce, as the experts who score vulnerability may change over time, leading to biases in scoring. Other CVA approaches may have limited reproducibility due to the availability of data and computer code used in the analysis.

4 Climate vulnerability in fisheries

To illustrate the diversity of climate vulnerability and risk assessment approaches within the reviewed documents and their varied use in fisheries contexts, we examine five key studies as case studies.

4.1 Case Study 1: Trait-Based CVA for the U.S. Northeast

Methodology: Hare et al. (2016) is an example of an *expert assessment approach*, whereby experts scored 82 fish and invertebrate species from the Northeast U.S. continental shelf for their climate vulnerability according to pre-defined traits (Figure 3), using a semi-quantitative scoring method. The methodology combines two of the three core CVA dimensions: exposure and sensitivity. The authors define climate vulnerability as the extent to which abundance or productivity in the northeast US could be impacted by climate change and decadal variability.

Exposure was assessed using projections from an ensemble of global climate models for 2006–2055 (under RCP 8.5), focusing on 12 climate-related variables including sea surface temperature, salinity, ph, precipitation, air temperature, sea level rise, and ocean currents.

Sensitivity was captured using 12 biological attributes, including adult mobility, early life stage dispersal, reproductive strategy, prey and habitat specificity, population growth rate, and stock status. These traits were selected to reflect the species' ability to resist environmental changes. Experts scored each trait on an ordinal scale from low to very high sensitivity.

Each species received a climate exposure score and a sensitivity score, which were then combined using a logic model (e.g., pre-defined rules for scoring) to yield an overall semi-quantitative climate vulnerability score (low, moderate, high, or very high). Additionally, the study assessed each species' potential for distributional change (based on traits such as mobility and dispersal capacity) and the directional effect of climate change (positive, neutral, or negative), including a bootstrapped analysis to estimate uncertainty.

The experts used a 5-level scoring system per attribute, allowing them to express uncertainty in their evaluations. The results showed that approximately half of the assessed species were highly or very highly vulnerable, particularly diadromous fish and benthic invertebrates. A subset of species was identified as likely to shift distribution or benefit from warming conditions across the study area.

The analysis also included leave-one-out sensitivity testing, a review of functional group patterns, and species-level narratives containing rationale and logic behind the vulnerability scores, providing a rich dataset for management use. The methodology strikes a balance between scientific rigor and practicality, offering a structured yet flexible approach to screening many species in data-limited contexts.

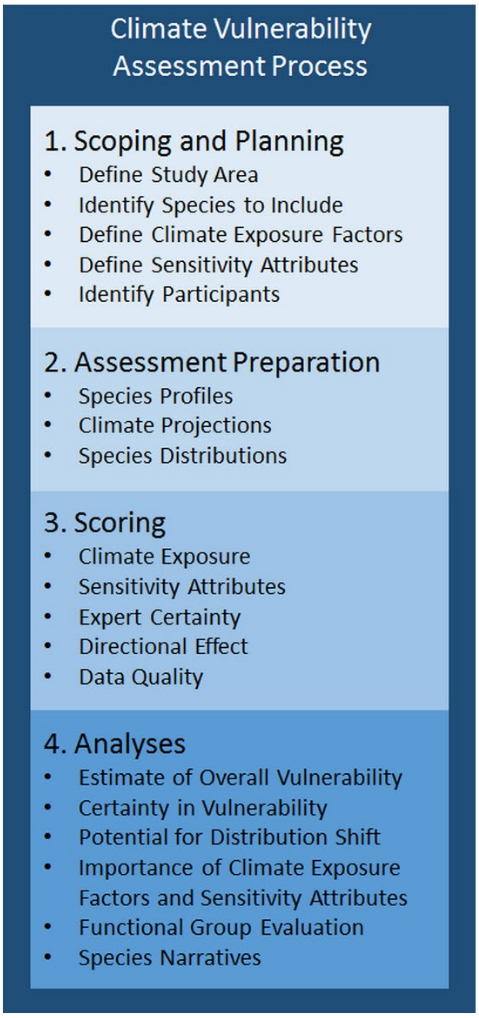

Figure 3*:* | Steps used in Hare et al. (2016) CVA.

Strengths:

- Comprehensive: assessed multiple stressors, and traits
- Flexible: involves expert knowledge and stakeholder input; useful in data-limited scenarios or where detailed climate impact information is required.
- Could potentially incorporate indigenous local knowledge.
- Transparent
- Could potentially be used to evaluate different life cycles

Limitations:

- Semi-quantitative: reliance on expert opinion could introduce bias, especially where data or information is limited
- Labour-intensive: requires significant input from expert scorers; may limit repeated application, especially for a large number of species/stocks
- Not spatialised: limited spatial information; does not distinguish among local populations or stocks
- Species-level: does not evaluate community or ecosystem vulnerability
- Does not include other factors important to fisheries, such as infrastructure, economic, or social factors

Implications for New Zealand: Hare et al.'s approach is relevant and feasible for New Zealand, especially for an initial national-scale screening of fisheries vulnerability and could be enhanced by integrating indigenous local knowledge. Trait-based assessments are useful for New Zealand's diverse and data-variable fisheries (e.g., deep-sea species, invertebrates). Like the United States, New Zealand has a limited capacity for mechanistic modelling across all stocks, so this approach provides a manageable way to prioritize. Existing trait databases (e.g., FishBase, NIWA species info, Aquatic Environment and Biodiversity Reports, Fisheries Assessment Reports) could be used to populate sensitivity attributes.

However, applying Hare et al.'s approach in New Zealand would also require adaptation to adjust exposure factors (e.g., accounting for local upwelling systems and acidification hotspots), integrating Māori fisheries and ecosystem knowledge into expert panels, and possibly adapting for stock-level assessment, especially for species with multiple QMS stocks.

Key Takeaways: The Hare et al. (2016) study presents a robust, structured, and scalable method to assess the climate vulnerability of marine species using expert-elicited trait and exposure data. It is a valuable tool for resource-limited contexts and can inform proactive adaptation and management strategies. This framework offers New Zealand a practical pathway to identify climate-sensitive species or stocks, guide research priorities, and support national climate-resilient fisheries planning.

4.2 Case Study 2: Using fuzzy logic to assess marine species vulnerability to climate change

Methodology: Jones & Cheung (2018) developed a *trait-based*, fuzzy logic framework to assess the climate vulnerability of 1074 marine species globally, including many from the North Atlantic. It allows for a flexible, probabilistic approach to scoring vulnerability rather than strict binary classifications.

The method assesses species across three key dimensions: exposure, sensitivity, and adaptive capacity. However, this framework integrates the latter two (sensitivity and adaptive capacity) into a single biological vulnerability score. Climate exposure is based on the magnitude of projected sea surface temperature (SST) change within each species' distribution range (from AquaMaps models) under the high-emissions RCP 8.5 scenario.

Sensitivity and adaptive capacity for each species are estimated using biological and ecological traits, including range size, dispersal potential, habitat specificity, depth range, and reproductive characteristics. Each trait is scored using fuzzy membership functions that assign degrees of vulnerability on a scale from 0 to 1, with rule-based logic to combine these into an overall vulnerability score.

Species with narrow ranges, low fecundity, specialized habitat needs, or limited dispersal ability received higher sensitivity scores. The final output is a continuous vulnerability index for each species, enabling ranking and comparative analysis across taxa and regions. The fuzzy logic system accommodates uncertainty and variability in trait data, making it suitable for data-limited contexts.

Strengths:

- Fuzzy logic system allows for nuanced scoring and quantification of uncertainty.
- Scalable across many species and areas.
- Explicitly evaluates data gaps.
- Rapid to implement for many species.

Limitations:

- Based on ocean temperature, and does not include all climate stressors (e.g., acidification, dissolved oxygen).
- Data gaps in trait data lead to approximations or reliance on related species, especially for under-studied taxa.
- Not explicitly spatialised.
- Does not include other factors important to fisheries, such as infrastructure, economic, or social factors

Implications for New Zealand: This method is relevant for application in New Zealand. New Zealand has a diverse array of endemic species, many of which have specialized habitat requirements, making trait-based assessments particularly valuable. The method's flexibility makes it ideal for screening across multiple species or stocks, including those with limited data. Adaptation would be required to integrate New Zealand-specific oceanographic forecasts, regional climate projections (e.g., from NIWA), and Māori knowledge systems, particularly when evaluating adaptive capacity and cultural significance.

Key Takeaways: The Jones & Cheung (2018) framework offers a transparent and globally scalable method for estimating the relative climate vulnerability of marine species, utilizing trait-based and fuzzy logic techniques. While not a replacement for process-based models or detailed stock assessments, it is a powerful tool for identifying species at risk, especially in data-limited contexts or when rapid screening is needed.

4.3 Case Study 3: Socioeconomic Vulnerability in Lobster Fisheries

Methodology: Greenan et al. (2019) developed a combined trait-based and correlative CVA for American lobster (*Homarus americanus*) fishing communities in Atlantic Canada by integrating environmental, biological, infrastructural, and socioeconomic data at the scale of fishery management units (Lobster Fishing Areas, LFAs). The approach used biophysical modelling, infrastructure analysis, and socioeconomic indicators. They constructed two primary indices: the Coastal Infrastructure Vulnerability Index (CIVI) and the Lobster Vulnerability Index (LVI).
The CIVI evaluated the vulnerability of small craft harbour fishing infrastructure, and was calculated from factors related to climate exposure, fishing infrastructure, and socioeconomic factors. Exposure incorporated sea level rise, wave and wind climate, sea ice decline, and coastal material erodibility. These were scored on a semi-quantitative 1–5 scale using modelled or observational data. Infrastructure assessed harbour condition, protection, and replacement costs using engineering evaluations and expert judgment. The Socioeconomic Sub-Index (SESI) captured vulnerability in terms of population size, percent of income from fishing, landings per vessel, and species value diversity, with data drawn from tax records and fisheries databases.

The Lobster Vulnerability Index (LVI) included both exposure and stock status. Exposure was defined as the percent change in suitable habitat for lobster based on projected bottom temperature changes derived from two regional ocean models (BNAM and CM2.6). Stock status for each LFA was assessed using four variables: projected potentially suitable habitat, habitat occupancy, recent abundance (based on landings), and early life-stage food availability.

Potentially suitable habitat was modelled using Generalized Additive Models (GAMs) with predictor variables such as bottom temperature, depth, location, season, and year. Suitability was quantified for both current and future climate scenarios, and then averaged over 100 bootstrapped iterations to enhance robustness and quantify uncertainty. Change in suitability per LFA was then used to estimate exposure. Habitat occupancy was calculated as the ratio of realized to potential suitable habitat. Recent abundance was proxied by mean landings from 2013–2016 relative to historical maxima. Early-stage life food availability trends were estimated using copepod abundance and trends from DFO's Atlantic Zone Monitoring Program.

Final vulnerability scores for each LFA were assigned using a semi-quantitative 5×5 scoring matrix, which combined exposure and stock status into a value ranging from 1 (low) to 5 (high). These were then compared and integrated with the CIVI results to assess overall regional vulnerability, identifying hotspots where climate risks intersected with biological and socioeconomic sensitivity.

Strengths:

- Multidimensional: integrates environmental, ecological, infrastructural, and socioeconomic dimensions.
- Fine-grained: community or port-specific information incorporated.
- Multiple stressors and impact pathways considered.

Limitations:

- Requires high-quality, spatially resolved socioeconomic data, which can be challenging to acquire (e.g., sometimes not publicly available), particularly for a larger number of species or stocks. For instance, the study excluded inshore lobster habitats due to data limitations.
- A semi-quantitative vulnerability scoring system may not be applicable beyond Atlantic Canada (no global standardization).
- Primarily based on ocean temperature with limited consideration of other climate stressors (e.g., acidification, dissolved oxygen).
- Semi-spatialized: estimates vulnerability at the fisheries management scale.

Implications for New Zealand: Relevant for assessing small scale fisheries or isolated communities where infrastructure and livelihood options are limited. New Zealand has access to high-resolution ocean projections (e.g., NIWA), catch and effort data, and some social vulnerability indicators (e.g., Statistics New Zealand). With some development, a Climate Vulnerability Index by QMA or Iwi fisheries management area could be constructed, incorporating both ecological and social dimensions.

Key Takeaways: A comprehensive framework for assessing climate vulnerability in fisheries by combining ecological models with infrastructure and socioeconomic indicators. Identifies mismatches between biological resilience and social vulnerability. For example, communities highly dependent on lobster but with weak adaptive capacity are most at risk.

4.4 Case Study 4: Climate risk for European fisheries

Methodology: Payne et al. (2021) present a large-scale, *combined trait-based correlative* CVA for the European fisheries sector. Their framework quantifies climate risk across both coastal regions and fishing fleets by incorporating three key climate risk components: hazard, exposure, and vulnerability (e.g., sensitivity and adaptive capacity); (Figure 4). The foundation of the analysis is a "population-specific" hazard index for 556 fish and shellfish populations in 23 FAO subareas based on species traits and the concept of Thermal Safety Margin (TSM). In this study, population is defined as a single species occupying a single FAO subarea.

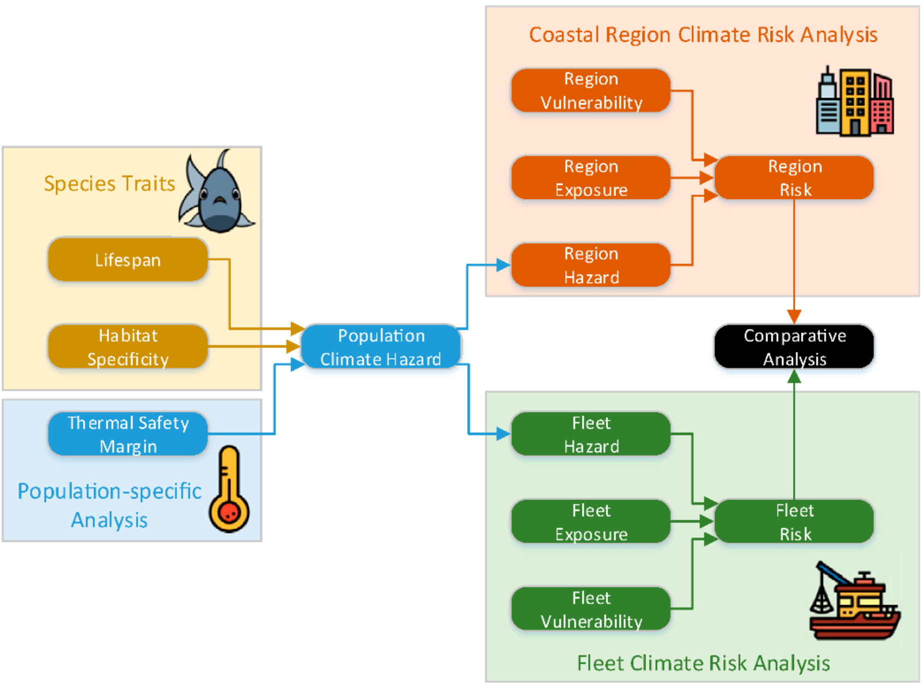

Figure 4 | Climate risk for European fisheries. Diagram illustrating the approach used by Payne et al. (2021) to estimate climate risk in European fishery-dependent coastal regions and fishing fleets. Species traits and population-specific analyses are combined to give population-specific climate hazard, which forms the basis for the region- and fleet-level CVAs. Lastly, the region and fleet risks are combined into a comparative analysis.

TSM was calculated as the difference between the current environmental temperature and the species' upper thermal tolerance (from AquaMaps 90th percentile values), providing a physiological context to climate change impacts. Species lifespan and habitat specificity were also incorporated to account for ecological sensitivity. These components were combined into a hazard index weighted at 50% (TSM), 25% (lifespan), and 25% (habitat specificity).

Hazard scores for the coastal region CVA were aggregated based on the economic value composition of species landed in each region. Exposure was measured by the diversity and dominance of fisheries landings using the Shannon diversity and Simpson dominance indices. Vulnerability was quantified using regional GDP per capita as a proxy for adaptive capacity.

In the fleet CVA, hazard was calculated based on the economic value composition of landings for each of the 380 fleet segments (defined by country, vessel size, gear type, and fishing area). Exposure was again measured using diversity metrics of species landed, while vulnerability was proxied by net profit margin (NPM) — fleets with higher profitability were considered less vulnerable.

The final climate risk score for both coastal regions and fleets was calculated as the average of percentile-ranked hazard, exposure, and vulnerability scores. The authors conducted a comparative analysis between regions and fleets within countries to identify where risk was most concentrated, and they visualized these patterns geographically and by sector.

This framework identifies spatial and sectoral climate risk hotspots, allowing for tailored adaptation strategies. The study discusses adaptation actions, including diversification, governance improvements, and sustainable fisheries management.

Strengths:

- Population, region, and fleet specific resolution allows fine-scale differentiation of climate risk among areas and populations.
- A unified hazard layer enables direct comparison of risks across fleets and coastal regions.
- The use of economic indicators (GDP per capita, net profit margin) enhances socioeconomic relevance.
- Scalable and reproducible: based on publicly available data and open-source tools.
- Risk-based.

Limitations:

- Requires high-quality, spatially resolved data, which can be challenging to acquire, particularly for a larger number of species or stocks.
- Primarily based on ocean temperature: does not include multiple climate stressors (e.g., acidification, dissolved oxygen).
- No life stage analysis.
- Uses proxy variables (e.g., GDP, NPM) that may not fully capture social vulnerability or resilience.
- Less applicable to data-poor or artisanal fisheries without profit or landings data.
- Semi-spatialized: estimates vulnerability at the fleet, population, or regional scale (although the definition of population boundaries is unclear).

Key Takeaways: The Payne et al. (2021) framework provides a robust and comparative method for assessing climate risk across fleets and coastal communities, combining ecological and socioeconomic dimensions. By focusing on population-level hazards and using consistent metrics of exposure and vulnerability, the method identifies risk hotspots and provides actionable insights for adaptation planning. Its strength lies in its transparency, scalability, and integration of physiological ecology with economic realities.

Implications for New Zealand: This method is relevant and feasible for application in New Zealand, particularly given the country's diverse marine species, strong fisheries data infrastructure, and need for climate-resilient planning. New Zealand species distributions and temperature tolerances can be integrated via trait databases and national habitat models. Fisheries catch and economic data are collected and could potentially populate the fleet exposure and vulnerability metrics. Implementation would require collaboration among ESNZ, MPI, and academic partners to refine TSMs for New Zealand species and tailor socioeconomic indicators. As with Europe, such a CVA would be valuable for prioritizing adaptation resources and informing spatial management strategies under climate change.

4.5 Case Study 5: The Climate Risk Index for Biodiversity (CRIB)

Methodology: The Climate Risk Index for Biodiversity (CRIB); (Boyce et al. 2022, 2023, 2024) exemplifies a *combined* trait-based correlative CVA approach. It integrates spatially explicit species distribution estimates and independent climate projections with species traits, external stressors and other risk factors to represent climate impact pathways on marine species. Using publicly available data layers and a statistical framework, it calculates 12 climate indices that are used to estimate three climate dimensions (exposure, sensitivity, and adaptive capacity), which are used to calculate climate vulnerability and risk (Figure 5); (Boyce et al. 2022). The CRIB considers how species traits dynamically interact with historical, present-day, and future climate conditions at individual locations where those species exist to better understand their climate risk. It evaluates climate vulnerability and risk and its statistical uncertainty at the species and ecosystem levels in a spatially explicit manner (different values for vulnerability and risk in different parts of a species' range) under different projected ocean futures. As a flexible and scalable approach, it can be used to estimate climate vulnerability and risk at various spatial resolutions and scales, utilizing user-configured input data sources. Due to this flexibility, it can be used to comparatively and consistently evaluate vulnerability and risk in different geographic locations (e.g., from global to local), for different species assemblages or stocks, over different periods, under different emission scenarios and spatial resolutions, and using different input data sources. Because the CRIB is quantitative and standardized, climate vulnerability or risk estimates for Atlantic cod (*Gadus morhua*) in Atlantic Canada can be directly compared to, for instance, grey mullet (*Mugil cephalus*) in New Zealand. Illustrating its flexibility and broad application, the CRIB has been used to assess climate vulnerability and risk of 24 000 species globally (Boyce et al. 2022); about 2000 species and 131 fish stocks at a higher spatial resolution across the Northwest Atlantic (Boyce et al. 2024); and climate risk representivity across ecosystems in the Canadian marine protected area network (Keen et al. 2024).

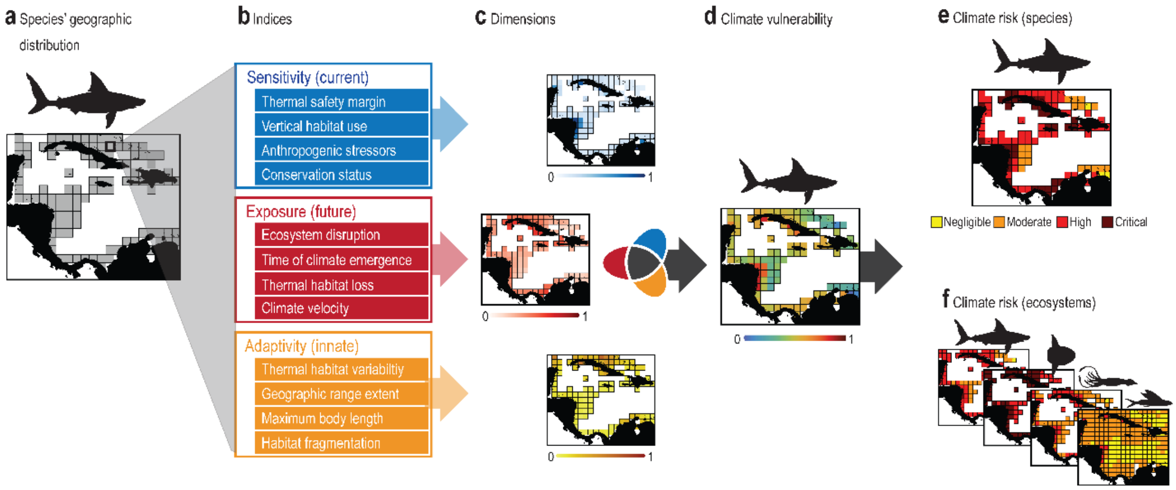

Figure 5 | CRIB framework for species and ecosystems. Within each grid cell across the native geographic distribution of a species (a), 12 standardized climate indices are calculated (b) and used to define the three dimensions of climate vulnerability (c): present-day sensitivity (blue), projected future exposure (red), and innate adaptivity (yellow). The dimensions are used to calculate the species' climate vulnerability (d), and the relative vulnerability scores are translated into absolute climate risk categories (e). f) Species maps are superimposed to assess the climate vulnerability and risk for marine ecosystems. Figure taken from Boyce et al. (Boyce et al. 2022).

Strengths:

- Rapid and data driven.
- Flexible and reproducible.
- Fully spatialized: can estimate vulnerability/risk at multiple spatial scales.
- Estimates vulnerability and risk.
- Incorporates past, present, and projected future climate conditions (multiple emissions scenarios).
- Vulnerability and risk outputs for species, ecosystems, and fisheries.

Limitations:

- Requires high-quality, spatially resolved environmental data.
- Primarily based on ocean temperature and does not include all climate stressors (e.g., acidification, dissolved oxygen).
- No life stage analysis.
- Does not include other factors important to fisheries, such as infrastructure, economic, or social factors.

Implications for New Zealand: The CRIB approach is relevant and applicable to New Zealand's fisheries. The CRIB framework combines species present-day distributions from species distribution modelling, trait-based assessments, and climate exposure analysis to offer a powerful, integrated method for evaluating climate risk at both the species and ecosystem levels. This is particularly important for New Zealand, where fisheries are a critical economic sector, and there is growing national interest in implementing ecosystem-based management and identifying climate-resilient strategies for sustainable use of marine resources.
The CRIB's ability to identify areas where climate risks are concentrated across multiple species or stocks makes it a valuable tool for climate-considered marine spatial planning and prioritizing stocks for additional research and management. The CRIB is methodologically well-suited to New Zealand's existing data and institutional capacity. Its emphasis on spatial prioritization, vulnerability mapping, and the integration of future climate scenarios would enhance New Zealand's marine managers' ability to anticipate ecological shifts and make informed decisions for the long-term sustainability of marine resources.

Key Takeaway: CRIB is a flexible, quantitative, and spatially-explicit CVA that is rapid and cost-effective to implement. It excels at identifying risk hotspots and informing regional adaptation planning. For New Zealand, a CRIB-style assessment using New Zealand-specific environmental models and fisheries catch data could identify priority species and/or areas for management. Modification would be required to consider social and economic factors or additional climate stressors.

5 Vulnerability work in New Zealand

Cook et al. (2024) provide a trait-based climate CVA of Aotearoa New Zealand's benthic marine taxa, carried out to inform conservation planning. The methods adapt an existing terrestrial CVA framework to marine environments, using expert elicitation to define relevant traits across three dimensions: sensitivity, exposure, and adaptive capacity. Assessments considered 33 traits, covering ecological, physiological, and distributional factors, alongside projected environmental changes under two climate scenarios (SSP2-4.5 and SSP3-7.0) for mid-century and end-century. Experts evaluated 83 functional and taxonomic groups, including bryozoans, corals, crustaceans, echinoderms, macroalgae, molluscs, and sponges, with some assessments at the species level for commercially or culturally important taxa. Outputs were categorical vulnerability scores, with groups rated as "Highly Vulnerable" if all three dimensions scored high; results were presented under both optimistic (unknowns treated as low risk) and pessimistic (unknowns treated as high risk) approaches. Although not spatialized, the framework incorporated spatial projections of temperature, pH, aragonite, calcite, and marine heatwaves across the New Zealand EEZ. The analysis is semi-quantitative, relying on structured scoring and expert judgment rather than numerical models. Strengths include broad taxonomic coverage, transparent criteria, and the ability to flag knowledge gaps that can guide future research. Limitations include reliance on expert knowledge when empirical data are lacking, the subjectivity of trait scoring, and the limited capacity to capture dynamic ecological or fishery-specific processes. From a fisheries perspective, the study represents a valuable first step in identifying vulnerable species and prioritizing management actions; however, future efforts would benefit from more quantitative, spatially explicit, and fishery-focused assessments.

Cummings et al. (2021) provide an expert assessment of the risks and opportunities posed by climate-related changes in New Zealand's waters to the seafood sector. Its methods combine a synthesis of observed and projected ocean changes—warming, acidification, stratification, and circulation shifts—with species-specific expert reviews. Vulnerability was assessed by examining the sensitivity and exposure of 32 commercial species or species groups, including shellfish (pāua), inshore fish (snapper), and deepwater species (hoki), as well as others of ecological and economic significance. Output included both species-level profiles and sector-wide guidance on adaptation and management strategies. It is semi-spatial, drawing on ocean models and distributional projections, but not producing fine-scale maps, and it is semi-quantitative, blending empirical data with expert opinion. Strengths include the breadth of environmental drivers considered, integration of fisheries biology with climate science, and engagement of stakeholders in adaptation planning. Limitations stem from data limitations for many species, uncertainty in downscaled projections, and the reliance on expert judgment. From a fisheries perspective, the study provides a foundation for adaptive management, but highlights the need for more quantitative and spatially resolved analyses to fully inform decision-making.

The National Climate Change Risk Assessment (NCCRA) for New Zealand (Ministry for the Environment 2020) establishes a values-based framework for evaluating climate risks across five domains: natural, human, economic, governance, and built environment. Its methods follow a three-stage process: a first-pass risk screen to identify the most significant hazards, a detailed assessment of exposure, vulnerability, and consequences for priority risks, and a final stage that assigns urgency ratings for adaptation actions. Climate vulnerability is assessed by examining the interaction between hazards, exposure, and sensitivity/adaptive capacity, supported by literature reviews, expert elicitation, and stakeholder engagement. While the study does not focus solely on fisheries, it considers marine systems within the natural environment and economy domains, including risks to aquaculture and wild capture fisheries. Outputs include qualitative risk statements, magnitude of consequence ratings across present, mid-century, and end-century timeframes, and urgency profiles that indicate where immediate adaptation is needed. The assessment is national in scale, with sub-national zones considered, including New Zealand's Territorial Sea and EEZ, but results are aggregated and not spatially explicit. It is not a fully quantitative analysis, relying primarily on structured expert judgment and qualitative scoring, though supported by modelled climate projections. Strengths include its holistic, cross-sectoral approach, incorporation of cultural values, and transparent methodology. Limitations include the limited quantitative precision, aggregation that may obscure local or species-level risks, and the absence of detailed species or fisheries-specific modelling. Overall, it is a strategic tool for setting national adaptation priorities; however, fisheries managers would need more targeted, spatially resolved, and quantitative assessments to guide operational decisions.

The Australian Fisheries Management Authority (AFMA) Climate Risk Framework (AFMA 2024) is designed as a transitional tool to help integrate climate change considerations into the management of Australia's Commonwealth fisheries. Its methods are structured around a four-step process: first, assessing species risk by combining climate vulnerability (from modelling, sensitivity traits, or projections) with stock status; second, reviewing whether current science, management, or industry measures already provide precautionary adaptation; third, adjusting the risk profile based on those measures; and fourth, providing tailored advice to decision makers. The framework evaluates all Commonwealth-managed species; however, data-rich species may be assessed using models and projections, while data-poor species rely more heavily on trait-based sensitivity ratings. The outputs are risk rankings (ranging from extreme negative to extreme positive), along with recommendations for management adjustments such as quota changes, closures, or new monitoring. It is not a fully quantitative system; rather, it blends semi-quantitative scoring with qualitative expert judgment, making it applicable across diverse fisheries contexts. While it is not inherently spatial, it can incorporate spatial considerations through closures or range-shift indicators. Its strengths include flexibility, precautionary orientation, and the ability to operate even where data are limited, thereby offering managers a practical way to bridge science and policy under uncertainty. Limitations include limited quantitative precision, potential subjectivity in risk rankings, and reliance on existing measures rather than fundamentally new management approaches. It is a pragmatic, adaptive approach, but one that will need to evolve into more quantitative and spatially explicit tools as data and models improve.

6 CVA strengths, limitations, and best practices

The reviewed studies and the selected case studies consistently emphasize that integrating CVAs into fisheries management can support and strengthen conservation and sustainability under climate change in several ways, including:

- **Prioritizing resources**: Identifying species, ecosystems and areas at the highest risk allows managers to allocate resources effectively. For example, NOAA Fisheries has conducted CVAs to guide research and management priorities in the northeast United States (Busch et al. 2016; Hare et al. 2016; Morrison et al. 2016).

- **Informing adaptive strategies**: Understanding vulnerability informs the development of adaptive management strategies, such as adjusting catch limits, modifying fishing seasons, adjusting spatial fishing zones and closures, mitigating abatable stressors, and/or protecting critical habitats.

- **Enhancing resilience**: Assessments can identify factors contributing to resilience, guiding efforts to bolster these attributes within fisheries and associated communities.

However, while the field of CVA has grown considerably over the past few decades and their methods are consistently evolving, this review also highlights that it remains limited in some key aspects. For instance, resolving the impacts of climate change on predator-prey dynamics (e.g., trophic relationships) is notoriously challenging, and very few CVAs attempt to incorporate them into their frameworks, which could affect the veracity of the assessed vulnerability. Second, most CVAs use temperature as the primary climate stressor and metric of climate change, yet additional stressors may alter responses, including changes in dissolved oxygen and pH, mixing and nutrient flux, sea ice, and modified biotic interactions. While temperature is the most well-studied climate impact stressor, and temperature observations and projections are widely available, failing to consider other climate stressors may limit the accuracy of CVA outputs. Third, almost all of the reviewed CVAs focus on the vulnerability at the adult life stage, with limited or no consideration of the spawning, larval, or juvenile life stages. This contrasts with most fisheries assessment methods, which explicitly consider different life stages when assessing stock productivity and could affect the reliability of CVA outputs. The lack of climate vulnerability information for early life stages is a known limitation of CVAs and stems from a lack of reliable climate impact information at the juvenile and larval stages for many species(Dahlke et al. 2020). Furthermore, most of the CVAs reviewed assess vulnerability for fisheries living resources (e.g., species, populations, stocks), socioeconomic components (e.g., communities, fisheries economies), or decision-making structures (e.g., management and quota-setting procedures), but do not consider these components in conjunction with one another. Treating these three fisheries components separately simplifies the assessment and communication of vulnerability but neglects the coupled socio-ecological nature of fisheries. Lastly, the majority of CVAs in this review estimate vulnerability, rather than risk. While vulnerability can be a useful measure of concern for many purposes (e.g., ranking fisheries vulnerability), for other applications, such as communicating the absolute level of threat, risk can be a more effective measure. Notwithstanding these limitations, CVA methodologies have undergone significant improvements over the past few decades, and methods have become increasingly robust. Considering the reviewed

CVA studies, we provide a set of overarching best practices for developing their application for fisheries (Figure 6):

1. **Spatially explicit frameworks**: Fisheries are inherently spatial, and adopting spatialized approaches to CVA facilitates their uptake into fisheries decision-making processes more readily. Approaches like CRIB or trait-sensitivity maps (Jones & Cheung 2018; Boyce et al. 2022, 2024), or other spatialized CVA approaches (e.g. Foden et al. 2013; Albouy et al. 2020) could help adjust quota allocation, determine if seasonal or spatial fisheries closures are needed, prioritize species, stocks, and areas for priority monitoring, identify abatable climate hazards, and explore climate-informed zoning under climate change.

2. **Taxonomically and geographically standardized outputs:** Species or fisheries vulnerability assessments are predominantly conducted locally or regionally (Pacifici et al. 2015; Payne et al. 2021; Boyce et al. 2024), with their outputs reported on relative scales (e.g., 'high' or 'low'), often making it difficult to interpret them meaningfully, in absolute (e.g., global) terms. This can sometimes limit their communication, inter-comparison, meaning, and use. CVAs that can evaluate vulnerability on standardized absolute scales facilitate the comparison of vulnerability for species and locations outside the study area, helping to understand the magnitude of climate risk and the urgency of implementing risk reduction actions.

3. **Flexible and adaptable:** The utility of any CVA will depend on its goals and objectives, which may differ across situations and intended users and uses. For instance, a spatially-inexplicit assessment that ranks species' or stocks' vulnerability may be suitable when seeking to prioritize species or stocks for climate adaptation resources (e.g., strategic funding for increased monitoring and/or ship time), while a more detailed, spatially-explicit assessment could help to more effectively determine targeted adaptive strategies (e.g., setting quotas or determining closures). CVA frameworks should be flexible and adaptable to accommodate different users and situations, and incorporate new or additional climate impact information as it becomes available. This can be facilitated by, for instance, representing climate impact pathways that operate consistently across exploited species with varying taxonomies and life histories (e.g., generalized impact pathways), and by evaluating vulnerability fully and comprehensively to support different users or management actions (see item #6, below).

4. **Quantitative, transparent and reproducible:** Objective, data-driven, reproducible methods are a hallmark of good science. Embracing these principles, for instance, by using quantitative, validated, and publicly available information sources, facilitates the transparency, reproducibility, and rigour of CVAs, as well as the quantification of uncertainty and reliability of the outcomes. Likewise, increased transparency and reproducibility can help encourage ongoing use and development of CVAs.

5. **Forward- and backward-looking:** Considering the past dynamics to which a stock or species has been exposed can provide valuable insights into its potential climate adaptability, resilience, or plasticity, critical components of its vulnerability. On the other hand, the capacity to consider future climate conditions and their impacts on fisheries can support more proactive fisheries decision-making. Temporally explicit approaches can also help pinpoint when and possibly where species or fisheries are likely to be impacted by climate hazards, allowing managers to plan in advance and implement conservation measures proactively.

6. **Comprehensive and detailed information:** Climate impacts on species are complex and multifaceted, with many pathways linking climate hazards to their effects on species; thus, a species' vulnerability can't be adequately defined by a single index or dimension. Despite this, de los Ríos et al. (de los Ríos et al. 2018) reported that only 11% of vulnerability assessments included all three dimensions, and those that did often contained only a single index to define each dimension. Assessing all components of vulnerability and providing

detailed information on how vulnerability arises can help support more effective evidence-based decision-making regarding climate change. CVAs that can provide both high-level summaries or rankings of vulnerability, as well as more detailed information about how, why, where, and how vulnerability arises, can better support the operationalization of CVAs for a larger number of users or fisheries conservation settings.

7. **Consider Ecological and Socioeconomic Dimensions**: Fisheries are inherently social-ecological systems, and evaluating their vulnerability fully requires consideration of species vulnerability alongside fleet, community, and governance capacity (Clay & Colburn 2020; Payne et al. 2021). While such approaches can be challenging due to the difficulty in acquiring the necessary economic or social data at the requisite resolutions, doing so allows for vital human components to be considered when assessing climate vulnerability.

8. **Foster Knowledge Co-Production**: Fisheries assessment and management is a complex process often involving competing objectives and perspectives. Engaging rightsholders, stakeholders, fishers, managers, indigenous and local knowledge-holders, and scientists from the outset could help facilitate the relevance, credibility, and uptake of CVA results (e.g. Li et al. 2023).

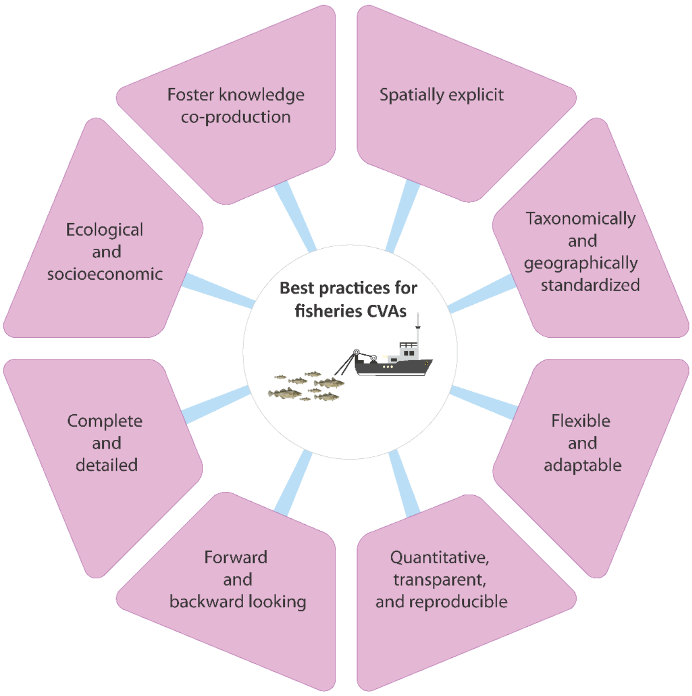

Figure 6 | Best practices for CVA development in fisheries.

7 CVA development

Developing a CVA involves carefully considering the advantages and limitations of different approaches, balanced against the desired outcomes of the CVA and practical constraints. As a final step, we present a progression of steps that practitioners could follow to guide the development of a CVA for fisheries (Figure 7).

A first step in the process of CVA development for fisheries involves considering the CVA **objectives**: why the CVA is required, how it will be used in fisheries management, and who the end users will be. The objectives could focus on high-level strategic goals such as ranking and prioritizing stocks for climate adaptation resources; such resources could include, for instance, additional research, funding, ship-based monitoring, or other actions that support climate resilience across the fishery. Alternatively, the objectives could be more focused on shorter-term tactical goals, such as providing contextual climate impact information that can be used to adjust catch quotas to consider the climate's effects on stock productivity. Identifying the end users, whether they be policymakers, managers, scientists, or fishery rights or stakeholders, will inform the level of complexity needed for the CVA and means of communicating its outputs.

Once the overarching objectives are determined, the next step in CVA development involves discussing the features that are important and would help meet the previously identified objectives. This could essentially be a “wish list” or what the ideal CVA would include. This could include, for instance, a CVA that produces spatially explicit outputs, considers socioeconomic as well as ecological information, or incorporates knowledge co-production from additional fishery rights- and/or stakeholder groups. If monitoring vulnerability over time is important, developing a CVA that is reproducible, rapid to implement, and standardized could be an essential feature.

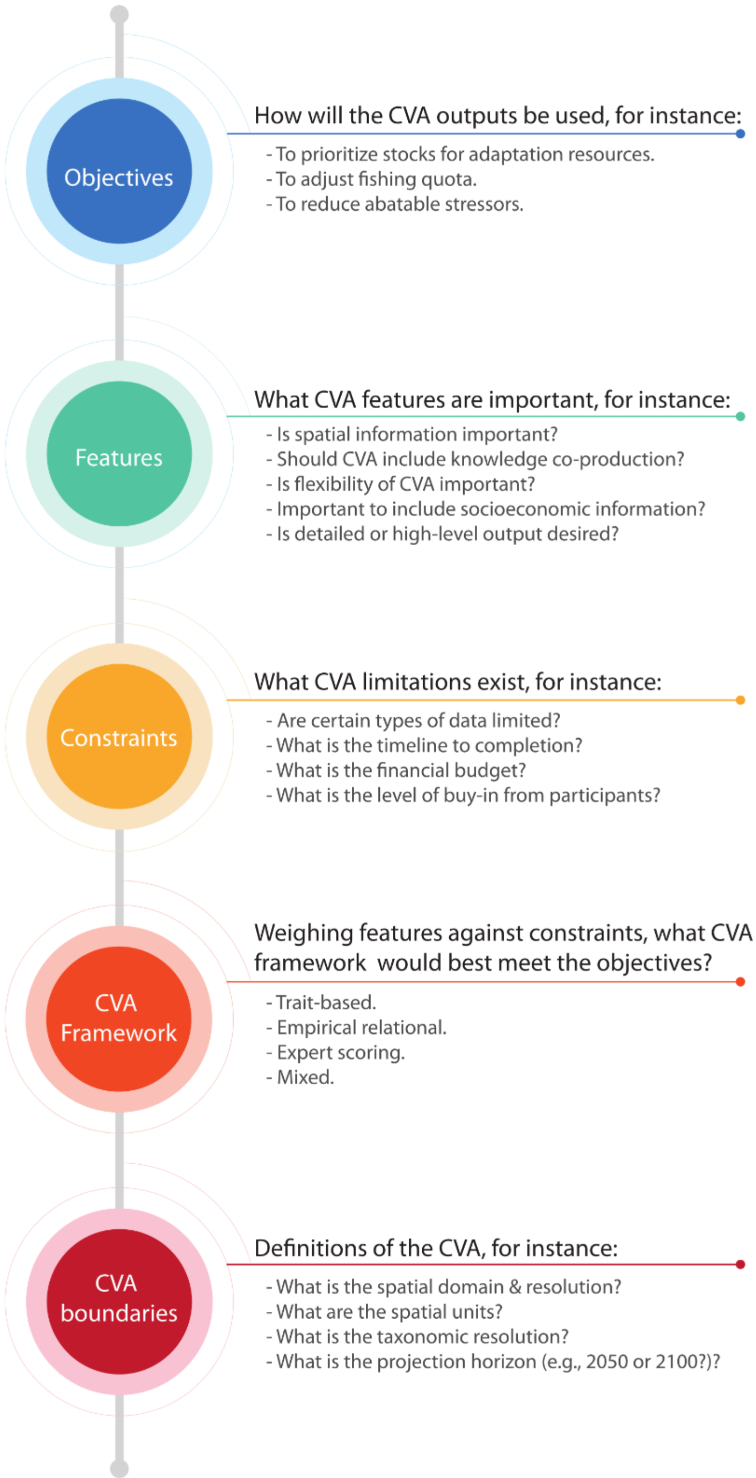

Figure 7 | CVA development for fisheries. Circles depict the generalized steps and workflow in developing and implementing a CVA for fisheries from start (top) to finish (bottom).

Next, considering the practical **constraints** of the CVA is necessary to help bound it. For instance, a CVA constrained by a short timeline, a small budget, limited data, or low involvement of participants or stakeholders would help understand what features identified in the previous step are feasible.

To develop a comprehensive CVA framework, the next step involves carefully weighing the features sought in the CVA against the practical constraints that could eliminate them from consideration. For instance, in a data-limited situation, with high participant or stakeholder involvement, and a longer timeline, an expert assessment approach might be a good starting point. Alternatively, if the objectives required spatialized outputs and a flexible approach that could track changing vulnerability over time in a standardized way, a mixed approach such as the CRIB could be more useful.

Lastly, with a general CVA framework determined, the final step involves determining the **boundaries** that define the analysis. This includes determining the primary units of the analysis (e.g., species, populations, fish stocks, communities, or ecosystems), setting the geographic boundaries of the CVA (e.g., management units for a fish stock or cumulative distribution for species), and determining what climate stressors will be considered (e.g., temperature, oxygen, pH, or sea ice). For spatialized CVAs, the spatial resolution must be set, and for those that consider past and future climates, the projection horizon must also be determined.

This simplified approach to CVA development can help identify the overarching priorities of the CVA exercise, broad features to be included, and practical constraints to implementation, all of which can inform a generalized CVA framework. From here, more specific details must be incorporated to develop the framework fully. These include, for instance, the data sources to be used, the specific traits to be considered and how they will be scored or assessed, which climate stressors will be evaluated, and how the information will be combined and communicated.

8 Conclusions

This systematic review reinforces that the impacts of climate change on marine life and fisheries are complex and challenging to project, and that climate vulnerability analyses seeking to capture the impacts of climate change on marine life and fisheries are remarkably varied, often employing different methods, data sources, and underlying assumptions. This is largely because CVAs are used for different purposes by different users, and no single CVA is ideally suited to all situations. Because of this, there is no universally accepted approach to CVA implementation—no "right" way to assess vulnerability—and the most appropriate vulnerability framework is often situational and context-dependent.

Expert assessments often provide a high level of detail and nuance of climate impacts and may be most relevant in tactical fisheries management (e.g., quota setting). However, expert assessment CVAs are less practical to implement rapidly and synoptically, as they require a high level of species-specific knowledge, which is often lacking, access to and significant investments of time and effort from "experts," and produce semi-quantitative outputs. Given such time and resource constraints, applying expert assessment CVA methods to New Zealand's 402 managed fish stocks is less practical in the near term.

Alternatively, data-driven CVA approaches, such as the CRIB, may offer less relevance to direct fisheries quota setting, but can often provide unique information about where and when climate impacts could occur for stocks or species, helping to inform management decisions; they can also provide climate impact information rapidly across multiple species or stocks, helping to guide strategic decision making and climate resource allocation. However, because such approaches are generalized across species or stocks, they likely neglect some climate stressors or climate impact pathways.

For New Zealand, adopting a flexible, data-driven CVA approach offers the quickest and most practical path to providing climate impact information for its approximately 402 marine stocks and approximately 100 managed species. Ensuring the CVA approach is flexible would enable it to remain "evergreen," allowing for the incorporation of additional climate impact information as it becomes available. Such an approach could operate using input data layers and parameters specific to New Zealand. To hedge against the limitations of such data-driven approaches, expert assessment

CVAs could be developed separately to provide more detailed, stock-specific information and could be viewed independently of the data-driven CVA, or potentially, integrated with it.

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11 Appendix – Supplementary Material

Table S1 | Climate vulnerability in marine fisheries studies reviewed in this report.

Study	Location	Taxonomic	Temporal	Methods	Key Findings	Application to New Zealand
(Aragão et al. 2022)	Spain (Atlantic and Mediterranean coastal regions)	Demersal fisheries	Current period analysis with projections	Climate vulnerability assessment (CVA) using 19 indicators covering exposure, fisheries sensitivity, species sensitivity, and adaptive capacity.	Higher climate vulnerability was found in Mediterranean demersal fisheries due to greater exposure and lower adaptive capacity. The study emphasizes the importance of regional assessments in climate risk analysis.	Applying a similar CVA approach to NZ fisheries could provide a regionalized climate vulnerability assessment. However, differences in ecosystem dynamics, governance, and species composition would require adaptation of the indicators used in the assessment.
(Atlas et al. 2021)	Koeye River, coastal British Columbia, Canada	Sockeye salmon (*Oncorhynchus nerka*)	4 years (2013–2016)	Empirical, correlational analysis of tag-recapture data linked to river temperature and flow; Bayesian statistical models	Sockeye salmon survival dropped significantly when river temperatures exceeded 15°C, especially under low-flow conditions. Delays in migration and mortality due to thermal stress and reduced flows suggest high climate sensitivity.	Methods are highly relevant for NZ migratory species like salmonids or eels. Pros: Empirical, high-resolution data and direct assessment of physiological thresholds. Cons: Site-specific, labour-intensive tagging studies may be hard to scale nationally or apply to offshore species. The application is best for targeted, high-priority populations or habitats.
(Australian Fisheries Management Authority 2024)	Australia (Commonwealth fisheries, EEZ)	Commonwealth-managed species/stocks (fisheries)	Operational, with annual consideration linked to TAC/TAE decisions; near-term climate impacts highlighted.	Four-step process: (1) assess species risk from climate change and stock status, (2) review existing mitigation/adaptation, (3) determine residual risk, (4) advise additional measures; intended as a transitional mechanism until climate is embedded in harvest strategies and ERAs.	(Australian Fisheries Management Authority 2024)	Australia (Commonwealth fisheries, EEZ)

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(Bartelet et al. 2025)	Great Barrier Reef, Australia	Coral reef ecosystem (ecosystem level, not specific species)	Surveys in 2018 and 2022	Public perception survey using structured questionnaires and statistical models (e.g., regression analysis); data on trust, climate risk perception, and support for interventions.	Public support was high for coral seeding and rubble stabilization and lower for genetic engineering. Trust in science and perceived climate threats strongly influenced support for adaptation strategies.	This study doesn't directly assess fisheries' climate risk but informs the social acceptability of novel adaptation measures. In NZ, such public perception studies could guide social license for ecosystem interventions or fishery closures. Limited ecological specificity, but strong in evaluating societal readiness for climate actions.
(Boyce et al. 2022)	Global (marine species in upper 100m of water column)	24 975 marine species (including fish, invertebrates, and primary producers)	Present-day and future projections under SSP1-2.6 and SSP5-8.5 scenarios	Developed a spatially explicit climate risk index assessing exposure, sensitivity, and adaptive capacity using 12 climate indices.	Under high emissions, nearly 90% of assessed species are at high or critical risk. The highest risks occur in low-income countries heavily dependent on fisheries.	The spatially explicit framework could be adapted for NZ fisheries by incorporating local climate models and species data. The approach's strength lies in its global applicability but would need refinement to include NZ-specific socioeconomic and ecological factors.
(Boyce et al. 2023)	Canada (all marine fisheries)	Fish stocks, fishing infrastructure, and fishery operations	Future climate scenarios (to 2100)	Developed a Climate Adaptation Framework for Fisheries (CAFF) to assess species vulnerability and adaptation potential quantitatively.	The framework identifies climate-related vulnerabilities and informs fisheries adaptation planning across multiple stakeholders.	The CAF approach could be applied in NZ to develop climate-adaptive fisheries management. However, NZ would need to adjust the framework for its distinct fisheries governance structures and species composition.
(Boyce et al. 2024)	Northwest Atlantic (Canada)	2 000 marine species, 90 fish stocks	Current conditions and future scenarios (SSP5-8.5 and SSP1-2.6)	Applied the Climate Risk Index for Biodiversity (CRIB) to assess climate risk spatially across species distributions.	High-value harvested species are disproportionately at risk under high emissions scenarios, particularly in warming hotspots.	NZ could apply CRIB to identify high-risk fisheries, but adjustments would be needed to account for local oceanographic patterns and socioeconomic dependencies on specific fish stocks.

Study	Location	Taxonomic	Temporal	Methods	Key Findings	Application to New Zealand
(Cook et al. 2024)	New Zealand.	Functional/taxonomic groups of benthic taxa (e.g., bryozoans, corals, crustaceans, echinoderms, macroalgae, molluscs, sponges); 83 groups assessed.	Two time horizons: 2050 and 2100 under SSP2-4.5 and SSP3-7.0.	Trait-based CCVA with three dimensions (Sensitivity, Exposure, Adaptive Capacity) via expert elicitation; two treatments of unknowns to bracket uncertainty.	Provides an adapted, marine-specific CCVA framework and pilot that identifies relative vulnerability ranks across 83 benthic groups and supports DOC's adaptation planning.	Trait-based approach is tractable for data-poor species and can be extended from benthic groups to commercial taxa or fishery guilds; explicit SSP/time horizons aid alignment with climate services; dual "unknowns" treatments clarify uncertainty effects. Cons: Current focus is conservation-oriented and benthic; commercial species, mobile fishes, and fishery dynamics may require additional traits and exposure metrics; expert-elicitation dependence needs careful calibration and documentation.
(Bueno-Pardo et al. 2021)	Portugal	74 commercial fish and invertebrates	Future projections under RCP 4.5 and RCP 8.5	Expert-based ecological vulnerability assessment incorporating physical-biogeochemical model outputs.	Migratory species and elasmobranchs were most vulnerable, with climate vulnerability highest in the Central region.	The expert-based approach is useful but may require additional empirical data to be applied to NZ fisheries. The methodology's reliance on expert judgment may limit reproducibility.
(Clay & Colburn 2020)	United States	Fishing communities	Current and long-term assessments	Social impact assessment (SIA) framework to evaluate community vulnerability to climate change impacts on fisheries.	Identified key social indicators for fishing community resilience and adaptation planning.	NZ fisheries management could integrate social vulnerability indicators into climate risk frameworks, but adaptation strategies should align with NZ's socio-cultural and economic context.
(Colburn et al. 2016)	Eastern & Gulf Coasts, United States	Fishing-dependent communities	Current and projected climate scenarios	Developed climate vulnerability indices integrating social and ecological data to assess community-level risks.	Fishing communities face exposure to sea-level rise and climate-driven species shifts, requiring adaptive governance approaches.	NZ could apply similar social-ecological vulnerability assessments to coastal fishing communities, though localized socioeconomic variables would need to be integrated.
(Crozier et al. 2019)	California Current Large Marine Ecosystem	Pacific salmon and steelhead (Oncorhynchus spp.)	Future climate projections	Expert-based climate vulnerability assessment ranking biological sensitivity, climate exposure, and adaptive capacity.	Salmon in California Central Valley and Oregon are most vulnerable due to warming stream temperatures and habitat fragmentation.	The methodology could be applied to NZ diadromous fish species, but adjustments would be needed to reflect local hydrological and ecological factors.

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(Cummings et al. 2021)	New Zealand	Species-level review of 32 key fisheries species, with detailed examples for paua, snapper, and hoki.	21st century.	Synthesises observations/projections of physical changes, species biology/ecology, and evaluates species' potential responses; highlights decision-support and vulnerability tools applicable to fisheries management.	Data gaps constrain precise attribution/forecasting, but many NZ fisheries are likely affected by warming and acidification; the report notes 13 of 21 species groups may be affected by warming and seven by acidification. Demonstrates the value of risk/vulnerability approaches and provides species summaries co-developed with managers and industry.	Directly targeted to NZ fisheries; provides species-level context, tools, and adaptation examples; pragmatic bridge to management decision-support. Cons: Heterogeneous data across species and drivers; vulnerability findings are contingent on evolving projections and monitoring.
(de los Ríos et al. 2018)	Global	Review of climate vulnerability studies	Analysis of 743 studies from 2000-2016	Meta-analysis of methods, taxonomic biases, and geographic trends in vulnerability assessments.	Findings highlight methodological biases, taxonomic gaps (especially for invertebrates), and lack of studies in developing regions.	NZ could use insights to refine its fisheries vulnerability assessments, ensuring coverage of underrepresented taxa and consistent methodologies.
(Ding et al. 2017)	Global (109 countries)	National marine fisheries	Current and projected climate change scenarios	Country-level vulnerability assessment scoring exposure, sensitivity, and adaptive capacity, with a focus on food security.	Developing countries in Africa, Asia, Oceania, and Latin America are most vulnerable due to their reliance on fisheries for food security.	As a developed nation with strong fisheries governance, NZ would have a lower vulnerability. However, lessons from food security risks could inform policies for Pacific Island nations dependent on NZ fisheries.
(Dudley et al. 2021)	United States (case studies: Dungeness crab, red sea urchin, North Pacific albacore)	Fisheries Social-Ecological Systems (FSESs)	Current and future climate scenarios	Comprehensive Climate Vulnerability Assessment (CVA) framework analyzing ecological, fished species, fishery, and human community interactions.	Indirect effects of climate change, such as shifts in fishing effort and species distribution, were found to be more impactful than direct species abundance changes.	NZ could benefit from this FSES framework to integrate ecological and socioeconomic factors in fisheries management. The challenge would be aligning it with NZ's existing ecosystem-based management policies.
(Ekstrom et al. 2015)	United States (coastal shellfisheries)	Shellfish fisheries (oysters, clams, scallops)	Current and projected ocean acidification scenarios	Integrated social-ecological vulnerability assessment based on exposure to ocean acidification and socioeconomic resilience.	The Pacific Northwest shellfish industry is particularly vulnerable due to acidification, requiring adaptive aquaculture strategies.	NZ shellfish industry could apply similar risk assessments, though local ocean chemistry and economic dependencies would need to be factored in.

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(Engelhard et al. 2024)	Namibia	Eight large-scale fishery sectors, plus small-scale and recreational fisheries	Current and projected climate scenarios	Climate risk assessment integrating species sensitivity, climate hazard exposure, and socioeconomic vulnerability.	Rock lobster and small-scale artisanal fisheries were most at risk. Adaptation measures were discussed through stakeholder workshops.	NZ fisheries could apply a similar multi-sector risk assessment, but differences in governance and ecosystem productivity would require local adjustments.
(Farr et al. 2021)	Northeast US.	Marine, estuarine, and riverine habitats (52 habitat types)	Current and projected climate scenarios	Trait-based vulnerability assessment evaluating habitat sensitivity and exposure through expert elicitation.	Living habitats, including coastal wetlands and seagrass beds, were identified as the most vulnerable.	A similar assessment could inform NZ marine spatial planning, particularly for protecting habitats supporting key fisheries species.
(Gaichas et al. 2014)	Northeast US.	Demersal fish, pelagic fish, benthic invertebrates	10-year climate projections	Risk-based climate vulnerability assessment using exposure-sensitivity analysis for different fish communities.	Benthic invertebrates showed the highest sensitivity, with climate risks from temperature rise and salinity shifts rated moderate to high.	NZ could apply this approach to evaluate risks for different fisheries sectors, but species-specific response models would be required.
(Giddens et al. 2022)	Pacific Islands	83 marine species (fish, invertebrates)	Projections to 2055	NOAA Rapid Vulnerability Assessment; expert scoring of exposure and sensitivity; included climate models and literature synthesis	Invertebrates are the most vulnerable, and reef-associated fish are moderately so. Key drivers included temperature, acidification, and oxygen. The method identified regional gaps and emphasized species' reliance on threatened habitats.	It could support regional assessments, especially where habitat-forming species or culturally important taxa are vulnerable. The method is scalable but requires regional calibration and expert panels.
(Greenan et al. 2019)	Atlantic Canada	American lobster fishing communities	Future climate projections using ocean models	Geographical vulnerability assessment integrating climate change impacts on lobster habitat and fishing infrastructure.	Lobster populations may shift, creating regional disparities in fishery sustainability.	NZ rock lobster fishery could adopt similar climate-adaptive planning, but regional differences in habitat responses need consideration.
(Hare et al. 2016)	Northeast US Continental Shelf	82 fish and invertebrate species (exploited, forage, protected species)	Future climate projections	Species-based vulnerability assessment integrating climate exposure and biological sensitivity.	Half of the assessed species had high or very high climate vulnerability, with diadromous and benthic species most at risk.	NZ fisheries management could use a similar approach to prioritize conservation and adaptation strategies, especially for sensitive taxa.
(Hinz et al. 2024)	Mediterranean (Balearic Islands, Spain)	Fish communities associated with *Posidonia oceanica* seagrass meadows	45-year historical analysis and future projections	Risk-based assessment integrating species€™ thermal envelopes, habitat preferences, and climate risk index.	Some high-risk species declined while others increased in abundance, possibly due to adaptation or non-climate factors.	NZ seagrass-associated fisheries (e.g., snapper nurseries) could benefit from similar assessments, but long-term monitoring data would be needed.

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(Ho 2022)	Taiwan	Marine fishery industry (sector-level)	Current and forward-looking	Stakeholder-based risk management and adaptation planning; integrated governance and social perception approach	Emphasized stakeholder participation, risk perception, and consensus building. Advocates for integrated climate risk management across institutions.	Strong relevance for governance and adaptation planning. NZ could adopt participatory models, especially with Māori fisheries governance. Focus on social acceptance of adaptation is a unique strength.
(Hoang et al. 2020)	Vietnam (Tam Giang - Cau Hai Lagoon)	Small-scale estuarine fisheries	Current period analysis	Livelihood Vulnerability Index (LVI) and LVI-IPCC framework, incorporating socioeconomic indicators and climate exposure variables.	Livelihood strategies and food availability were key factors in determining vulnerability. The LVI-IPCC framework effectively assessed community-level climate risks.	NZ could apply this framework to assess climate vulnerability in small-scale fisheries, particularly in Māori and rural fishing communities. However, differences in governance and social structures would require adaptation.
(Hobday & Pecl 2014)	Global	Marine hotspots and general species groups	Historical to projected trends	Hotspot identification based on rapid warming rates; reviewed vulnerability and adaptation frameworks	Identifies marine hotspots as early indicators of climate change. Highlights need for sentinel species and locations to monitor ecological responses and guide adaptation.	NZ is itself a hotspot, especially on the southeast coast. Monitoring and adaptation frameworks can help identify early warning signals. Relevance is high for policy development and long-term planning.
(Jepson & Colburn 2013)	US Northeast and Southeast	Fishing communities, not species-specific	Based on decadal census data	14 indices were developed using secondary socioeconomic data (e.g., gentrification, dependence), as well as factor and cluster analysis.	Provided a replicable framework for assessing the vulnerability and resilience of fishing communities. Tools enable the identification of at-risk communities for targeted management.	Highly relevant to Māori and small coastal communities. The index approach is transferable, but data collection must match NZ governance and community structures.
(Jones & Cheung 2018)	Global	1074 exploited marine species	Future projections under RCP 8.5	Fuzzy logic-based vulnerability assessment integrating species sensitivity, adaptive capacity, and climate exposure.	Large-bodied, endemic species were most vulnerable. Fuzzy logic provides a flexible approach for assessing species-level climate risk.	NZ could use this approach for data-poor species, but local adaptation would be needed to account for unique environmental conditions and fisheries policies.
(Kim et al. 2023)	Global oceans, coral reef regions	741 coral species	Historical (1900-1994) to projected (mid-21st century)	Species-specific exposure and vulnerability using distribution ranges, climate analog loss, and projected stress	Many coral species will lose their historical climate range. Small-range and high-latitude species are most at risk. SSP5-8.5 drastically increases risk.	Can inform benthic and habitat-forming species risk (e.g., bryozoans, sponges). Highlights the importance of climate refugia and trait-based risk assessment.

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(Kjesbu et al. 2022)	Northeast Atlantic (Norwegian, North, and Barents Seas)	39 fisheries stocks (local conspecifics)	Projections to 2050 (RCP4.5)	Hybrid expert-based and mechanistic approach; stock-specific responses to exposure and sensitivity	Contrary to many forecasts, several stocks may benefit from warming. Latitude and life history are key to stock-specific responses.	Insightful for regional variability. Combining expert elicitation with mechanistic modelling could be powerful for NZ's diverse stocks and habitats.
(Lawrence et al. 2021)	New Zealand	Institutional and governance frameworks	Current and future planning scenarios	Policy review assessing the adequacy of NZ planning frameworks for climate adaptation.	Current planning frameworks are inadequate for addressing dynamic climate risks, necessitating a transition to adaptive risk management.	Directly relevant to NZ fisheries governance, highlighting the need for more adaptive, forward-looking policy measures.
(Le Bris et al. 2018)	Northwest Atlantic (US and Canada)	American lobster (*Homarus americanus*)	Current and projected climate scenarios	Model linking ocean temperature, predator density, and fishing effort to population productivity.	Lobster fisheries in the Gulf of Maine benefited from conservation measures, while those in southern New England collapsed due to warming and overfishing.	NZ rock lobster fisheries could use similar models to assess resilience under climate change, but region-specific predator-prey dynamics would need to be incorporated.
(Lettrich et al. 2023)	Western North Atlantic, Gulf of Mexico, Caribbean	108 marine mammal stocks	Present-day with future projections	Trait-based vulnerability assessment using expert elicitation. Combined exposure (climate variables) and sensitivity (ecological traits) to assign vulnerability scores.	44% of marine mammal stocks had very high vulnerability. Drivers included temperature, ocean pH, and oxygen, with indirect effects via prey and habitat.	This method could be adapted for NZ marine mammals, offering a structured approach for species with limited data. Useful for informing conservation, especially for endangered or endemic species. Requires expert panels and trait data.
(Li et al. 2023)	Global	Multiple fisheries across regions	Review of past studies	Synthesis of climate vulnerability assessment (CVA) methodologies and scales, highlighting gaps in research and application.	Uneven research focus and gaps in data availability hinder effective climate vulnerability assessments, particularly in developing countries.	NZ could use insights from this review to refine its CVA methodologies, ensuring a comprehensive assessment of species and fisheries at appropriate scales.
(Ling et al. 2009)	Global	Marine capture fisheries	Current and projected climate change scenarios	Vulnerability assessment framework considering exposure, sensitivity, and adaptive capacity of fish stocks.	Marine fisheries face increased risks due to climate change, particularly from warming, acidification, and altered circulation patterns.	NZ fisheries management could use this framework to prioritize adaptation strategies, but region-specific oceanographic and economic factors would need to be considered.
(Ma et al. 2024)	Northeast Atlantic	26 fish stocks	Historical hindcasts to 2090s (SSP scenarios)	Bayesian statistical framework linking productivity trends to temperature and secondary production; hindcasts and forecasts	Most stocks showed declining productivity linked to warming, especially in high-latitude areas. Some stock responses were positive but inconsistent.	The quantitative model offers valuable forecasting potential for NZ stocks, especially those with strong monitoring data. Requires robust time series and modelling capacity.

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(Mahu et al. 2022)	West Africa	Mangrove oyster (*Crassostrea tulipa*)	Future climate projections	Expert-based climate vulnerability assessment incorporating habitat-specific climate stressors.	Oyster fisheries are highly vulnerable to climate change due to habitat dependency and salinity sensitivity.	NZ aquaculture sector could benefit from similar vulnerability assessments, particularly for shellfish industries sensitive to ocean acidification.
(Maltby et al. 2022)	ROPME Sea Area (Arabian Gulf, Gulf of Oman, northern Arabian Sea)	Ecosystem- and sector-level (biodiversity, infrastructure, society)	Current and projected risks	Climate risk assessment based on literature and expert workshop; 45 risks across biodiversity and socioeconomic sectors identified and scored	Thirteen severe risks were identified, including coral reef loss, fisheries shifts, and infrastructure impacts. Emphasized the need for transboundary adaptation.	The holistic and participatory framework is useful for NZ EEZ-wide risk screening. Valuable for integrating biodiversity and socioeconomic risks. Could inform marine spatial planning.
(Mathis et al. 2015)	Pacific-Arctic boundary regions (Bering, Chukchi, Beaufort Seas)	Ocean chemistry and calcifying species	Historical to future projections (2025-2044)	Combined oceanographic models with field observations; projected aragonite saturation state decline	Aragonite undersaturation will occur in sequential shelf seas by mid-century, putting calcifiers and dependent fisheries at risk. The Bering Sea may be more resilient due to variability.	OA risk modelling applicable to NZ shellfish and benthic fisheries. Highlights the need for monitoring saturation states and regional carbonate chemistry.
(McClenachan et al. 2020)	Maine, USA	American lobster fishery	Current perceptions and future projections	In-depth interviews and fuzzy logic cognitive mapping (mental models); assessed perceptions of climate change, adaptation, and agency among lobster fishers	Most fishers perceive warming waters as a threat but prioritize other issues. Adaptive capacity varies based on beliefs about causes of warming, trust in institutions, and perceptions of personal agency.	Highlights the importance of understanding fisher perceptions and social drivers of adaptation. NZ fisheries management could benefit from incorporating cognitive mapping and mental model approaches, especially in co-managed or customary fisheries.
(Mcleod et al. 2015)	Global	Coastal communities and ecosystems	Review of past applications	Review of community-based climate vulnerability and adaptation assessment tools.	Various tools exist, but their effectiveness depends on local capacity and data availability.	NZ fisheries management could integrate these tools into ecosystem-based adaptation planning, but customization for local socio-ecological systems is required.
(Mcleod et al. 2019)	Pacific Islands	Ecosystems and communities (not species-specific)	Current and recent efforts (2015-2018)	Case studies of ecosystem-based adaptation (EBA); integrated traditional knowledge and modern conservation strategies	Pacific Islanders are leading community-driven EBA efforts such as marine protected areas, salt-tolerant crops, and climate-smart planning. These approaches build resilience to multiple threats.	Strong parallels with Māori-led stewardship and EBA initiatives. Reinforces the value of traditional knowledge, which benefits food and water security and local governance for climate resilience in NZ.

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(Ministry for the Environment 2020)	New Zealand (national).	Cross-sector, not taxon-specific; spans value domains (natural environment, human, economy, built, governance).	Present (past 10-20 years), Near term (~2050), Long term (~2100). RCP4.5 and RCP8.5 were used for projections.	Three-stage national risk assessment using IPCC AR5 framing with consequence-focused scoring, stakeholder engagement, and urgency ratings.	Provides a values-based, staged method (screening + detailed assessment + adaptation urgency) that emphasizes consequence over likelihood for climate risks. Sets common criteria for exposure, vulnerability, magnitude, confidence, and urgency, and documents an engagement process to support a future National Adaptation Plan.	Offers an IPCC-consistent risk framework that can be applied to marine sectors and scaled to Territorial Sea/EEZ; aligns cross-sector criteria for exposure, vulnerability and urgency; centres te ao Maori principles and engagement. Cons: Not species- or stock-specific; consequence-only rating may not capture probabilistic elements used in fisheries management.
(Moll et al. 2024)	Western Baltic Sea (Germany, Denmark)	22 fish species (marine, brackish, freshwater)	Current and future climate scenarios	Expert-based climate vulnerability assessment evaluating species exposure and sensitivity.	Traditional target species (cod, herring) are at high risk, while adaptable or invasive species may thrive.	NZ fisheries could apply similar species-level assessments, though adjustments would be needed for local species assemblages and oceanographic conditions.
(Monnereau et al. 2017)	Global (focus on Small Island Developing States and Least Developed Countries)	National-level fisheries	Current and projected climate change scenarios	Analysis of methodological biases in climate vulnerability assessments, focusing on indicator selection, data scaling, and redundancy.	Findings suggest that previous assessments underestimated the vulnerability of Small Island Developing States (SIDS), highlighting the importance of methodological choices in determining outcomes.	NZ could benefit from refining its own climate vulnerability assessments using lessons from this study, ensuring robust, transparent, and region-specific methodologies.
(Morrison et al. 2015)	United States	Marine fish and shellfish species	Current and projected climate change scenarios	Expert-based climate vulnerability assessment integrating species' exposure and sensitivity to climate change.	Vulnerability varied widely across species, with mobile species generally less vulnerable than sessile or habitat-dependent species.	NZ fisheries could use this methodology for large-scale assessments, though local adaptation would be needed to reflect specific environmental conditions.
(Nadeau et al. 2017)	Global	Various marine and terrestrial species	Historical, current, and future climate conditions	Framework integrating historical climatic variation to predict species' climate vulnerability.	Historical climate conditions strongly influence species' adaptive capacity and sensitivity to future change.	NZ could use this approach to refine risk assessments by considering past climate variability's influence on local species' resilience.
(Nyboer et al. 2021)	Global	Marine and freshwater recreational fish	Future climate projections	Trait-based vulnerability assessment mapping species' exposure and conservation efforts.	Mismatches exist between climate vulnerability and conservation efforts, particularly in freshwater ecosystems.	NZ could use this framework to assess climate risks for recreational fisheries and ensure conservation funding aligns with vulnerability levels.

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(Olusanya & van Zyll de Jong 2018)	Newfoundland and Labrador, Canada	Freshwater fish species	Current and projected climate conditions to 2050	National Marine Fisheries Service (NMFS) framework using expert scoring of species' exposure, sensitivity, and adaptive capacity.	Some species are highly vulnerable due to warming temperatures and changing precipitation patterns.	NZ could apply this framework to assess freshwater fisheries' climate vulnerability, but species- and region-specific adjustments would be needed.
(Payne et al. 2021)	Europe	556 fish populations across 380 fishing fleets	Current and projected climate risks	Risk-based approach combining biological traits, physiological metrics, and climate hazards.	Southeast Europe and the UK face the highest climate risks, highlighting the need for tailored adaptation strategies.	NZ could apply this method to evaluate climate risk at the fleet and regional level, though governance and economic differences would require adjustments.
(Pearson et al. 2014)	Global	Multiple species across marine and terrestrial ecosystems	Future climate projections to 2100	Extinction risk model combining life history traits and spatial characteristics.	Species with small population sizes and restricted ranges are at the highest risk of climate-driven extinction.	NZ could apply these models to evaluate extinction risk for its most vulnerable marine species.
(Peterson Williams et al. 2022)	Gulf of Alaska	Pacific cod (Gadus macrocephalus)	2013-2020 (heatwave event)	A case study using ecological monitoring, bioenergetics modelling, and fisher interviews	Pacific cod decline is tied to marine heat waves and reduced prey availability. The closure of the 2020 fishery illustrates the urgency of adaptive, climate-informed management.	Reinforces the need for early warning indicators and inclusion of fisher knowledge. Relevant to NZ pāua and rock lobster fisheries under marine heatwave stress.
(Pita et al. 2021)	Mediterranean Sea	100 commercially exploited species	Current and projected climate scenarios	Climate Risk Assessment (CRA) using a trait-based approach and socioeconomic parameters.	Northern Mediterranean fisheries target more vulnerable species, while North African countries are more socio-economically vulnerable.	NZ could apply a similar combined ecological-socioeconomic approach for comprehensive climate risk assessments of its fisheries.
(Quinlan et al. 2023)	Gulf of Mexico	75 fish and invertebrate species	Future climate projections under RCP 8.5	NOAA climate vulnerability assessment framework integrating biological sensitivity and climate exposure.	20% of species showed high climate vulnerability, particularly groupers, elasmobranchs, and diadromous fishes.	NZ fisheries management could benefit from adopting this structured, quantitative assessment method.
(Rahman et al. 2022)	Bangladesh	Coastal and inland fisheries, shrimp aquaculture	Current and projected climate change scenarios	Integrated vulnerability assessment considering exposure, sensitivity, and adaptive capacity.	Climate change impacts include sea level rise, salinity intrusion, and extreme weather events, significantly affecting shrimp and prawn farming.	NZ could use a similar integrated assessment for aquaculture sectors, particularly shellfish and finfish farming, but adjustments are needed for local oceanographic conditions and governance structures.

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(Ramos et al. 2022)	Northern Humboldt Current System (Peru)	28 fishery resources (benthic, demersal, pelagic)	Projections to 2055	Trait-based Climate Vulnerability Assessment (CVA) using expert elicitation and exposure-sensitivity analysis.	36% of species had high or very high climate vulnerability, with benthic species most at risk.	NZ could adopt this trait-based approach, but species-specific data for NZ fisheries would be needed for accurate assessments.
(Razgour et al. 2019)	Europe	Forest bat species	Future climate projections	Integration of genomic and ecological modelling to assess genetic adaptation potential under climate change.	Accounting for adaptive genetic variation reduces projected species range loss and highlights evolutionary rescue potential.	NZ fisheries assessments could benefit from integrating genetic data, particularly for species with high dispersal or adaptive capacities.
(Rheuban et al. 2018)	Northwest Atlantic	American lobster (*Homarus americanus*)	Historical to 2100 (RCP4.5 and RCP8.5)	Statistical downscaling of CMIP5 models to project benthic temperature changes and link to lobster biology	Southern New England lobster habitats will become inhospitable by mid-century. The Gulf of Maine may remain suitable. Projected warming alters recruitment, growth, and spatial distribution.	A valuable modelling approach for forecasting habitat changes under warming. NZ could adapt these tools to species like rock lobster. It would require detailed oceanographic and biological data.
(Rinnan & Lawler 2019)	United States	Montane mammal species	Future climate projections	Ecological-niche factor analysis (ENFA) for spatially explicit vulnerability assessment.	Provides detailed spatial insights into species' climate risks, showing how exposure and sensitivity vary geographically.	NZ could apply ENFA to spatially map fisheries' climate vulnerabilities, but it requires detailed climate and species occurrence data.
(Ruane et al. 2022)	Global	Not taxon-specific; sector-wide application including fisheries	Contemporary to long-term future (supporting AR6)	Introduces Climatic Impact-Driver (CID) Framework categorizing 33 types of climate conditions (e.g., heatwaves, ocean acidification) affecting ecosystems and society. Designed for co-production of sector-specific climate risk assessments.	Provides a standardized, neutral framework linking climate indices to sectoral risk. Supports IPCC risk assessment and climate services through a system-tailored, impact-relevant approach.	Highly adaptable for identifying key climatic hazards affecting NZ marine sectors (e.g., heatwaves, deoxygenation). Supports integration into national risk assessments and fisheries planning. Requires coupling with ecological and socioeconomic sensitivity data.
(Ruiz-Díaz et al. 2020)	Galicia, Spain	Stalked barnacle (*Pollicipes pollicipes*) fishery	Current period analysis with climate projections	Social-ecological vulnerability assessment based on exposure, sensitivity, and adaptive capacity of TURF (Territorial Use Rights in Fisheries) systems.	The most vulnerable TURF zones were identified as MuxÃa and O Pindo due to high ecological vulnerability, social sensitivity, and low adaptive capacity.	NZ could adopt a similar TURF-based assessment, especially for its small-scale fisheries. However, the effectiveness depends on governance structures and property rights regimes in NZ fisheries.

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(Saba et al. 2023)	Northeast United States	Commercial and protected marine species	Past trends and future projections	NOAA climate-ready fisheries research, including stock assessments, ecosystem models, and climate vulnerability assessments.	Warming in the US NES has led to species shifts, requiring climate-informed fisheries management strategies.	NZ could benefit from NOAA climate-informed stock assessments and scenario planning approaches, but localized data and model calibration would be necessary.
(Sainsbury et al. 2019)	Caribbean (St. Lucia, Grenada)	Fisheries sector (general)	Contemporary and future climate events (e.g., storms)	Descriptive and evaluative analysis of COAST: first fisheries index insurance. Uses weather indices (e.g., storm surge, wave height) to trigger payouts.	Innovative insurance tool, but challenges include equity, maladaptation, and moral hazard. Highlights the need for inclusive governance and risk communication.	Weather index insurance could improve resilience for small-scale fleets exposed to extreme events (e.g., storms in Hauraki Gulf). Governance and data availability are key constraints. Equity and transparency in fund distribution would be critical.
(Samhouri et al. 2024)	US West Coast (California, Oregon, Washington)	Groundfish fleets (multispecies)	Historical to projected future (multi-decade)	Coupled social-ecological risk model integrating fleet exposure, dependence, and adaptive capacity (mobility, diversification)	Poleward fleets face higher exposure and economic dependence. Adaptation strategies vary across regions. Locally grounded flexibility is key to resilience.	Applicable to NZ's diverse inshore and offshore fleet structure. Risk analysis could help tailor local adaptation options (e.g., gear, species-switching). Requires fine-scale fishery and climate data and co-development with communities.
(Schleussner et al. 2024)	Global	System-wide, not species-specific	Multi-decadal projections (up to 2100+)	Scenario analysis using carbon cycle and climate models (FaIR) to assess overshoot risks and net-negative emissions uncertainty	Reversal of warming after overshoot is highly uncertain due to Earth system feedbacks. Highlights risks of relying on carbon dioxide removal to reverse climate impacts.	Cautions against long-term overshoot optimism in planning. Supports precautionary, near-term adaptation strategies in NZ fisheries. Emphasizes irreversibility of some marine impacts (e.g., acidification, species range loss).
(Shackell et al. 2013)	Marine Atlantic Basin (Canada)	Fish and invertebrate species	Past trends and future projections	Integrated climate risk analysis for marine ecosystems, incorporating oceanographic and species-specific factors.	Warming, acidification, and oxygen depletion present risks for commercial species such as lobster and scallops.	NZ could apply a similar ecosystem-based vulnerability approach but must consider local ocean conditions and fisheries structures.
(Sousa et al. 2021)	Macaronesia (Azores, Madeira, Canary Islands)	21 cetacean species management units	Contemporary	Trait-based climate vulnerability assessment adapted from the NOAA MMCVA method, using expert elicitation to score sensitivity, exposure, and data quality	62% of units assessed were found to be Very High or High vulnerability. Species with archipelago-specific residency (e.g., bottlenose dolphin, pilot whale) were most at risk due to limited range and high site fidelity.	Applicable to NZ marine mammal conservation under climate change. The method requires expert panels and trait data but is scalable and transparent. Could support prioritization in marine spatial planning and MPA design.

Study	Location	Taxonomic	Temporal	Methods	Key Findings	Application to New Zealand
(Spencer et al. 2019)	Eastern Bering Sea (Alaska)	36 fish and invertebrate stocks	Projections to 2039	Trait-based vulnerability assessment incorporating climate projections and uncertainty analysis.	Species showed variable sensitivity and exposure, with temperature being a key driver of vulnerability.	NZ could benefit from this trait-based framework, though localized environmental variables and fisheries dynamics need to be considered.
(Steen et al. 2017)	United States (Prairie Pothole Region)	Wetland-dependent bird species	Future climate projections	Species distribution modeling (SDM) evaluating different sources of uncertainty.	Future climate uncertainty was the largest source of variation in vulnerability projections.	NZ fisheries models could improve by incorporating uncertainty analysis to better guide conservation and management actions.
(Talbot et al. 2024)	Palawan, Philippines	Key tropical marine fishery species (multispecies)	Projections to mid-century (RCP4.5 and RCP8.5)	Size-spectrum dynamic bioclimate envelope model (SS-DBEM) driven by POLCOMS-ERSEM model outputs; spatial meta-analysis of abundance trends under climate and fishing pressure.	Projected widespread declines in pelagic fish abundance due to climate change, especially under RCP8.5. Emphasizes the need for spatially targeted MPAs and adaptive management.	High-resolution mechanistic models like SS-DBEM could inform NZ spatial fisheries planning. Useful for identifying refugia and projecting regional vulnerability under various emissions and effort scenarios.
(Tigchelaar et al. 2021)	Global (219 countries)	Aquatic food systems (marine/freshwater capture and aquaculture)	2021–2040, 2041–2060, 2081–2100 (CMIP6 scenarios)	Integrative food system approach linking ESM-derived hazard scores to aquatic food system outcomes (nutrition, health, livelihoods, equity)	Wild-capture fisheries in Africa, Southeast Asia, and SIDS face the highest compound risks. Reducing societal vulnerability is as impactful as emission reductions in lowering food system risk.	Supports cross-sectoral planning. Highlights the need to integrate equity, health, and governance into fisheries' climate risk assessments. Useful at a national planning scale.
(Wade et al. 2017)	United States	Multiple species	Review of climate change vulnerability assessments	A critical review of CCVA methods, focusing on their scientific rigour and comparability.	Findings emphasize the need for consistency and validation in vulnerability assessments.	NZ fisheries management could adopt best practices from this review to improve the reliability of its own vulnerability assessments.
(Ward et al. 2024)	Northeast Pacific (North America's west coast)	30 groundfish species	Historical to contemporary (multi-decadal)	Spatiotemporal species distribution models (SDMs) estimating thermal niches from long-term trawl survey data	Thermal niches vary by species and region; some are stable, while others are warming and narrowing. The tool supports identifying vulnerable species and refining essential fish habitats.	Highly applicable to NZ groundfish species. Helps identify species at risk from warming and guide spatial protections. Requires long-term monitoring and modelling infrastructure.

Study	Location	Taxonomic	Temporal	Methods	Key Findings	Application to New Zealand
(Wheatley et al. 2017)	Global	Multiple taxonomic groups	Historical trends and future projections	Comparison of 12 climate vulnerability assessment methodologies to assess consistency and reliability.	Different methodologies yield inconsistent vulnerability rankings, with trend-based methods generally outperforming trait-based ones.	NZ could use insights from this study to refine its vulnerability assessment framework, ensuring consistency and validation of methods.
(Williams et al. 2008)	Global	Multiple species and ecosystems	Current and future climate projections	A conceptual framework integrating exposure, sensitivity, resilience, and adaptive management.	A unified framework is necessary for prioritizing species conservation under climate change.	NZ could implement elements of this framework for its fisheries, ensuring an integrated approach to climate adaptation.
(Willis et al. 2015)	Global	Various species across ecosystems	Current and projected climate scenarios	Integration of species distribution models (SDMs) and trait-based vulnerability assessments.	Combining SDMs and trait-based approaches enhances climate risk assessments and conservation planning.	NZ could adopt this integrated approach to improve fisheries risk assessments, particularly for species with limited distribution data.
(Wilson et al. 2020)	Atlantic Canada (including Quebec)	Commercially harvested shellfish species (e.g., oysters, mussels, crabs)	2000 baseline with projections to 2050 and 2090 (RCP 2.6 and 8.5)	Dynamic Bioclimate Envelope Model (DBEM) projecting catch potential changes under OA and warming, integrated with a socioeconomic impact index	Shellfish fisheries will face regionally variable declines due to OA and climate change. Socially vulnerable provinces like PEI and Newfoundland may be less exposed biophysically but more sensitive to changes.	A comprehensive approach combining species distribution modelling and regional socioeconomic indices could guide NZ shellfish sectors. Requires robust catch and social data by region. Useful for assessing adaptation equity and spatial prioritization.
(Wongbusarakum et al. 2021)	Micronesia and Guam	Small-scale fisheries and communities (not species-specific)	Surveys conducted 2017–2018	Assessment of social adaptive capacity using five domains (diversity/flexibility, access to assets, learning/knowledge, governance, agency); household surveys, focus groups, and interviews	Communities showed strong social networks and high perceived agency, but governance capacity was relatively low. Coral reef dependence is significantly correlated with higher adaptive capacity.	Highly relevant for assessing the social readiness of Māori and coastal NZ communities. The framework helps target capacity-building efforts and improve participatory management.
(Yin et al. 2025)	Haizhou Bay, China	33 functional groups (ecosystem-level)	2011–2099 (SSP1-2.6 and SSP5-8.5)	Ecopath with Ecosim dynamic modelling, simulating biomass and ecosystem responses to warming and alternative fisheries management strategies	Climate warming threatens ecosystem structure and fisheries productivity. Harvest control rules and multispecies management improve resilience, but effectiveness declines under high emissions.	Ecosim-based simulations can assess trade-offs among yield, ecosystem health, and economic goals. Adaptable for NZ multispecies fisheries with sufficient input data. Emphasizes urgency of mitigation alongside adaptation.

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