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Perspective

Identifying the critical elements for a next generation of climate vulnerability assessments for fisheries

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ABSTRACT

The biological impacts of climate change on ocean ecosystems and fisheries are an increasing global concern, influencing fish distribution, phenology, and productivity. To address these challenges, fisheries management agencies are developing climate-informed strategies to build resilience in marine species, ecosystems, and fisheries. Climate vulnerability assessments (CVAs) have been widely used to evaluate the vulnerabilities of species, ecosystems, fisheries, and communities to climate change, but their uptake in decision making has been limited. Here, we explore the factors that are hindering broader adoption and integration of CVA results into active fisheries management. We identify the critical components of a next-generation CVA framework that is dynamic, adaptive, and better suited to support climate responses and adaptation by fishers, fisheries managers, and coastal communities. These elements will serve to improve applicability of CVAs while emphasizing the integration of qualitative and quantitative data, including experiential knowledge, embracing dynamic models, and quantifying uncertainty to create impactful spatially and temporally explicit vulnerability assessments. The proposed changes to existing CVA approaches aim to improve fisheries management by more explicitly linking ecological and socio-economic systems and providing actionable insights for climate-resilient fisheries. These components also better align CVAs with ongoing efforts by various government initiatives and offer a path forward for improving the climate resilience of fisheries and coastal communities.

INTRODUCTION

Biological impacts of climate change are apparent across every ecosystem on Earth and are a growing concern for ocean fisheries. Common climate impacts on fish stocks include changes in geographic distribution (Braun et al., 2023; Cheung et al., 2010), changes in phenology (Asch, 2015), and continuing

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declines in fisheries production (Britten et al., 2016; Cheung et al., 2010). In light of the critical contribution of marine fisheries to economies, livelihoods, food provision, and culture, fisheries management agencies worldwide are strengthening climate-informed science and management capabilities and developing strategies to help sectors mitigate and adapt to climate change (e.g., United States: Climate, Ecosystems, and Fisheries Initiative and Climate Science Strategy; Australia: Climate Adaptation Program; United Kingdom: Fisheries Act 2020; Ireland: Kopke & O'Mahony, 2011). One key feature of these climate action plans is understanding climate vulnerability or risk for exploited marine species, dependent industries, and coastal communities to design management and governance strategies that promote resilience (Barange & Cochrane, 2018; Foden et al., 2019).

Climate vulnerability assessments (CVAs) are used to evaluate how species, habitats, and coupled socio-ecological systems, such as fisheries, may respond to climate change (e.g., Boyce et al., 2024; de los Ríos et al., 2018; Foden et al., 2019; Frusher et al., 2016; Pacifici et al., 2015; Payne et al., 2021). Response is measured as "vulnerability" following established international frameworks (e.g., Intergovernmental Panel on Climate Change, 2007) and is a function of exposure, sensitivity, and adaptive capacity to climate change (Adger et al., 2005; Lindegren & Brander, 2018). Exposure describes the magnitude of climate change to which the system will likely be subjected. Sensitivity is assessed across a range of attributes that modulate a system's response to change. Adaptive capacity describes the ability to adjust to those impacts. In recent years, there has been a shift in CVAs to also account for climate risk rather than just climate vulnerability (Intergovernmental Panel on Climate Change, 2022; Li et al., 2023). Climate risk assessments incorporate the likelihood of climate hazards that are used to assess the likelihood of adverse consequences due to climate change following the Intergovernmental Panel on Climate Change "Reasons for Concern" framework (O'Neill et al., 2017). Combined or integrated risk and vulnerability assessments are increasingly being used to address both relative vulnerability to climate change and risks of specific impacts (Boyce et al., 2024; Li et al., 2023).

There have been nearly 80 published CVAs relating to marine fisheries (de los Ríos et al., 2018; Li et al., 2023). Their outcomes have been used to varying degrees for prioritization and planning in fisheries management and, in some cases, for promoting a precautionary approach. Despite these efforts, CVAs have rarely translated to directly support operational fisheries management, although they have been instrumental in reframing the priorities of management agencies and have led to an active exploration of on-ramps for adaptive management (e.g., Pepin et al., 2022). While CVAs will continue to be an important tool for strategic planning and development of institutional priorities at decadal scales, there is an urgent need for more actionable information on climate vulnerability to inform operational fisheries management (Mason et al., 2023). This will allow the development of new management strategies that are explicitly designed to reduce climate vulnerability and risk in both the short and long terms. Here, we critically examine factors to advance broader CVA uptake in both strategic (e.g., long-term planning) and tactical (e.g., short-term actions) fisheries management, and we provide a vision for the critical elements in a next-generation CVA framework that can directly support climate-resilient fisheries and fisheries-dependent communities.

BRIEF HISTORY OF CVAS FOR FISHERIES

Climate vulnerability assessments for fish and fisheries are commonly used to triage species, habitats, stakeholders, or communities at risk of adverse climate impacts (Holsman et al., 2019). They were developed in the 1990s as scientists and resource managers began recognizing the risks that climate change poses to fish stocks, ecosystems, and communities; they were adapted from disaster planning in terrestrial systems (Kelly & Adger, 2000) and ecological risk assessments in marine systems (Samhouri et al., 2019; Zhou et al., 2016). Climate vulnerability assessments have since been applied to systematically evaluate how changes in environmental conditions might impact a wide range of fish species (e.g., Hare et al., 2016). Recent CVA efforts have evolved to focus on climate change impacts on broader ocean ecosystems, including multiple fish stocks, associated habitats, and coupled socio-ecological systems (Li et al., 2023). These efforts include a range of relevant species–environment interaction effects, such as habitat changes, prey availability, and species interactions. Most of these efforts have been divided into relevant regions or species assemblages that reflect unique fishery management mechanisms or challenges. Climate vulnerability assessments have become increasingly collaborative, involving scientists, policymakers, and local communities to develop comprehensive management and adaptation strategies among various stakeholders (Carroll et al., 2023; Frusher et al., 2016). This increasingly holistic and multidisciplinary perspective has led to CVA applications that seek to quantify climate impacts on fishing communities, accounting for the direct and indirect impacts that climate change can have on linked ecological and socio-economic systems (Carroll et al., 2023; Dudley et al., 2021; Koehn et al., 2022; Koomson et al., 2020; Li et al., 2023).

Despite these advances and the promise of CVAs as tools for managing climate change impacts on fishery systems, CVAs have faced challenges that may have limited their uptake in operational fisheries management (Skern-Mauritzen et al., 2016). These challenges include the semi-quantitative output of many CVAs, where the relative climate vulnerability of species, fisheries, or communities is ranked from "low" to "very high," which is informative about relative risk but provides limited actionable information with which to design specific management measures beyond prioritizing the species or stocks that most urgently need attention (Bryndum-Buchholz, 2020). For example, early regional-scale CVAs, such as the National Oceanic and Atmospheric Administration (NOAA) northeast U.S. shelf assessment (Hare et al., 2016), provided relative vulnerability rankings for more than 80 fish and invertebrate species, which proved valuable for prioritizing species of concern but offered limited guidance on how managers might adapt harvest strategies or spatial management in response to those rankings. Similarly, the Caribbean small-scale fisheries CVA (Dudley et al., 2021) successfully combined ecological and social indicators to identify vulnerable fishing communities but, like many semi-quantitative efforts, stopped short of linking those findings to specific management interventions

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or thresholds for action. Likewise, the Tasmanian rock lobster *Jasus edwardsii* CVA (Pecl et al., 2009) demonstrated how detailed, interdisciplinary analyses can identify climate-related risks and adaptation options for a major commercial fishery; however, despite its comprehensive evaluation of biological, economic, and governance pathways, the semi-quantitative structure of the CVA similarly required additional steps to translate vulnerability findings into specific operational management actions (Pecl et al., 2009). These examples illustrate that while relative scoring frameworks are powerful for triage and awareness-raising, their semi-quantitative outputs can make direct operationalization difficult.

In addition, many CVAs produce a single vulnerability score across the range of a species, population, or stock (but see Crozier et al., 2019; McClure et al., 2023; Payne et al., 2021), potentially obscuring significant spatial variation that is critical to fisheries management (e.g., Braun et al., 2023; Robinson et al., 2015) and precluding meaningful estimates of uncertainty that can inform decision-making processes. More spatially explicit efforts (e.g., for Pacific salmon *Oncorhynchus* spp.: Crozier et al., 2019; for U.S. West Coast commercial fish stocks: McClure et al., 2023) demonstrate the value of resolving regional differences in vulnerability and highlight how spatially explicit CVA outcomes can improve relevance to fisheries decisions. Likewise, assessments that use a single, fixed time horizon (commonly 2050 or 2100) may inadvertently mask the timing of emerging vulnerabilities. For instance, McClure et al. (2023) showed that some U.S. West Coast fish stocks exhibit near-term shifts in exposure well before mid-century, suggesting that fixed-horizon CVAs may underrepresent short-term risks relevant to current management cycles. Finally, many CVA frameworks rely heavily on expert elicitation, an approach that has been central to the success of large-scale syntheses (e.g., Giddens et al., 2022; Hare et al., 2016), yet the reliance on expert scoring introduces subjectivity and variation across studies. Although these methods produce context-rich insights, their qualitative nature can make it challenging to reproduce results—even with well-codified scoring procedures—or to rapidly update assessments as new data become available.

CRITICAL ELEMENTS FOR NEXT-GENERATION CVAS

The critical questions regarding changes in ocean conditions and fisheries remain: Which species, fisheries, and communities are most vulnerable to climate shifts? Where are they most vulnerable, when will they become vulnerable, and why (sensu Foden et al., 2019)? Climate vulnerability assessment frameworks that leverage the simplicity of current approaches while also resolving spatial heterogeneity and time horizons of vulnerability are needed to refine communication with stakeholders and policymakers and to facilitate the development of climate-informed fisheries management strategies. This will require new elements for the next generation of CVAs that leverage published advances in CVAs and related fields, including fisheries, climate science, oceanography, and ecological forecasting. These elements fall into four categories: (1) formal integration and synthesis of qualitative and quantitative data, (2) leveraging dynamic models, (3) relying on flexible assessment frameworks, and (4) explicitly characterizing uncertainty (Figure 1). While some of these critical elements have been implemented in some CVAs (e.g., Boyce et al., 2022), the elements have yet to be widely adopted. By including these elements, next-generation CVAs can more readily support a dynamic and adaptive approach to ocean management and bolster climate readiness and resilience in fisheries.

USING QUALITATIVE AND QUANTITATIVE DATA

Climate vulnerability assessment frameworks can be broadly split into those that are quantitative and those that are semi-quantitative or qualitative (Figure 1). Qualitative or semi-quantitative approaches often use rankings by experts—primarily scientific experts (e.g., Hare et al., 2016). A strength of expert-driven CVAs lies in their ability to capture diverse expertise and perspectives and to assess all species or fisheries of interest, even in data-limited contexts. However, relying on expert opinion may increase uncertainty due to the inherently subjective nature of such input and the varying pool of experts from one CVA to the next. Expert knowledge elicitation has also been shown to speed up the development of CVAs across various sectors, including agriculture, biosecurity, and fisheries (Hadjigeorgiou et al., 2022; Hare et al., 2016; Hossain et al., 2023), as knowledge gaps can be filled relatively quickly without the need for additional data collection. However, if sufficient data are available (or can be borrowed from oceanographically similar regions or related species), data-driven CVAs may be updated simply by iterating a computational workflow, perhaps between more detailed expert-driven assessments, and thus can enhance the utility of CVA outcomes in the context of dynamic ocean processes and their ability to inform rapidly evolving management needs.

Recently, some CVAs have begun to use more quantitative approaches driven by empirical data and integrating state-of-the-science advances (e.g., Boyce et al., 2022), similar to the rapid advances in climate modeling (e.g., Ross et al., 2024). Quantitative approaches offer the benefit of greater reproducibility and more data-driven vulnerability evaluations and can apportion total climate vulnerability by life history stage, climate stressor, and environmental process. As such, data-driven, quantitative approaches can provide rapid, cost-effective, and comprehensive vulnerability assessments for many species (Boyce et al., 2022).

Qualitative, experiential data have long been integrated into CVAs in the format of expert opinion from scientists (Morrison et al., 2016). Increasingly, CVAs and other similar efforts have also considered knowledge generated by local communities and Indigenous peoples about their environment and the relationships between people and that environment (Li et al., 2023). Efforts to understand and include local and Indigenous knowledge in CVAs require a sustained commitment to understanding the specific knowledge and experience of Indigenous communities (e.g., Charlie et al., 2022; Proverbs et al., 2021) and recognizing that these knowledge sources have been undervalued, marginalized, and often ignored in ecological analyses. However, local and Indigenous knowledge may be critical to detecting deviations from baseline conditions or long-standing

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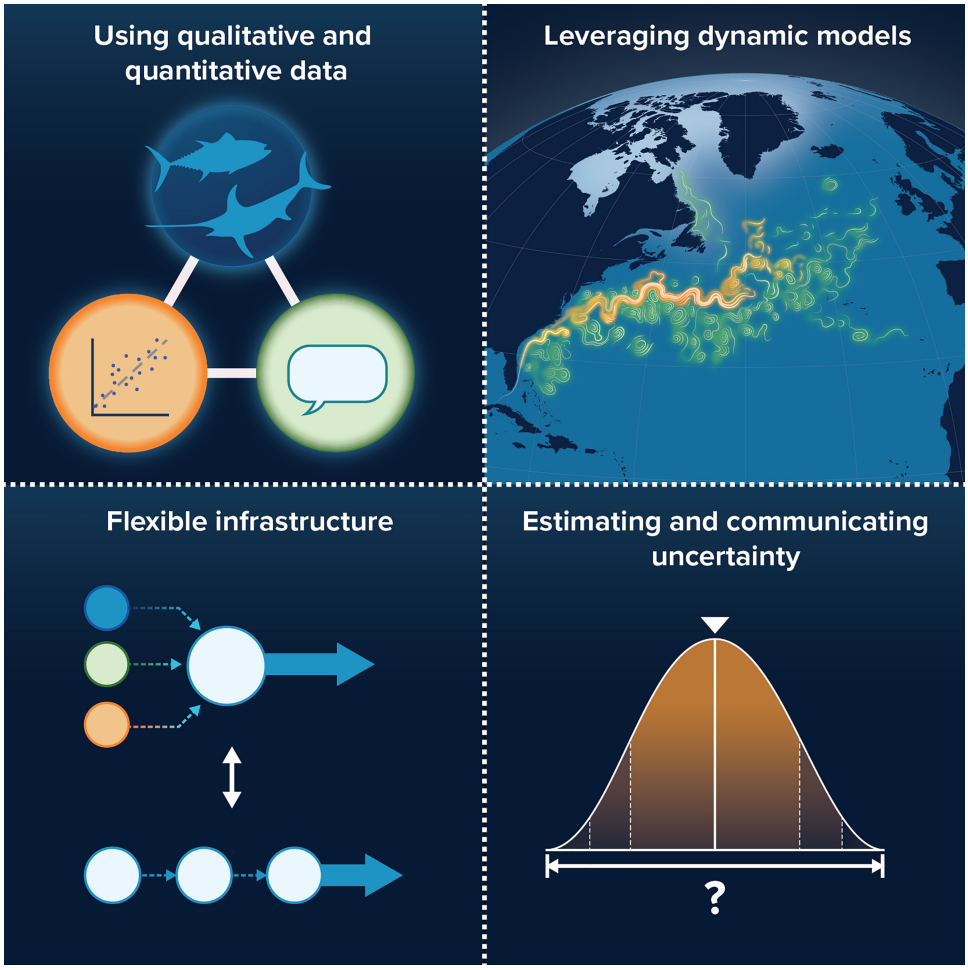

Figure 1. The four critical elements for a next generation of climate vulnerability assessments for fisheries: integrating multiple data types, leveraging dynamic models, flexible and adaptable frameworks, and capturing and communicating uncertainty. These criteria build on recent research advances cited in the text.

patterns, especially at local scales that are not well resolved by global climate models, thus providing unique insights into system dynamics (Riedlinger & Berkes, 2001).

Beyond the norm of acquiring qualitative vulnerability classifications, experiential data may be quantitatively leveraged in CVAs by, for example, informing variables to test in predictive fish and fishery distribution models, establishing a weighting scheme for components of model ensembles, deciding on informative priors for key parameters undergoing estimation, or determining necessary facets of climate-informed, social–ecological system models (e.g., Hollowed et al., 2025; Kuhnert et al., 2010). Experiential data from traditional Indigenous knowledge and expert opinion could also be specified as a prior belief in a Bayesian modeling framework (Kuhnert et al., 2010; van de Schoot et al., 2021) and then integrated with quantitative or empirical data. Ultimately, synthesizing the best available information from multiple sources of knowledge into a single framework may best capture climate vulnerability (Mills et al., 2023). This approach would allow more information to be used for characterizing vulnerability while retaining the flexibility to update the CVA as new information becomes available.

LEVERAGING DYNAMIC APPROACHES

Traditional CVA approaches have relied on spatially and temporally static representations of species distributions despite their goal of understanding and managing climate-driven changes to fish stocks in a dynamic ocean. There is an opportunity to leverage a growing suite of dynamic management tools that align scales of management, species movement, and fisheries footprints to support climate-ready fisheries (Figure 1; Hazen et al., 2018; Lewison et al., 2015). Species distribution models can be a powerful tool for predicting patterns of species' occurrence or abundance based on ocean conditions and underlying species ecologies. Over the past decade, species distribution models have expanded to account for rapidly changing ocean dynamics and have been used to understand species' vulnerabilities to climate change (Braun et al., 2023; Welch et al., 2023). Most species distribution model approaches use contemporary species–environment relationships to forecast how species distributions will likely respond to changing ocean conditions from episodic climate events like marine heatwaves (Farchadi, McDonnell, et al., 2025; Welch et al., 2023) to long-term warming (Braun et al., 2023), and these approaches can include species' innate sensitivities

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to change (e.g., metabolic oxygen demand; Muhling et al., 2017). Model predictions include several relevant metrics that can be directly incorporated into CVAs. These include quantifying changes in species range limits (e.g., leading and trailing edges; centers of gravity), range size (e.g., gain or loss of habitat), suitability of critical habitats at different life history stages (e.g., spawning and nursery areas), and shifts in spatial overlap between species and their prey and predators. There are also well-established methods for assessing model predictive skill given historical conditions (Thorson, 2019), the potential impact of novel environments (Allyn et al., 2025; Farchadi, Braun, et al., 2025), and the ability to predict complex physical–biological relationships under non-stationary conditions (Ward et al., 2022).

One of the advantages of leveraging dynamic model frameworks, such as species distribution models, in next-generation CVAs is that the outputs can provide spatially explicit estimates of climate vulnerability over multiple temporal scales. The inherent flexibility of these approaches supports vulnerability assessments that can accommodate a range of spatial and temporal scales, such as making daily (Hazen et al., 2018), weekly (Haflinger & Gruver, 2009), seasonal (Brodie et al., 2023; Hobday et al., 2016), or longer-term (Braun et al., 2023) estimates of species vulnerability. These analyses can also inform vulnerability assessments from small-scale, local fisheries (e.g., Carroll et al., 2023) to wide-ranging, multi-national fisheries that encompass multiple species and stocks (e.g., Giddens et al., 2022; Payne et al., 2022). While the dynamic spatial and temporal nature of the next-generation approach can easily become daunting (e.g., daily global predictions over the next century), careful decisions can be made about meaningful spatial and temporal extents and resolutions for the CVA itself and in how the results are ultimately summarized for actionable outcomes. For example, vulnerabilities can be summarized at relevant spatial scales (e.g., fisheries management units), life history stages, and time horizons (e.g., short, medium, and long term, spanning next season to the end of the century). The dynamic nature of this approach could provide specific vulnerability results for many species (Boyce et al., 2022), which can be regularly updated as new species–environment relationships are identified and as species-specific responses are better characterized. Ultimately, species' responses to their ocean environment are inherently dynamic and thus necessitate a CVA process and resulting metrics that can provide accessible representations and summaries of vulnerability over space and time that are responsive to stakeholder needs. Additionally, as novel data across oceanographic and socio-ecological systems are continually collected, more dynamic CVAs can respond and evolve based on this new knowledge.

FLEXIBLE AND ADAPTABLE FRAMEWORKS

Another critical design criterion for next-generation CVAs is to embody a flexible and modular framework that can be adapted to specific CVA needs and contexts (Figure 1). This flexibility could help to ensure that CVAs can accommodate the spectrum of "data-rich" to "data-limited" scenarios and prioritize accessibility, transparency, and reproducibility in the CVA process and its outcomes. A modular framework can comprise interoperable components, including data ingestion, indicator scoring, integration and weighting, and output visualization, which can be reconfigured depending on available information and management needs.

Practical analogs already exist in related assessment domains. The Integrated Ecosystem Assessment Program (NOAA) and the Ecosystem Approach to Fisheries Management (International Council for the Exploration of the Sea) use modular architectures that allow ecosystem indicators and vulnerability metrics to be updated as new data streams or models become available (Holsman et al., 2019; Payne et al., 2021). Similarly, tiered assessment frameworks, such as those developed for ecological risk assessments (Zhou et al., 2016), provide a scalable path from qualitative to semi-quantitative and fully quantitative tiers as data availability and analytical capacity increase. In some cases, flexible frameworks can be combined with participatory assessments to first identify potential vulnerability challenges and then re-engage the community to explore adaptation strategies and solutions (e.g., Benguela Current Large Marine Ecosystem assessment: Sowman, 2020). These systems demonstrate how flexibility can be built into the assessment process to ensure continued relevance and methodological consistency across diverse regions, species, and governance contexts while remaining inclusive and solution-oriented.

Flexible frameworks can also integrate multiple data sources, such as biophysical model outputs, socio-economic indicators, and experiential knowledge, through established statistical methods, such as Bayesian hierarchical modeling or decision analysis. For example, Boyce et al. (2022) used a hierarchical Bayesian framework to combine empirical data and expert-derived information within a single probabilistic structure to estimate species-specific vulnerability and uncertainty. Likewise, multi-criteria decision analysis approaches can weight and combine diverse indicators of exposure, sensitivity, and adaptive capacity to create integrated indices that are spatially and temporally explicit, linking dynamic species distribution models or Earth System Model projections with socio-economic data at management-relevant spatial and temporal scales (Champion et al., 2023). The result is a platform that can assimilate dynamic oceanographic and ecological data alongside human dimensions, producing vulnerability metrics that evolve with new information.

As a CVA aims to systematically measure responses to climate change, there are competing needs to use standardized metrics that allow cross-study comparison while also tailoring assessments to specific management objectives. Standardization of core metrics and procedures facilitates comparability across assessments and broadens accessibility for stakeholders, while the modular structure allows flexibility to adapt the CVA to local ecological, cultural, or management contexts. For example, CVA outputs can retain traditional qualitative ranks (e.g., from "low" to "very high" climate vulnerability) while also incorporating quantitative indicators of risk and magnitude of change to inform tactical decision making (sensu Boyce et al., 2024). Moving beyond a single qualitative vulnerability score across a species' range will ensure that next-generation CVAs highlight important spatial or temporal variability in vulnerability to provide information that is more directly applicable and actionable in fisheries management.

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The flexibility of the proposed approach explicitly promotes the concurrent development of both standardized vulnerability metrics that support interoperability across CVA efforts and products that are tailored to specific management needs. Under this next-generation framework, spatially and temporally explicit vulnerabilities of key target species can be developed into metrics that identify new fishing opportunities and adaptation pathways (Colburn et al., 2016) alongside standard vulnerability rankings. For example, indices that characterize the vulnerability of specific fishing ports to climate change (Rogers et al., 2019) could guide proactive management of emerging target and nontarget species, promote adaptive fishery portfolios, and inform flexible permitting and policy instruments that enable gear and species diversification (Fisher et al., 2021). These outcomes are hallmarks of climate-resilient, dynamic, and adaptive fisheries management (Lewison et al., 2015).

Finally, flexibility must extend to the iterative and computational dimensions of CVA design. The ability to update and iterate CVAs efficiently is central to the flexible structure and necessarily adaptive nature of next-generation CVAs. Computationally flexible frameworks that blend expert and experiential knowledge with empirical data can promote iterative assessments that are responsive to new information. The use of reproducible, script-based workflows supports transparency, encourages data reuse, reduces the need for repeated expert scoring, and allows assessments to be updated rapidly with minimal personnel time or resources. Together, these attributes—modularity, multi-source integration, standardization with adaptability, and iterative capacity—position flexible frameworks as the operational foundation for next-generation CVAs that are designed to support proactive, climate-ready fisheries management.

CAPTURING AND COMMUNICATING UNCERTAINTY

Central to robust next-generation CVA approaches is the ability to quantify and communicate uncertainty, as both are critical to guide climate-focused planning and decision making (Figure 1). Uncertainty is inherent to all systems and should be recognized as a key input to—not a barrier for—effective management. Within the flexible and modular frameworks described above, uncertainty can be systematically quantified, propagated, and updated as data and models evolve.

Uncertainty in CVAs arises from many sources (Monnereau et al., 2017), including the quality of input data, model structure and parameterization, emission scenarios, and temporal or spatial scaling. Flexible frameworks are particularly suited to addressing these challenges because their modular design allows different analytical approaches to be combined to capture distinct components of uncertainty. For instance, the hierarchical Bayesian models described above can integrate diverse data types within a single probabilistic structure and propagate the associated uncertainty through each level of analysis (Boyce et al., 2022). Ensemble and multi-model approaches (Tittensor et al., 2021) quantify structural uncertainty across alternative climate models or emissions pathways, while Monte Carlo and bootstrapping techniques can characterize statistical uncertainty in model outputs or vulnerability scores. Data fusion approaches allow experiential knowledge to be included as prior information or likelihood modifiers (Kuhnert et al., 2010; van de Schoot et al., 2021), enabling uncertainty to be quantified even when information is semi-qualitative. This connection between flexible architectures and probabilistic methods ensures that uncertainty is not ignored but instead becomes an explicit and transparent feature of the assessment.

Understanding and communicating uncertainty are equally critical. Many of the same modeling tools used to estimate vulnerability can generate spatially explicit estimates of uncertainty that identify where predictions are more or less reliable (Pennino et al., 2016). Ensemble and probabilistic visualizations can further illustrate the degree of confidence in future vulnerability hotspots or the relative influence of different drivers (Brodie et al., 2022). Clear communication of uncertainty enhances climate literacy among stakeholders and reinforces that uncertainty is inherent to all CVA approaches and should not deter proactive management (Kujala et al., 2013).

By embedding explicit uncertainty estimation and visualization within adaptable, iterative CVA frameworks, next-generation assessments will provide both best estimates and transparent confidence bounds. This integration strengthens the scientific credibility and usability of CVAs while supporting the development of resilient, climate-ready fisheries management strategies.

THE PATH TO INNOVATION AND IMPLEMENTATION

Despite the hundreds of peer-reviewed CVAs across marine and terrestrial systems (Foden et al., 2019; Li et al., 2023) worldwide and despite the extensive literature on species' vulnerability to climate change (e.g., de los Ríos et al., 2018), the potential of CVAs to support climate resilience in the form of fisheries management responses and actions has yet to be fully realized. We see several pathways to innovate both CVA development and the implementation and adoption of CVA findings in climate-ready fisheries and adaptive management. These pathways require diverse, data-driven, dynamic, and flexible CVAs that capture and account for uncertainty.

We envision next-generation CVAs that integrate different types of data (qualitative and quantitative) and experiential knowledge, representing a more holistic and comprehensive framework that aligns with a "two-eyed seeing" approach (Reid et al., 2021). Elevating multiple knowledge pathways can advance CVA implementation, as Indigenous and other experiential knowledge is often accrued based on daily observations and transmitted over longer time scales (Gadgil et al., 1993). Flexibility in data types can also facilitate vulnerability assessments in data-poor scenarios by using local ecological knowledge, such as from fishers (Carroll et al., 2023), or by parameterizing vulnerability attributes using knowledge or data from oceanographically similar regions or related species. Advances in computational capacity and approaches, including machine learning, make such a holistic and comprehensive approach to knowledge and data integration a tangible pathway to achieving a flexible, pluralistic approach to CVAs.

Climate vulnerability assessments typically yield a qualitative score to denote the degree of climate vulnerability. One of

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the central challenges in connecting CVAs to feasible interventions or management actions (i.e., the levers managers can pull to ensure that CVAs can support direct management) is ensuring that these efforts yield management-relevant and usable outputs. Current CVA frameworks often incorporate valuable expert opinion (Hare et al., 2016) or local knowledge (Carroll et al., 2023; Frusher et al., 2016) that could be integrated with the latest quantitative distribution or climate data to maximize the impact and applicability of these assessments for management action. Some precedent already exists for building a more comprehensive framework that involves synthesizing quantitative data with expert and traditional knowledge (Boyce et al., 2022; Champion et al., 2023), thus facilitating reproducibility and the tracking of changing vulnerability through time. Integrating the latest climate science and climate data as the backbone for CVAs is critical to ensure that CVAs incorporate the "state of the science." For example, recent CVA applications that were built on the latest global climate model outputs (sensu Boyce et al., 2024) illustrate the utility and importance of this integration to evaluate spatially explicit climate risks, which may be necessary to create on-ramps for CVA-driven fisheries management and conservation decisions and actions. Downscaling global models in key regions can further advance and represent important regional dynamics, such as upwelling and boundary currents (e.g., Ross et al., 2024), and, when available, can help to account for uncertainty in model-based representations of the future ocean.

Climate vulnerability assessment frameworks that link ecological and socio-economic systems in a cohesive assessment will also be better suited to support specific, climate-informed fishery management policies (e.g., rebuilding plans, allocations, and governance) and can focus attention on success across multiple bottom-line outcomes (e.g., ecological, economic, and social; Anderson et al., 2019). These integrated CVA approaches reflect the complexity of climate change impacts (Rogers et al., 2019). For example, research efforts have identified climate vulnerabilities and opportunities that could be integrated into a CVA framework to shift fishing effort distribution away from vulnerable species (Hazen et al., 2018) or toward emerging fishing areas at critical time periods (Fisher et al., 2021). For example, NOAA's ground-truthed community social vulnerability indicators for coastal communities along the U.S. East Coast and Gulf Coast provide quantitative indicators of social vulnerability and fishing dependence that can be integrated into a CVA framework to better account for the socio-economic consequences of these same climate impacts (Colburn et al., 2016; Griffith et al., 2015). Similar CVA-relevant socio-economic indicators are available in many nations and for a variety of fisheries (e.g., India: Senapati & Gupta, 2017; Brazil: Martins & Gasalla, 2020). Climate vulnerability assessments could also be used to develop sustainable and proactive fishing practices and to inform management response to species distribution changes across national and international management units (Cochrane et al., 2020; Pinsky et al., 2018).

These critical elements for a next-generation CVA framework build on and amplify knowledge from the existing CVA literature to outline a flexible approach for assessing relative and absolute climate vulnerability that can be used in risk assessment. The next-generation CVA approach (1) enables evaluation across a species' geographic range in a spatially and temporally explicit, quantitative, and reproducible manner; (2) can be flexibly applied at scales from local to global across a range of data quality scenarios; (3) can incorporate new information as it becomes available; (4) is transparent; and (5) evaluates the statistical uncertainty of estimated vulnerability and its components. This next-generation CVA vision also aligns with ongoing governmental efforts, such as NOAA's National Climate Science Strategy and Climate, Ecosystems, and Fisheries Initiative; Australia's Climate Adaptation Program; and Denmark's Sustainable Management of the Sea and Fisheries Scheme, which aim to provide managers and decision makers with actionable information and the capacity needed to prepare for and respond to changing ocean conditions. These initiatives need next-generation CVA approaches to operationalize decision support, reduce climate impacts on socio-ecological systems, increase resilience, and help communities adapt to changing ocean conditions.

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Data sharing is not applicable to this article.

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CONFLICTS OF INTEREST

None declared.

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