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Assessing and reducing vulnerability to climate change: Moving from theory to practical decision-support

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ABSTRACT

As climate change continues to impact socio-ecological systems, tools that assist conservation managers to understand vulnerability and target adaptations are essential. Quantitative assessments of vulnerability are rare because available frameworks are complex and lack guidance for dealing with data limitations and integrating across scales and disciplines. This paper describes a semi-quantitative method for assessing vulnerability to climate change that integrates socio-ecological factors to address management objectives and support decision-making. The method applies a framework first adopted by the Intergovernmental Panel on Climate Change and uses a structured 10-step process. The scores for each framework element are normalized and multiplied to produce a vulnerability score and then the assessed components are ranked from high to low vulnerability. Sensitivity analyses determine which indicators most influence the analysis and the resultant decision-making process so data quality for these indicators can be reviewed to increase robustness. Prioritisation of components for conservation considers other economic, social and cultural values with vulnerability rankings to target actions that reduce vulnerability to climate change by decreasing exposure or sensitivity and/or increasing adaptive capacity. This framework provides practical decision-support and has been applied to marine ecosystems and fisheries, with two case applications provided as examples: (1) food security in Pacific Island nations under climate-driven fish declines, and (2) fisheries in the Gulf of Carpentaria, northern Australia. The step-wise process outlined here is broadly applicable and can be undertaken with minimal resources using existing data, thereby having great potential to inform adaptive natural resource management in diverse locations.

1. Introduction

Understanding vulnerability to climate change provides insight into which parts of social-ecological systems are most likely to change, what is driving this potential change, and how conservation and management actions can minimise impacts and maximise resilience. Assessing the vulnerability of species, ecosystems and resource-dependent industries to climate change is a critical step to identify effective adaptations and prioritise management that enhances resilience. Vulnerability is the degree to which a system or species is susceptible to, or unable to cope with, the adverse effects of climate change [1], and depends on exposure (extrinsic factors), sensitivity and adaptive

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capacity (intrinsic factors). The Intergovernmental Panel on Climate Change (IPCC) has provided an approach to understanding vulnerability and its elements that has become a universally recognised vulnerability assessment framework [2]. In the IPCC framework, exposure and sensitivity determine potential impacts, which are tempered by adaptive capacity to yield vulnerability to climate change.

In this framework, exposure is defined as the degree to which the component assessed (e.g. species, ecosystem or resource-dependent industry or community) is likely to experience climate change at the local scale, given their preferred habitats, ranges, behaviour and mobility. Sensitivity is the degree to which a component can be directly altered by a change in climate or indirectly altered, for example, by a change in a species' habitat. Adaptive capacity is the potential to reduce exposure or adjust sensitivity so as to maximise fitness and moderate or cope with the detrimental effects of climate change [1]. These terms are commonly used when assessing vulnerability and are consistent with existing approaches [see 3,4,5]. Assessing the vulnerability of complex socio-ecological systems (SES) to climate change can identify effective adaptation options and help construct targets for resilience-based management [6].

There has been an evolution in thinking on climate change vulnerability over the last 15 years [7–9] and a range of approaches to assess vulnerability have been proposed and applied [e.g. 4,10,11,12]. Central to all existing approaches is understanding and accounting for the complexity and uncertainty associated with: climate change and other global stressors, the integration of social and ecological data, and SES thresholds of change [13]. These are multi-faceted challenges typically addressed with resource-intensive methods that require significant data and/or expertise, e.g. multi-dimensional models [14], fuzzy cognitive mapping [15], paleo-ecological reconstructions or scenarios as proxies [16]. Management uptake of these approaches has been limited, creating a niche for a relatively simple, robust semi-quantitative approach to assess vulnerability to climate change.

In response, criteria-based approaches have emerged that use indices for social and ecological factors or 'indicators' and then integrate scores or classifications for indicators to produce a relative assessment of either vulnerability or resilience [17–21]. In addition, for many developing countries, although national assessments of vulnerability to climate change are available they cannot be easily downscaled and localized assessments that provide species-, community- or location-specific information are required.

2. Method

The framework described here for semi-quantitatively assessing vulnerability to climate change builds on this recent thinking to provide a framework for local assessments. The framework has evolved through applications by the author team to ecosystems [22–24], national industries and economies [25,26], fisheries [17,27,28], resource-dependent communities [20,26,29], and aquaculture [30]. This evolution has refined techniques for identifying and selecting indicators and for quantifying ecological responses. The result is a broadly applicable assessment framework and step-wise process, and a practitioners guide is provided in the Supplementary Material. The process uses available data and expert judgment to generate results on relative vulnerability for practical decision-support targeting management and conservation.

2.1. Semi-quantitative assessment method

The semi-quantitative assessment (SQA) method involves a customisable 10-step process that directs the assessment focus and application of results, particularly for targeting management (Fig. 1). Glick et al. [31] outlined the key steps for assessing vulnerability to climate change, with the vulnerability assessment results informing broader adaptation planning. Building on this concept, the SQA method presented here includes clear steps to assess climate change vulnerability (steps 2–8) as well as applying results to inform adaptation (steps 9 and 10). All 10 steps may not be applicable in all circumstances, and selecting which steps to complete is part of customising the process to the study context. In particular, 'review and reassess' (step 8) may not be required depending on the results of the sensitivity analysis. Similarly, 'prioritisation' (step 9) may be skipped if the selection of components (in step 2) already considered values and importance. The SQA method is designed for application by decision-makers seeking transparent support for managing natural resources, conservation areas, community-based actions and climate change impacts (see practitioners guide in the Supplementary Material). Including participation by local experts, stakeholders and communities throughout the process ensures the results are robust and maximises uptake, delivering direct translation to management actions [32,33].

The described framework has already been applied by tailoring the 10 steps to assess the vulnerability of ecosystems and communities in tropical SES's. Two of these applications are summarised in detail as case examples of applying the 10 steps: (1) Pacific Island food security from fisheries [17,25]; and (2) Gulf of Carpentaria fisheries [28], in Section 3 and a third application – Torres Strait fisheries [20] – is used to demonstrate the method in each step of the SQA method and in Fig. 1.

2.1.1. Step 1: set management objectives

This step involves managers and stakeholders determining the core objectives and scope of the assessment and how the results will inform decision-making. The objectives will determine the management needs, scale (spatial and temporal) of the assessment, components to be assessed, and ultimately the focus of any identified management actions. Determining the scale of the assessment includes which climate projections and impacts are most relevant for the management objectives, in terms of future timeframes and emissions scenarios. For example, the objectives of the Pacific Island food security SQA were to identify: (1) which nations were most vulnerable to climate-driven declines in fish supply by 2035 under a high emissions scenario, and, (2) which fisheries adaptations can support filling the gap between demand and supply [17,25].

2.1.2. Step 2: set vulnerability assessment focus

This step involves selecting the SES components to assess (e.g. species, habitats, resource-dependent industries or communities) and the type of sensitivity analyses to conduct in partnership with local experts and stakeholders. This step also requires identifying situation-appropriate indicators and criteria. The case applications outlined in this paper used a workshop brainstorming session to choose a representative suite of components that are relevant to the management objectives. The selection can be based on specific criteria, for example: (1) conservation, social, economic and/or cultural importance; (2) known or expected sensitivity to climate change; and/or (3) data availability [28]. A review process with a wide group of stakeholders is used to validate the selected list of components to assess. Stakeholder engagement should be as inclusive of different stakeholder types as possible but guided by the stakeholders likely to be most affected by climate change, similar to that described by Heenan et al. [33].

2.1.3. Step 3: identify and select indicators

The SQA uses known biology, ecology and responses to climate variation to develop a series of indicators for: (i) exposure, (ii) sensitivity and (iii) adaptive capacity. Indicators for exposure are based on climate projections. Sensitivity indicators are based on known tolerances or responses to environmental variables [e.g. 27]. Indicators for adaptive capacity are based on research that identifies which characteristics (or traits) of species/systems support recovery and ultimately confer resilience [e.g. 34–38]. The exposure, sensitivity and adaptive capacity indicators for assessing vulnerability should be customised to the spatial and temporal context, and the components being assessed (see Table 1 for example indicators). Relevant and appropriate indicators can be identified using known responses to climate drivers, or expert judgement. Indicators are generally more situation-appropriate if developed and reviewed with local experts [13] to develop a final suite that are applicable to the components being assessed.

Exposure indicators are based on the specific environmental variables predicted to be important for the components being assessed, and the criteria for scoring these are developed to reflect the local or regional conditions (see step 4). Appropriate indicators for exposure will depend on whether the assessment is focusing on coastal, marine or terrestrial species, a particular industry or a resource-dependent community. For each emissions scenario used (e.g. 2030 RCP8.5), the exposure indicators are developed specifically for the model projections that corresponded to that particular future scenario and location. For example, the assessment of Pacific Island food security included exposure indicators for 'reef fish available (kg) per person per year', and the 'expected shortfall in fish (kg) per person per year' (see Supplementary Table 2).

Sensitivity is complex to conceptualize because part of a species' or system's response to exposure to the effects of environmental change can be attributed to the extent of its environmental specialisation [39]. Pecl et al. [27] provide a detailed explanation of the development of sensitivity indicators for temperate fisheries based on different aspects of species' population and life history characteristics likely to be affected by climate change – abundance, distribution and phenology. For habitats, resource-dependent industries or communities, sensitivity indicators are based on known responses and tolerances to environmental variables or dependencies on environmental services. Sensitivity indicators applied in the Gulf of Carpentaria fisheries SQA include 'reliance on environmental drivers' and 'early development duration (dispersal capacity of larvae/young)' (see Table 1).

Adaptive capacity (AC) includes two facets: the ability of species or habitats to cope with changes (ecological or autonomous adaptation), or the ability of resource-dependent industries and communities to cope with or influence changes (socio-economic or planned adaptation). AC indicators are developed for both of these facets. However, vulnerability assessments of ecological components of a system can focus on indicators related to governance and management of pressures, as these will influence responses to disturbance and recovery. On the other hand, assessments of resource-dependent industries and communities should include indicators that encompass the adaptive capacity of people, industries or communities. Such indicators will significantly influence how people and communities adjust to and persist in the face of change. Possible indicators include measures of ecological status – fishery stock status or replenishment potential (see Table 1) – or social indicators of health, education, economy size and governance (see Supplementary Table 1). It is particularly important that industries and communities that will be affected by changes be involved in the development of appropriate socio-economic indicators [33].

2.1.4. Step 4: define criteria for scoring indicators

Criteria are developed for scoring each indicator taking a risk-based approach using ecologically relevant triggers and relationships. Ideally, categories for scoring each indicator are empirically based. However, known thresholds for such criteria are rare and expert-based thresholds are usually required. The low-medium-high scale used in this SQA scoring system reduces a common tendency to focus on having 'precise values' for each attribute. This is especially helpful when data are limited, and allows the system to be used by a wide range of experts [e.g. 27]. Indeed, the purpose of criteria- or trait-based approaches is to provide a rapid assessment of the relative vulnerability of a large number of species. Undertaking detailed quantitative analysis to

Table 1
A sub-set of the indicators applied in the Gulf of Carpentaria fisheries assessment to demonstrate examples for exposure, sensitivity and adaptive capacity indicators and the scoring criteria developed and refined during an SQA (Adapted from Welch et al., 2014).

INDICATORS		**Low=1**	**Medium=2**	**High=3**
Exposure (2030 A1FI/ RCP8.5 projections)	Sea surface temperature increase +0.3 to +0.9 °C	Adult spends <50% of time in surface (<25 m) waters	Adult spends 50–80% of time in surface (<25 m) waters	Adult spends 80–100% of time in surface (<25 m) waters
	Changing rainfall patterns & more extreme rainfall events	Spends no time in estuarine or freshwater habitats during any life history phase	Spends <50% of time in estuarine or freshwater habitats; no critical (larvae, juvenile, spawning) life history phase in these habitats	Spends >50% of time or has critical (larvae, juvenile, spawning) part of life cycle in estuarine or freshwater habitats
Sensitivity	Reliance on environmental drivers	No correlation to environmental variable	Weak correlation to environmental variable	Significant correlation to environmental variable
	Early development duration (dispersal capacity of larvae/young)	>8 weeks	2–8 weeks	<2 weeks or no larval stage
Adaptive capacity	Fishery stock status	Overfished or on the verge of overfishing	Undefined or fully exploited	Sustainably fished
	Replenishment potential	Late maturing (>6 years), slow growth or few young	Matures at 3–6 years, moderate growth or moderate numbers of young	Early maturing, fast growth or many young
	Fishery resource dependence	No alternate species and/or significant gear/modifications required to target other species	Some alternate species that could be targeted with minor gear/practice modifications	Multiple alternate target species that could be targeted without any gear/practice modifications

determine specific thresholds is not in the spirit of the rapid assessment approach and is usually time or cost-prohibitive. Consistent application of set criteria (see example scoring criteria in Table 1) is important as this avoids arbitrary classification into the low, medium, high categories. This is especially problematic when uncertainty is high (e.g. in estimating thresholds of response, see [14]). A weakness of the 3-point scoring system recommended (low-medium-high) is that there can be a 'central tendency' to the classifications, especially when based on expert-judgment; in that assessors often avoid the extremes (low and high). This can be avoided through, as describe above, setting and then *strictly* adhering to the criteria for the scoring classifications. Alternately, for a data-rich assessment, a 5-point Likert-scale system can be used, requiring criteria be set for 'medium-low' and 'medium-high', to avoid excessive use of the central tendency medium answer. In most cases, data availability and expert judgment will necessitate use of a 3-point scale only, emphasising the importance of the process of setting the scoring criteria.

The criteria for scoring exposure indicators are based on the likelihood of experiencing a change in that variable. Criteria for scoring sensitivity indicators are based on known relationships and tolerances and, for adaptive capacity indicators, scoring criteria are based on inherent resilience characteristics. In each instance, criteria have to be set that are inclusive of the full range of data or judgments possible for each indicator. This ensures there is no ambiguity when classifying the components into the agreed-upon relative scoring categories (i.e. low, medium, high) for each indicator. In step 4, criteria can also be set for two (i.e. low and high) or three (i.e. low, medium and high) classifications of confidence (or uncertainty) for each indicator. Such criteria could be based on the quality and quantity of quantitative data available or experts' confidence in their judgments. A side benefit of concurrent assessments of confidence/uncertainty when scoring is that it enables assessment coordinators to identify the components of the framework for which uncertainty is greatest. Consequently, lists can be readily developed of knowledge gaps and research priorities. Well-chosen criteria for indicator and confidence/uncertainty scoring provide a transparent and repeatable mechanism for scoring (example indicators and criteria are provided in Table 1).

2.1.5. Step 5: data collection

A key benefit of the SQA method is that it draws on and collates existing empirical data, including climatologies, projections, species and habitat thresholds and response, status and trends, demographics, available modelling and expert knowledge. There are three sources of data that can inform the assessment: (1) existing data, (2) expert judgment, and (3) critical data collection to filling knowledge gaps (if required). Structured expert elicitation offers a semi-quantitative way to estimate exposure, sensitivity and adaptive capacity [40], particularly when limited empirical data exists. Expert judgement is especially valuable when assessing the impact of climate change in data-poor areas. As described above, the level of confidence in scoring is determined by the quality and quantity of data inputs.

In some cases, it may be necessary to collect or re-analyse specific data that are essential for completing an assessment. For example, if the physiological thresholds for a key species are unknown, correlations between available biological and environmental data from similar species can fill this gap [28], or new data can be collected if it is deemed critical. Where data are lacking it is suggested that a category is scored higher (i.e. more sensitive to climate change, as per [27]) consistent with applying the precautionary principle and follows established risk assessment practice [e.g. 41].

2.1.6. Step 6: vulnerability metric: analysis and ranking

A vulnerability metric has been developed to quantify results so that SES components are systematically ranked based on their relative vulnerability to climate change. Scores are assigned for each indicator (from step 3) using a 3-point scale (or 5-point Likert scale) based on the criteria developed in step 4, and whereby low scores represent low vulnerability.

An index is calculated for each element (i.e. exposure, sensitivity and adaptive capacity) by averaging the indicator scores. Since interactions among the different assessment elements and the relative importance of different indicators are not well understood [35], indicators are generally given equal weighting. Also, the relative importance of each vulnerability element – exposure, sensitivity and adaptive capacity – can vary by region, and can be difficult to determine. For these reasons, the elements are given equal weighting except where it can be demonstrated that they should be differentially weighted.

The Potential Impact (PI) index is determined as the product of E and S Indices (PI=*S). The calculation of PI is based on the synergy (or multiplicative nature) of E and S since these factors interact rather than being additive. Although some analyses have used an additive approach [e.g. 18], the interaction of E and S are synergistic, and there is very little difference in the ranking outcomes between averaging (additive) and multiplicative approaches when estimating vulnerability using the same framework approach [35]. A comparative analysis using the Torres Strait and Gulf of Carpentaria data confirmed the Allison et al. [35] findings, and multiplying E and S scores has been used in the case applications presented in Section 3.

Since vulnerability is the degree to which a system or species is susceptible to or unable to cope with the adverse effects of climate change, the PI measured by the framework assumes a negative direction (i.e. high scores represent high potential impacts due to high exposure and sensitivity). However, some consequences of high E and high S can sometimes have positive outcomes for specific components. For example, skipjack tuna are projected to increase in abundance in the tropical eastern Pacific by 2035 due to high exposure and sensitivity to increasing ocean temperature, resulting in higher catches for fisheries in the central and eastern areas of the Western and Central Pacific Ocean [23]. To represent these potential positive effects, a 'Direction of impact' coefficient of −1 is applied only to components that are expected to benefit: $PI=(E^*S)^*-1$. This transformation inverses the PI score, resulting in negative vulnerability scores that are re-set to zero (low or no vulnerability), and eliminates spurious high vulnerability scores for components that will benefit.

Since adaptive capacity (AC) tempers exposure and sensitivity (i.e. high AC reduces vulnerability), the AC Index is standardized to a value between 0.0 and 1.0 (by dividing by the maximum score), and then inverted: AC index=1−AC.

The vulnerability (V) index is then calculated using the metric: $V=(PI\times AC\ index)+1$.

Due to the effect of standardization, 1 was added to avoid zero values, which could be misinterpreted as zero or 'no' vulnerability. Therefore, the species with the lowest relative vulnerability had a score of 1.00. The components are then ranked from highest to lowest relative vulnerability.

2.1.7. Steps 7 and 8: sensitivity analysis and review and reassess

A sensitivity analysis is conducted to determine the importance of the different indicators to the final vulnerability ranking. The sensitivity analysis identifies: (1) the indicators most influencing the rankings (overall), and (2) the indicators that have the most influence on the higher rankings, which are the components most likely to be targets for management actions. Each input (indicator) is systematically excluded to examine the effect on the output values (vulnerability ranking) using a bootstrapping approach. Data or expert judgments for the indicators most influencing the vulnerability rankings can be reviewed and re-assessed to maximise analysis robustness. For example, sensitivity analysis of the Torres Strait fisheries SQA results found that AC indicators were the most influential on vulnerability rankings. Five of nine AC indicators affected >50% of rankings, and influenced some movement of species between high and moderate vulnerability categories (referred to as category substitutions) (see Fig. 1). Consequently,

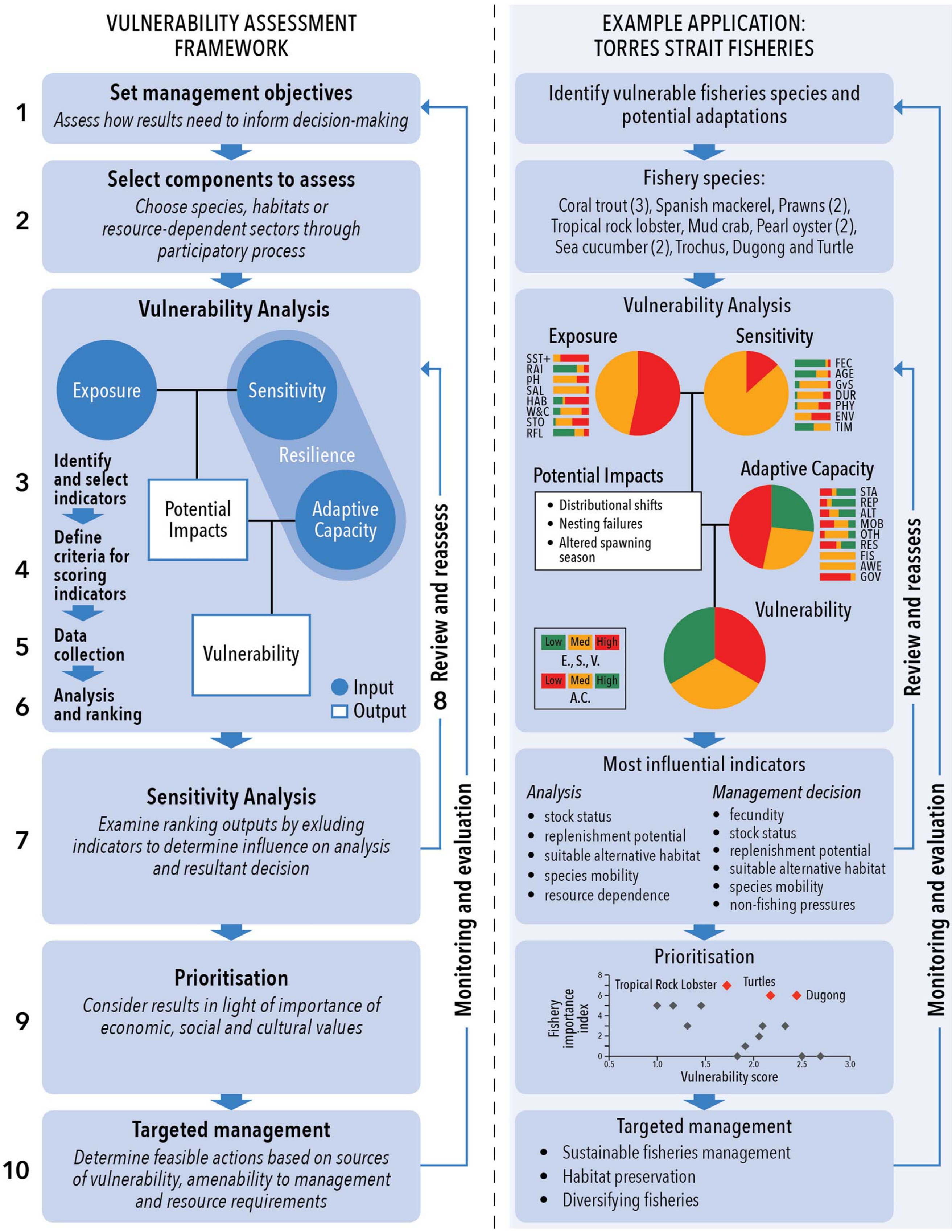

Fig. 1. (a) The 10-steps for applying the Semi-quantitative Assessment (SQA) method, and (b) Application of the SQA to Torres Strait fisheries, showing the results of each step (Welch and Johnson 2013, Johnson and Welch, 2015). The Torres Strait fisheries assessment objective was to identify which fish stocks and fisheries were most vulnerable to climate change under the A1FI SRES emissions scenario in 2035, to inform management actions and adaptation. Fifteen fishery species were assessed using E, S and AC indicators and criteria developed and reviewed by local experts. Low AC contributed significantly to high vulnerability of species. Indicators that most influenced the analysis results as well as possible management decisions were identified. After prioritisation based on economic and cultural values, three species were assessed as having the highest vulnerability: tropical rock lobster, dugong and turtles. Targeted management should focus on sustainable fisheries, marine habitat preservation (particularly seagrass), and diversifying species targeted by fisheries.

step 8 reviewed those data inputs for the Torres Strait SQA as a quality control step prior to finalising the analysis. Under Step 4, the value of concurrently assessing confidence/uncertainty when determining indicator scores is explained. It will be especially important to review and reassess indicators found during the sensitivity analysis to be strongly influencing rankings that also have low confidence/high uncertainty. This way, reviewing and reassessing can increase the robustness of the assessment and confidence among all parties involved that the assessment both reflects state-of-art understanding and objective assessments of uncertainty.

2.1.8. Step 9: prioritisation based on vulnerability results

The relative vulnerability rankings (i.e. outputs from Steps 2–8) identify the species, habitats or resource-dependent industries and communities with highest vulnerability to climate change. In many cases, components with high vulnerability will be priorities for management responses because a first step towards adaptation is reducing vulnerability and exposure to climate change [42]. However, relative vulnerability will rarely be the only consideration when prioritising components for management focus. The relative ‘importance’ of components should also be taken into account. Importance or ‘value’ scores can be calculated for each component using known conservation, economic, social, recreational and/or cultural values. The determination of values includes intrinsic values (e.g. conservation or culture) and therefore is not limited to fiscal calculations. This step requires stakeholder participation to determine values (particularly non-monetary values) specific to the location. The prioritisation step will adjust the rankings since components with high vulnerability scores combined with high importance scores are higher priorities for management or conservation. For example, in the Torres Strait, Johnson and Welch [20] plotted vulnerability against ‘importance’ for each component and used Euclidean distances to identify the highest combination of scores, and therefore highest priority components (species). In their SQA, dugong and turtle were ranked as the 3rd and 5th most vulnerable species but increased to the top two species after prioritisation as a consequence of their cultural importance as an indigenous fishery [24]. Further, weightings can be applied to different values as deemed appropriate in the calculation of overall importance values [see 20].

2.1.9. Step 10: targeted management

Managers can reduce climate vulnerability by reducing exposure or sensitivity or increasing adaptive capacity [43]. Step 10 involves

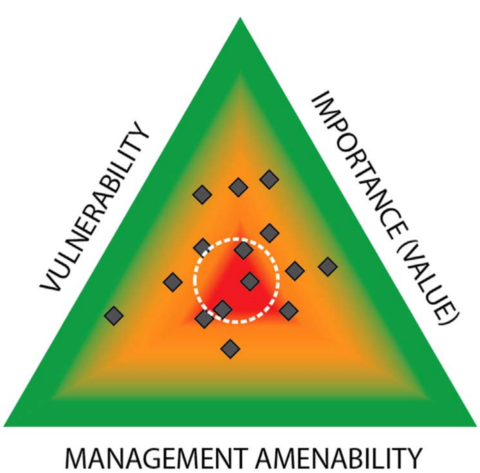

Fig. 2. Decision-support for selecting the assessment components for targeted management action. The centre (red) area represents components with high vulnerability to climate change, high importance (value) and high management amenability (cost effectiveness). Targets for management can focus only on those components circled or trade-offs among these three that are most aligned with management objectives.

managers and relevant stakeholders identifying the management actions most likely to reduce climate vulnerability. This is achieved by targeting the indicators from step 6 that contribute most to high vulnerability, focusing on components that were identified as high priority in step 9, and selecting actions that management can influence within reasonable resource requirements (Fig. 2). Additionally, the SQA may have identified indicators that are locally important and relevant but have high uncertainty. A key action for these indicators would be collecting essential data to enable a re-assessment. Step 10 includes monitoring and evaluation of the outputs against the management objectives (set in step 1) to assess the validity and performance of the assessment in terms of broader adaptation planning.

3. Results and applications

This SQA method has been applied to different ecosystems and communities in Oceania using steps customised to each study context. Two case studies are summarised below that provide contrasting applications of the method (further details for each study are available in the Supplementary material and references cited).

3.1. Case 1: vulnerability of Pacific Island nations to climate-driven food security issues

The vulnerability of 22 Pacific Island countries and territories (PICTs) to climate-driven declines in fish for food was assessed using the SQA method (Fig. 3) [44]. The objectives and focus of this SQA (steps 1 and 2) were to determine the coastal communities in PICTs where fish demand is projected to exceed supply by 2035 under the A2 SRES emissions scenario.

The SQA used situation-appropriate indicators for all assessment elements (steps 3 and 4) using data from an earlier phase that assessed fisheries vulnerability (step 5) (see Supplementary Tables 1 and 2). Exposure (E) was calculated using an index based on the availability per person (kg) of: (1) demersal fish, non-tuna nearshore pelagic fish and shallow subtidal and intertidal invertebrates in proportion to their contributions to the estimated production of 3 t per km^2 per year, and (2) freshwater fish based on current national catches [45], given future projected population growth. The availability of all reef-associated fish and invertebrates, and freshwater fish, was modified by the projected changes to their production under future climate change [17]. The resulting total availability of fish per person was then deducted from the 35 kg per person required for good nutrition to estimate the exposure of each PICT.

Sensitivity (S) was estimated as the recommended level of fish consumption for good nutrition (35 kg per person per year; [46,47]), or higher national levels of consumption where these occur [45,47].

Potential impact values (PI=E*S) were >1 and varied widely, so were normalized to range from 0 to 1, with higher values representing greater potential impact. No PICTs were expected to benefit from the average climate-driven changes and therefore the ‘Direction of Impact’ coefficient was not applied.

To assess adaptive capacity (AC), four indices were combined – health, education, governance and the size of the economy – on the assumption that PICTs with higher levels of human and economic development are in a better position to undertake planned adaptation. Health was estimated as a weighted combination of infant mortality rate (0.33) and life expectancy (0.66). Education was measured as the combination of the literacy rate for people up to 24 years of age (0.66) and the percentage of students enrolled in primary education (0.33). The World Bank governance index was used to amalgamate six equally weighted aspects of governance: political stability, government effectiveness, regulatory quality, rule of law, voice and accountability, and corruption. To indicate the size of the economy and purchasing power, parity GDP per person was used. The AC index for food security (the capacity of PICTs to adapt to shortages in the supply of fish) was

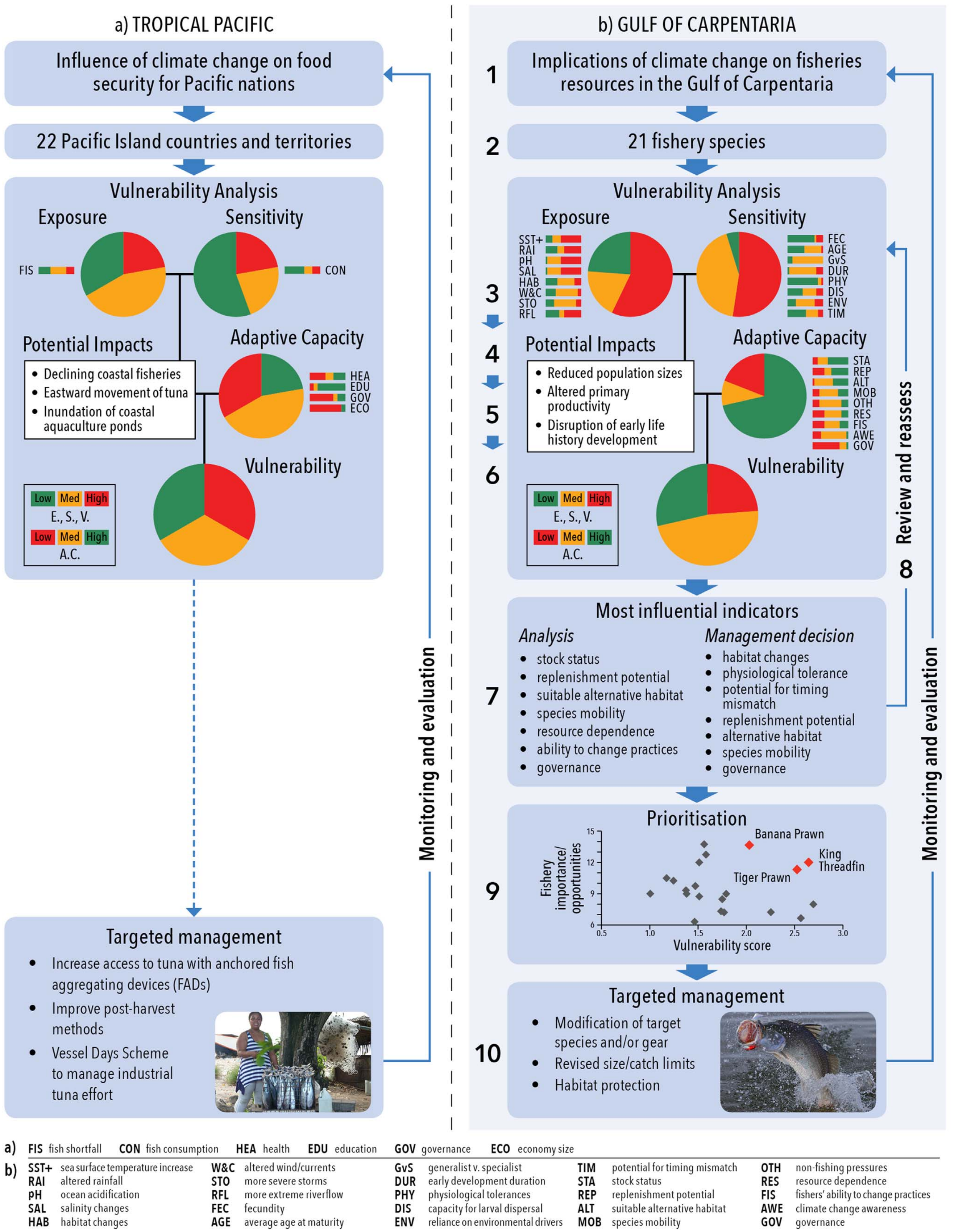

Fig. 3. Two contrasting case studies showing the application and results of the SQA method: (a) Pacific island countries and territories' vulnerability to climate-driven declines in fish for food security (Bell et al., 2011a, 2011b), and (b) Gulf of Carpentaria fisheries and supporting habitats. These example applications demonstrate how the SQA can be customised to the specific objectives and context of a study, and the steps tailored to address the management question.

estimated by weighting the values for the size of the economy (purchasing power) by 0.5, and the indices for health, education and governance by 0.167 (Supplementary Table 1). These weightings were based on the absence of plans to provide greater access to other sources of fish, thereby purchasing power plays a greater role in allowing individuals to acquire fish for food.

Nine PICTs were identified (of the 22 assessed) that will experience a gap between projected fish supply under future climate change and the recommended level of fish consumption for good nutrition (Supplementary Tables 1 and 2). Since all nine PICTs will require support to address this shortfall in fish supply, prioritisation (step 9) was not necessary to prepare a comprehensive suite of adaptations and policies for managers and governments [48].

The results have been disseminated through a participatory process with Pacific Island countries and development partners who have launched plans and initiatives to combat the food security problem (step 10). These include: the installation of nearshore fish aggregating devices to increase access by communities to tuna, protection and restoration of coastal habitats that support fisheries, distribution of bycatch and tuna from industrial fleets to urban areas, and improved post-harvest methods [26,44].

3.2. Case 2: vulnerability of Gulf of Carpentaria fisheries to climate change

The vulnerability of fisheries in the Gulf of Carpentaria under the A1FI SRES scenario by 2030 was assessed using the SQA method (Fig. 3) [28]. The project objective was to identify which fish stocks, and which fishery sectors, were likely to be impacted by climate change to prioritise species for action and identify potential adaptations (step 1).

The assessment of 21 fishery species targeted by commercial and recreational fishers (step 2) used E, S and AC indicators modified to the local context (steps 3 and 4) and assessed relative vulnerability using existing data and new data correlations (step 5) and the vulnerability metric (step 6). Generally, inshore species were assessed to be more exposed and sensitive to future climate change, and as a result the species in the inshore finfish fishery were ranked as having the highest vulnerability. Some species were identified that may benefit from climate change [28], with higher population sizes predicted due to projected increases in rainfall (e.g. banana prawns).

The sensitivity analysis (step 7) identified a suite of indicators that influenced both species' rankings and substitutions of the high vulnerability species, which are those most likely to be targeted by management. Eight indicators affected >50% of overall rankings, and seven indicators affected substitutions between the high and moderate rankings (see Fig. 3). Therefore, opportunities for future research should consider the information requirements for these indicators to enable a repeat assessment (step 8).

Prioritisation (step 9) resulted in a reduced focus on some inshore finfish species and an increased focus on highly valuable commercial species, such as tiger prawns. The assessment applied a highly participatory expert-driven process, with multiple structured expert elicitation sessions, and extensive stakeholder consultation during the final steps. The presentation of future scenarios to stakeholders allowed for identification of potential adaptation options (step 10). This proved to be an effective mechanism for delivering robust results and collective learning throughout the process, enabling a pathway for action through engaged stakeholders [28].

4. Lessons learned and future applications

Application of the SQA method presented here, as described above in the practical cases, has increased utility of the framework and method for management. There are considerations when implementing the approach that will maximise confidence in the results and focus outputs on management objectives. One general limitation of using indices and scores that should be considered before implementing this approach is that they do not provide direct measures of the expected impacts. That is, they do not quantify the magnitude of change (e.g. the size of range reductions or population declines, see [14]). If the primary management objective is to answer a specific hypothesis on the magnitude of change, then a vulnerability assessment of any kind is unlikely to be the appropriate method. All of the following are important to consider when implementing the SQA method: spatial scale of assessment, participation, weighting indicators, uncertainty and validation.

4.1. Spatial scale of assessment

A critical consideration when beginning a vulnerability assessment is to define attributes and the spatial and temporal scales of interest [49]. Place-based analyses that focus on a defined site or region but recognise nested scales and the dynamic nature of SES are recommended. The spatial scale of the assessment needs to be determined in step 1, and should assimilate scales of analysis with feasible scales of action. A limitation of multi-species climate change vulnerability assessments is that they can on occasion deliver spurious results for migratory species [50] or species with spatially extensive ranges. Application of this framework to such species should incorporate indicators and criteria (steps 3 and 4) that encompass connectivity and migration pathways. Conservation and migratory status are also considerations during prioritisation (step 9).

4.2. Participation

An integral part of this SQA method is effective participation with stakeholders, including decision-makers and communities, throughout the process. Effective participation maximises the quality of assessment outputs and uptake of results by stakeholders [33,51,52]. Thus, for the assessment to be successful it should: (i) draw upon diverse knowledge; (ii) be inclusive of all known perspectives; and (iii) build political will. Participation of stakeholders should be based on a human rights and human development approach to achieve gender equality, maintain relevant traditional customs and culture, and empower youth [53]. Improving the rigour and transparency of engagement with stakeholders during multiple steps of the assessment (e.g. in steps 1, 2, 3, 4, 6 and 9) will facilitate better multi-disciplinary integration and build support for the actions identified during step 10 (and beyond).

4.3. Weighting indicators

The SQA method outlined here and applied in different regions differentially weighted indicators in some cases. One benefit of criteria-based assessments is the ability to incorporate weightings if it is determined that some indicators are more important than others in determining climate change vulnerability. This is unlike trait-based assessments that typically do not include weightings [14]. Scientifically sound aggregation approaches that recognise and incorporate non-linearity and key drivers of vulnerability are essential for producing assessments that are valid and consistent [49]. The Pacific Island food security assessment provided such an application, where AC indicators were weighted based on known interactions between health and economic factors with adaptation of food security policy and communities. Expert participation provides an opportunity to determine if such weightings are necessary and which indicators and criteria should be weighted and how (steps 3 and 4).

4.4. Uncertainty

The most common sources of uncertainty in vulnerability assessments originate from the choice of criteria, parameterisation of thresholds of change, gaps in knowledge [54] and from assumptions of linearity in the relationship between indicators and vulnerability to climate change [49]. There is also a range of approaches for combining indicators (e.g. aggregated, averaged) and the weighting of these that would result in different outputs. The ordinal scoring approach described here, where particular characteristics are evaluated as increasing or decreasing the impacts of climate change rather than quantifying direct measures of vulnerability, addresses some of those concerns. By using science-based indicators and criteria applied consistently to all components being assessed, some of these sources of uncertainty can be addressed [49,55]. As examples, steps 3 and 4 should use qualitative and quantitative research when identifying indicators to reflect the processes that drive vulnerability to climate change and apply the scoring criteria consistently to minimise uncertainty. The sensitivity analysis and review (steps 7 and 8) aim to identify which indicators most influence rankings – reviewing and reassessing influential indicators for which confidence is low can help reduce uncertainty – this process emphasises the value of setting criteria for confidence scoring at the same time as setting criteria for indicator scoring (i.e. during step 4; as per [56]). Confidence scores can also be produced for each element index such as exposure or sensitivity [54], or for the final assessment results [56]. However, confidence scores are *most easily* developed as relative classifications of confidence or uncertainty (i.e. low, medium and high) for each of the indicators included, as described in step 4. Concurrently assessing uncertainty when determining indicator scoring increases the transparency of the results. This way, the final vulnerability classifications enable targeting of management actions to the major drivers of climate change vulnerability for which confidence is highest (or uncertainty is lowest).

4.5. Validation

Finally, validating the accuracy and precision of this SQA method is important for refining the approach and ensuring results are accurate and robust. Sensitivity analysis and review (steps 7 and 8) provide one avenue for checking if particular inputs (indicators) are especially influential and warrant further review. Comparisons of assessment results with observations, particularly under variable climate conditions, provide another avenue for validation. This type of validation is most appropriate during the monitoring and evaluation phase, where vulnerability results can be compared to the original management objectives (set in step 1) to verify if objectives are being met.

5. Conclusions

The SQA method described here overcomes many of the challenges of assessing vulnerability of complex SES, in that it can: (1) address specific conservation, socio-economic and environmental management objectives; (2) be implemented by decision-makers using available data and expert knowledge; (3) be customised to any context (spatial or temporal); (4) integrate social and ecological factors; (5) rank relative vulnerability of a range of SES components; (6) identify knowledge gaps critical to justifying actions or increasing analysis confidence, and (7) provide decision-support for managers enabling actions to be targeted to reduce climate vulnerability. The practical applications demonstrate the flexibility of the SQA method in that it can be applied to species, ecosystems or resource-dependent industries and communities anywhere. Once assessments are complete, they can be iteratively refined, particularly as new information becomes available. Through monitoring and evaluation, the analysis inputs and outputs can be regularly reviewed and the assessment repeated. This way, future assessments can either measure the progress made in reducing climate vulnerability and/or include new data or improved understanding of vulnerability drivers. Importantly, the results of a semi-quantitative vulnerability assessment can lead to a more transparent process for evaluating the trade-offs between short-term priorities and longer-term adaptation plans.

Data accessibility

All data for this paper and the semi-quantitative assessments are available in published reports available at ResearchGate (DOI 10.13140/2.1.4002.3846).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2016.09.024.

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