An integrated framework for assessing coastal community vulnerability across cultures, oceans and scales.

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1. INTRODUCTION

Across the globe, many coastal communities rely on marine resources for their food security, income and livelihoods and with predicted trends in human populations the number of people reliant on these resources is likely to increase (FAO, 2012). However, the effects of climate change including increased variability are already being experienced by coastal communities and appear to be accelerating (Doney et al., 2012). Depending on a range of factors, including location, these changes are having mild to severe impacts on communities both in direct and indirect ways (Miller et al., 2010). Communities in coastal areas, for instance, are particularly at risk due to sea level rise but also through their dependence on marine resources that are impacted by multiple climate change pressures. A change in the availability and condition of marine resources has consequences on the livelihoods of fishing populations or those who depend directly on fishing as a source of food (Badjeck et al., 2010).

Although mitigating climate change impacts remains the main priority in addressing climate change (IPCC, 2014), it is also important to develop adaptation strategies to climate change in locations where this is possible (Füssell and Klein, 2006; Young et al., 2010), particularly those already experiencing early effects (Hobday et al., 2016; Popova et al., 2016).. While mitigation is generally centred on changing behaviour at the national and/or global level, adaptation is a response that provides affected communities with a locally specific course of action. For a community to develop effective means to adapt to the effects of climate change, it is necessary to first determine and understand the vulnerability of that community (Adger, 2006; Norgaard, 2011). Once the vulnerability of a community is well understood, appropriate adaptation options can be developed through collaboration between local stakeholders, researchers and managers, and put into action through government and non-government institutions (Savacool et al., 2015). Recognising these dual stages (assess vulnerability and develop adaptation options) helps avoid a key criticism of vulnerability studies, in that they only determine the vulnerability of certain communities without providing the pathways and means to address the issues uncovered (Preston, 2012). It also reduces the chance of developing adaptation strategies that are ill-suited to the often complex social and ecological systems in which they are to be implemented.

Vulnerability studies, which have been used to address a range of research aims and have used a diversity of approaches, have attracted considerable scrutiny. The debate has centred around: measurement of an often imprecise or poorly defined concept (Füssell, 2007); delivery of a vulnerability score for a community that is relatively meaningless (Smit and Wandel, 2006); the aggregation of indicators to develop scores which can mask or overlook important factors that heighten or reduce vulnerability (Preston, 2012); assessments made at only one scale and then up- or down-scaled to make comparisons at other levels of complexity (Cutter et al., 2003), and; the high confidence placed in vulnerability mapping that is often performed using low-resolution secondary data (Preston et al., 2011). Often these studies leave policy makers and the communities that they serve unsure what these vulnerability results mean for their future livelihoods and overall sustainability, and what responses (if any) are implied.

This paper provides an improved framework for assessing the vulnerability of coastal communities across cultures, oceans, and scales, and suggests ways in which adaptation strategies can be conceptualized and implemented more effectively. In this context vulnerability integrates the qualities of being exposed to and sensitive to change in the marine environment and the degree to which adaptation strategies can counteract this. First, we describe an integrated vulnerability framework developed by members of the Belmont funded project known as

GULLS (Global Understanding and Learning for Local Solutions), emphasising its strengths in addressing key issues of cross country vulnerability comparisons and scaling up, and in providing a basis for integrated social and ecological modelling of climate change adaptation in the broader GULLS project. Second, we describe the unique manner in which the conceptual framework has been translated into a vulnerability analysis (through various ethnographic methods) and implemented in marine-based coastal communities across southern hemisphere countries, namely Australia, Brazil, India, South Africa, Madagascar, and Solomon Islands (Fig. 1). Finally, we provide a summary of results at the *country* level to evaluate the appropriateness of the new integrated framework and show its relevance and applicability. This framework was developed as part of a Belmont Forum multilateral-funded project (initiated in 2013 by the authors and various other colleagues [Hobday et al., 2016]) with the overall aim of addressing the issue of coastal community vulnerability more comprehensively and providing meaningful adaptation strategies to both policy makers and local populations in regions with relatively high exposure to climate driven changes in the marine environment.

FIGURE 1 GOES HERE

A unique aspects of the GULLS project is that it focuses on marine-dependent coastal communities in a number of *hotspot* countries, where coastal seas are warming faster than in other nations' marine areas. These marine hotspots are seen as priority areas for research as they are places where the effects of warming oceans are being observed and experienced first (Hobday and Pecl, 2014). These hotspot areas are in essence natural laboratories for biological and social change, and they provide valuable case studies for identifying generic and scalable measures and pathways of adaptation to the likely impacts of climate change for other coastal communities of warming seas in the near future (Pecl et al., 2014a). Distilling globally relevant learning outcomes from the GULLS case study countries is imperative, as many other locations may not have the capacity to carry out the level of preliminary research carried out as part of the GULLS project, due to lack of funding, expertise, political resolve or where the critical time frame for action requires immediacy.

A key component of the GULLS project was to collect rich, local level, social vulnerability data which would provide a fine understanding of the local scale processes influencing communities' vulnerabilities while allowing for the data to be scaled up to a regional, country, and global levels allowing integration with ecological and oceanographic models and comparisons among hotspot communities and countries. The vulnerability comparisons at the different scales, combined with the relevant ecological and oceanographic predictions, will provide accelerated learning mechanisms for communities likely to experience similar stressors and changes to their way of life in the future (Hobday and Pecl, 2014). Gaining new insights into marine social and ecological systems using different ecological modelling approaches combined with scalable social, economic, cultural and governance vulnerabilities will ultimately add to complex systems science (Berkes, 2006) and better prepare us for management of these systems in the Anthropocene. Conducting vulnerability assessments in this complex, multi-scale, cross-cultural context required development of a new conceptual vulnerability framework and implementation approach.

2. Existing Vulnerability Frameworks

There are a multitude of vulnerability frameworks reflecting different disciplinary backgrounds of vulnerability analysts and with different aims and objectives that are already available and in use (Cutter et al., 2003, Eakin et al., 2009; O'Brien et al., 2004; Adger et al., 2009). Each framework comprises different components including, for instance, risk-hazard models within geographical studies (Karim and Mimura, 2008), pressure-release models (Schröter et al., 2005) and social vulnerability/adaptive capacity models (Cutter et al., 2003; Vincent, 2004). The Intergovernmental Panel on Climate Change (IPCC, 2001) vulnerability framework has been utilised in many different studies as it comprises both ecological and social components and can be applied at a variety of scales from global to local. One criticism of using this framework alone centres on the potential to simplify adaptive capacity to economic components (Table 1). Other studies have tried to embed more nuanced social and economic components within the frameworks they have used. Allison and Horemans' (2006) study linked the Sustainable Livelihoods Approach (SLA) with the Livelihood Vulnerability Index (LVI) and had a strong emphasis on policies and institutions. However, for studies interested in the impacts of climate-induced change, this framework lacks any means to integrate climatic exposure and adaptation strategies. Another vulnerability framework is the Food Security (FS) framework (Table 1) which focuses on food availability and access. In isolation this framework often lacks meaning at the local level, and as such it tends to be used at higher (coarser) scales for regional and national decision making.

A number of studies have responded to the multi-dimensional nature of vulnerability in complex human-environment contexts by combining, or integrating, multiple frameworks. In the marine context, for example, Himes-Cornell and Kasperski (2015) developed an integrated vulnerability framework for analysing Alaska fishing communities that considered exposure through a rapidly changing Alaskan environment, rapid local resource dependence changes, and community adaptive capacity to climate change. Similarly, Colburn *et al.* (2016) developed a multi-dimensional framework to measure the vulnerability of US East coast fishing communities by analysing a series of new indicator under the context of climate change, and building on the National Oceanic and Atmospheric Administration's (NOAAs) existing Community Social Vulnerability Indicators (CSVIs). Allison et al. (2009) used the IPCC approach to estimate the vulnerability of national economies to climate-induced changes in the marine environment at the global scale. Metcalf et al. (2015) applied a similar approach to three geographically dispersed case studies in Australia. An integrated LVI and IPCC approach was used to estimate social vulnerability in a single region of Mozambique (Hahn et al., 2009) and a study of a specific urchin fishery in the USA (Chen et al., 2014). Cinner et al. (2012) also used an integrated IPCC/LVI approach in a regional comparison of vulnerability to climate change of communities in the Indian Ocean. Most recently, Mohan and Sinha (2015) combined IPCC and LVI frameworks to assess vulnerability to climate change in the Ganges River basin. However, to the best of our knowledge there has been no attempt made to develop an integrated approach to compare the vulnerability of coastal communities situated in different ocean basins characterised by different general climate norms, yet now all affected by warming oceans disproportionately (vis-à-vis other countries), and across countries with very different social, cultural, and development levels.

TABLE 1 GOES HERE

3. An Improved Integrated Vulnerability Framework

The vulnerability framework presented here (Fig. 2) comprises two high level components representing the biological and human subsystems. The framework allows for scaling up of the human vulnerability analysis to allow integration with change information available for the ecological system. The level of environmental exposure combined with the biological sensitivity of different marine species determines the ecological vulnerability in the ecological subsystem

(Pecl et al., 2014b). The ecological vulnerability, in turn, has a direct influence on the socio-economic subsystem. For instance, a crustacean species may be biologically very sensitive to warming ocean temperatures (see for instance Pecl et al., 2014b) and at its biological limit in a particular fast warming hotspot (thus making it ecologically vulnerable). In addition if the crustacean species is economically important for the local commercial fishery then the potential impact (in the human system) of climate driven change in the marine environment for this species will be relatively high.

FIGURE 2 GOES HERE

The potential impact in the socio-economic subsystem, aside from being influenced directly by the ecological characteristics of the system, is also defined by the dependence on marine resources of the people making up the socio-economic subsystem. Therefore resource dependence is part of the sensitivity component of the vulnerability framework which is not only defined in terms of economic dependence (often considered in isolation in developed countries and in many vulnerability assessments) but importantly also considers the level of social, historical and cultural dependence (which may be of importance in developing countries or where indigenous marine uses are relevant). Together, in the human system, exposure, resource dependence and adaptive capacity impact socio-ecological vulnerability (Metcalf et al., 2015). To provide a robust methodological approach for measuring vulnerability of marine dependent coastal communities to climate change that was applicable in countries with various levels of economic development, the sustainable livelihoods approach (SLA) forms the core element of adaptive capacity. An additional component of flexibility was incorporated to further refine the assessment of adaptive capacity (Fig. 2). The degree of flexibility across multiple scales (personal, occupational and institutional) through to institutional was included thereby better measuring people's and institutions' potential to influence their current situation and adapt to changing future conditions (Marshall and Marshall, 2007; Marshall, 2010).The proposed framework was not developed to directly assess risk (i.e., the possibility that an action or activity will lead to a loss or undesired outcome). However, risk is a component of the interactions of vulnerability, exposure and hazards (Oppenheimer et al., 2014) because vulnerability changes the probability that a risk will lead to undesirable outcome. Rather, the exposure to natural hazards was assessed in terms of household exposure (to storms, floods, droughts and shoreline changes), and it is thus also possible to evaluate risk using the proposed framework. The importance of considering vulnerability and adaptation together in the integrated framework is shown in Figure 2 with the development of adaptation options being informed by and in turn influencing both ecological and socio economic components.

Individual components within the exposure, sensitivity and adaptive capacity categories of the socio-economic subsystem were then further expanded to provide more detailed descriptors, or sub-components and measurable indicators (Fig. 3). The detailing of the sub-components allowed the team to develop a generalised survey instrument with individual questions. This research instrument provided information on each indicator, thereby allowing us to map the different components of the integrated framework (Fig. 3). The final framework comprised a total of 90 subcomponents, with 255 indicators providing the link between the conceptual framework (Fig. 2) and the survey methods that were developed and used across hotspot locations (allowing for comparison among hotspots at these higher levels). A link to the full survey can be found at http://gullsweb.noc.ac.uk/communitysurvey.php. Note that this conceptual framework not only emerges from the experience of GULLS members during this research but also from their prior work with issues surrounding coastal communities and vulnerability (e.g., Gasalla and Diegues, 2011; Shyam et al., 2014; van Putten et al., 2015; Aswani et al. 2015).

FIGURE 3 GOES HERE

4. METHODS

Comparative research into vulnerability is a crucial guide for resource allocation and policy, both at a national level and to aid international donor organizations (Vincent 2007). But since vulnerability assessments often remain ad hoc and use many indices, comparisons across countries and regions can therefore only be made with caution, especially since (due to the relative newness of vulnerability assessments using indices for adaptive capacity) researchers cannot yet be certain of the reliability of their chosen indicators to measure complex local realities (Vincent 2007). To overcome such uncertainty, researchers have to be transparent with their methodology. Also, it is important to move beyond offering a mere comparative snapshot of different communities' relative vulnerability and to expose the underlying dynamics of what constitutes this vulnerability (Thomalla et al. 2006). This entails the use of sophisticated statistical models in order to prevent data loss through aggregation. Such techniques in vulnerability studies were first introduced in the seminal paper by (Cutter et al. 2003) and later expanded to use non-parametric techniques (Hahn et al. 2009). However, to obtain truly comparative results vulnerability assessments must use the same indicators as different methodologies have been shown to generate significantly different results (Yoon 2012, Wirehn 2015). The necessity for broad-based vulnerability assessment (Bennett 2016) results in a proliferation of vulnerability indicators, each increasing the uncertainty that the indicators in question possess construct validity (Vincent 2007). As detailed below, to ensure that the data gathered would be truly comparative, the proposed framework and the survey instrument was constructed through careful collaboration and based upon best practice gleaned from the literature.

4.1. Producing a Survey

The first step to develop a survey methodology to establish the vulnerability of the coastal communities in the hotspot countries was to conduct a literature review and account for the weaknesses of typical vulnerability studies expressed in the literature (e.g., Preston, 2012; Preston et al., 2011; Füssel, 2007; Smit and Wandel, 2006; Cutter et al., 2003). In particular, to measure social vulnerability in different countries, the approach needed to be sensitive to local cultures and social contexts, both in terms of the process and the method used to gather the necessary information. Ultimately, the information gathered would need to be comparable between hotspots and the approach implementable across other (non-GULLS) hotspot and non-hotspot countries. The information needed to be generally comparable between locations, yet specific enough to make it possible to take into account the local context to identify ways and means for communities to adapt to their potentially common vulnerabilities or for different communities to learn from their unique differences. The methods developed as part of the GULLS project, therefore, were also designed to allow the social vulnerability analyses to be integrated with the GULLS ecological and oceanographic prediction and vulnerability research (reported in Hobday et al., 2016). Detailed primary data was collected for the social vulnerability analysis to ensure nuanced layers of human systems data fitted with the use of secondary data (or previously collected primary data) for the ecological and oceanographic modelling (Preston, 2012).

The second step was to develop a survey instrument and to field-test it in most participating countries. Field testing was carried out for approximately two weeks in each country and questions that did not produce reliable data were identified and subsequently improved or omitted. For example, during testing, the rating questions in the survey which use a Likert scale (with the typical strongly agree to strongly disagree continuum) were found to be difficult to interpret or answer by many participants. Rating questions were changed to item-specific responses to allow for clearer comprehension and in turn greater accuracy and reliability of the data collected (Saris et al., 2010). As an example, a question asked in testing was “Do you feel that you belong to this community?” and the respondent was asked to choose from “Strongly agree”, “Agree”, “Disagree”, “Strongly disagree”. Many respondents answered “Yes” or “No” despite the question format. This question was modified to give respondents a choice of “Strongly belong”, “Belong”, “Do not belong”, “Do not belong at all”. In sum, this pre-screening served to modify and streamline the survey instrument and allowed the individual country project teams to adjust questions to account for local circumstance, language, and understandings. Overall, more than 80% of the final survey questions were exactly the same across all hotspots indicating a flexible but, more importantly, a transferable method. In the less developed countries, for instance, an understanding of adaptive capacity was gained through questions about availability of electricity, water and sewage. These questions were not applicable in Australia, for instance, as the vast majority of people have access to these services. Overall, local level surveys in each hotspot country included at least one question from each sub category to ensure data spread across all domains of the framework (i.e., data on all of the subcomponents and indicators) and to ultimately ensure cross- country comparability (Fig. 4).

FIGURE 4 GOES HERE

Due to some further country differences including diverse resources and research person power availability, receptiveness of the target audience (due to survey fatigue), literacy rates, and access to online resources among the country hotspots, two different survey methods were applied (face-to-face and online surveys). The differences in sample size and proportion, research team size, field resources and interviewer training, language and use of translator services across the hotspot countries is shown in Table 2. For instance, the Australian researcher team conducted an online survey rather than a field-based household survey as adopted by the other countries. The web surveys were however unable to collect the large amounts of additional contextual data provided by informants in the field-based surveys. In South Africa, a single translator was used to conduct the household surveys, several translators were used in India, two in Madagascar, and four translators were used to perform the surveys in the Solomon Islands, whereas in Brazil and Australia *in situ* translators were not required. All translators were trained to use and carry out the survey before the data collection began. By developing the common framework and survey these differences could be accommodated, thereby ensuring the validity of future cross country comparison and analysis. This was challenging given that most countries involved in the research have both local and international researchers, spanning a wide range of academic experience and disciplinary backgrounds, yet this diversity of ideas, knowledge, networks and expertise enriched the research and discussions.

TABLE 2 GOES HERE

The sampling strategy consisted in ensuring comparability of estimated vulnerability across countries and agreeing in a uniform survey sampling universe (i.e. the groups/people to be sampled within the study community). The sampling universe was stratified to encompass randomly selected "people with regular interaction with the ocean". This meant the survey would not be limited to fishers (artisanal, customary, commercial or recreational) but could include anyone who interacted regularly with the sea. Note that industrial fishing was not included in our sampling universe as this would limit the comparability across all countries and sites. The unit of analysis for both the face-to-face and online surveys was the household randomly selected from a suitable and representative pool both in the pre-testing and in the final survey implementation. Household level surveys allowed detailed levels of information to be collected but was not as intensive as working at the individual level, especially when undertaken face-to-face. The target survey sample was made up of either members of a physical location (i.e. a coastal community or town) or members of a stakeholder group. Coastal communities were selected based on the following set of criteria: sites had to be "small" communities (<5000 inhabitants) and be marine dependent communities. To obtain a representative sample, the number of people interviewed differed between the two target audience groups due to their absolute size. For example, a stakeholder group can consist of, for example, only 50 members where a coastal community can contain a total of 5000 members. Survey samples in each coastal community were chosen to be representative (demographically) of the people who lived in that community. In the case of the survey sample for stakeholder groups (as in Australia where recreational fishers were targeted), the sample had to be representative of the total recreational fisher population.

In Brazil face-to-face surveys were conducted *in situ* in households of eight different coastal communities from the South Brazil Bight (SBB) coastal zone. The SBB corresponds to the most industrialized and urbanized region of the country but still shelters several traditional fishing communities. The selected sites represented a comprehensive sample of fishing communities, exhibiting a suite of different characteristics within the SBB. A total of 151 households were surveyed across the eight selected communities. Additional fishers' perceptions of climate and ocean conditions were also conducted based on the ethno-oceanographic framework (Gasalla and Diegues, 2011) and formed the basis for understanding exposure (Martins and Gasalla, 2017).

In India the research team engaged with local people from the respective communities (mostly educated and committed women and proactive college students) to conduct the survey. A pilot testing of the survey was carried out initially by the research team of the CMFRI institute, after which appropriate country specific modifications were made to the survey questions. First, the team developed relationships and rapport with the local self-government officials (Panchayath), line departments and women self-help groups within the communities by regular visits and focussed group discussions. The project inception took place in the village, which ensured active community participation in the survey process and acceptance of the project from the beginning. Second, each self-governed local district involved in the study educated local people for further training, prior to the implementation of survey. Third, the selected people were trained in topics covering climate change, vulnerability, sensitivity, exposure, adaptive capacity and resource management. They were also specifically trained in conducting household surveys among fishers. A total of 800 households were surveyed in the study across a number of communities.

Five different communities within the same coastal region of the southern coast of South Africa were chosen for the study. An important fishery in this area is the handline fishery performed by small crews of fishers on boats that leave from small harbours or river mouths. The sites consist of a spectrum of different size communities, proportion of households with regular interaction with the ocean and remoteness. The social vulnerability surveys were carried out by one researcher and a translator, as most communities speak Afrikaans. Extensive training of the translator was performed initially and then pre-testing of the survey was carried out to ensure accuracy of the translated survey in the local dialect as well as optimal understanding by survey participants. Overall, 65 surveys were conducted and following on from these, group focus sessions were carried out in each community to feed back some of the main early findings of the surveys.

In Australia, an online survey was developed to gather the vulnerability information because face to face interviewing was very difficult logistically (as people are spread out over a large region). The survey was applied to the recreational fishing community. The respondents were made aware of the survey using a social media site (Redmap) and a small incentive prize was offered for participation in the survey. The survey was aimed at people engaged with the ocean (as per the sampling protocol) but the large majority were recreational fishers in coastal communities of the south east of Australia which is the area that corresponds to the marine climate change hotspot area. A total of 56 useable surveys were obtained in this manner. A second call for recreational fisher participation was sent out to recreational fishers after the attempt to engage and survey commercial fishers was unsuccessful. The commercial fishing industry is the subject of many surveys in Australia and survey fatigue has become a serious problem for researchers. Even though engagement with the fishing sector occurs through government departments, engagement by research organisations and individual researchers often results in low response rates. Nevertheless, the recreational fishing sector in Australia takes a considerable portion of the catch, and participation is high in all States and Territories, at over 19.5% of the Australian population (Henry and Lyle, 2003)

The Solomon Islands, a non-hotspot country, was included in our study as a means of ascertaining the extent to which the GULLS social vulnerability survey could be applied in other countries. No pre-testing was done for the Solomon Islands region due to the high costs involved in travelling to the area, while complications such as a lack of printing facilities prevented the modification of the questionnaire on-site. However, a researcher with 27 years' work experience in the area and a complete grasp of two local languages modified the questionnaire to suit the specific environment. The second researcher received training in conducting the GULLS household survey from members of the South African research team in their field site prior to surveying in the Solomon Islands, which improved the reliability of the data gathered. Four educated translators with a grasp of the English language were used. Translators were trained to understand the point addressed by each survey question and agreed on the wording they would use when translating questions from English into the local language *in situ*. The response was then again recorded in English. A total of 110 surveys were completed for this region. Finally, Madagascar was surveyed by the same two researchers who performed the Solomon Islands survey. Pre-testing was again not possible due to the logistical complications of working in a remote location. The original survey text was first translated into French by two local students who then presented the questions in Malagasy to respondents, with the response recorded in English. A total of 48 surveys were completed between the two communities.

The presented framework was utilized for cross-cultural comparisons among the different coastal communities in the different hotspot countries. Not only did we make comparisons within each hotspot country across their different study sites but we identified interesting differences and/or similarities in vulnerability and adaptation patterns in countries where coastal communities have no clear contact or links. Including the Solomon Islands in this first application of the integrated framework provides an early indication of the transferability of the application of the survey method to non-hotspot countries. This created the potential for improved learning and adoption of effective adaptation measures from different places. In order to perform the statistical analysis, several questions were asked including: do commonalities exist across the chosen hotspots and do they manifest in similar ways? The survey approach developed in this paper allowed researchers to address the question as to what makes some communities more vulnerable than others to environmental change. The model's inherent flexibility while mapping back to a robust core framework allowed for quantitative and qualitative data to be collected, analysed, and compared within and among countries and regions.

4.2. Statistical Analysis

The total number of observation for all countries combined was 1,276 but accounting for incomplete observations, a dataset of 1,237 observations was retained. We restrict our survey data analysis to rating questions only and the variables for the current analysis are therefore *ordered ordinal*. For example, the survey question 'How difficult has it become to catch fish in the areas you fish?' has four levels: not difficult at all, not very difficult, somewhat difficult, and very difficult. The value of the rating question was between 1 and 4, with one being the better outcome and four being the worst outcome. Because some of the rating questions had 3, 5 or 6 possible categories, these were normalised to a value between 1 and 4 to allow for interpretive consistency. We report the results based on the average and median score for each of the components (we test for consistency and difference between the result using average and median scores). Our dataset has three characteristics which guide our use of statistical tools: the data is ordered categorical, not normally distributed, and the sample sizes are unequal (i.e. India's sample is larger than that of other countries). To determine statistical differences between countries we use nonparametric tests/distribution-free tests to account for a non-normal distribution and unequal sample sizes. In a nonparametric test the null hypothesis is that the two populations are equal, which is interpreted as the two populations are equal in terms of their central tendency. The test used to establish statistical differences between countries allows for unequal sample sizes.

We generated explanatory statistics such as samples means, medians, and standard deviation and test the data for correlation for all questions and within vulnerability categories. The Kruskal-Wallis Test was used to determine whether there are significant differences between hotspot countries with respect to rating the components for sensitivity, adaptive capacity, and exposure. Using the Kruskal-Wallis Test, we determined whether the population distributions are identical *without* assuming a normal distribution. The relationship between the vulnerability scores and the three categories can be visualised as indicated in Figure 5. For instance, if sensitivity or exposure are reduced (indicated by the inward facing arrows in b) in Figure 5 then vulnerability can be reduced. Alternatively, if adaptive capacity can be increased this will reduce overall vulnerability to change in the marine environment (indicated by the outward facing arrows in c, Fig. 5). Finally, we analyse country results in the context of socio-demographic characteristics (obtained from publically available dataset) to determine the relationship between the vulnerability scores and these social, economic, and demographic indicators and to gauge if country scores were significantly different. The following results are only an overview of our data at the *country level* to illustrate the applicability of this approach, as a more detailed analysis is presented elsewhere (van Putten et al. unpublished data).

FIGURE 5 GOES HERE

5. RESULTS

The countries included in this analysis are experiencing rapid change in the marine environment and their empirically derived sensitivity, adaptive capacity, and exposure gives insight into their relative vulnerability. Based on 80 survey rating questions applied in six different countries, coastal communities in Madagascar followed by India and South Africa are most vulnerable to change in the marine environment. Overall the difference in vulnerability to change in the marine environment between countries is statistically significant (Kruskal-Wallis chi-squared = 299.69, degrees of freedom = 5, p-value $< 2.2e-16$) (Fig. 6). The relatively high vulnerability of Madagascar is mainly attributable to Madagascar's economic dependence on marine resources making it very sensitive to change in the marine environment. Madagascar has high exposure (Fig 7a) caused by the number of observed changes and unfavourable perceptions and attitudes. The low adaptive capacity of coastal communities in Madagascar (Fig 7b) is caused by the low personal and occupational flexibility and limited physical capital. India is also vulnerable to change in the marine environment due to the high exposure (Fig 7a) that is mainly attributed to the high shoreline change and susceptibility to flood. The exposure of Indians coastal communities is not compensated for the relative low sensitivity (Fig 7c) attributed to the low attachment to the fishing occupation and intermediate adaptive capacity. The low vulnerability in Brazil is attributed to a high adaptive capacity and low exposure which compensates for a relatively high sensitivity due to a strong attachment to fishing and attachment to place. Several country characteristics were found to be highly correlated to the level of vulnerability. Government effectiveness was most highly correlated to country level vulnerability, indicating that a less effective government and high vulnerability tend to go together. Even though country characteristics are found to be related to the empirically derived vulnerability scores, it does not explain the highly complex relationship between coastal community sensitivity, adaptive capacity, and exposure to change in the marine environment that ultimately underpins their vulnerability (Table 3). Our framework, nevertheless, can down-scale to analyze community level sensitivity, adaptive capacity, and exposure and produce cross-community comparisons at the national level or cross-culturally.

FIGURE 6 GOES HERE

FIGURE 7 GOES HERE

6. DISCUSSION

Each of the examined hotspots is connected by the changes projected in the marine environment as shown by the general analysis. For further analysis, however, the hotspot communities analyzed in different countries have very different socio-economic and environmental characteristics. Therefore, in future analysis collapsing variables from the household survey into a small number of indicators or domains will need to be context specific. It is acknowledged that there are dangers in integrating local level indicators from such vulnerability surveys and aggregating data to allow for comparisons at higher levels. Yet aggregation is necessary to enable the rich local level data to provide further insight than only for a few selected communities. The proposed framework is flexible for the local contexts while maintaining important information that is consistent across all sites to allow for comparisons. The framework should be used as a tool to calibrate and validate regional to national level vulnerability assessments. The framework developed here gives us an opportunity to compare how the vulnerability assessment differs when estimated at different scales.

The framework can be used to merge a series of secondary datasets identified as indicator variables from widely available global data such as climate change projections, population projections, gross domestic production (GDP) and infrastructure data. Each component of the vulnerability framework can be aggregated from the gridded level to the hotspot and compared to the same components estimated from household surveys. This enables the research to begin considering the bias in vulnerability analyses performed on secondary data at the global level. Building on the survey the scaling up of results can be achieved through modelling and climate change scenario development and socio-demographic changes like population growth. This scaling up component creates a global gridded surface of marine and terrestrial exposure to climate change. The indicator variables selected for this purpose are correlated with food production and derived from the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification (MEDUSA 1.0) ecosystem model (Yool et al., 2011) and the Global Agro-ecological Zone (GAEZ) maximum potential yield of terrestrial crops under climate change (Fischer et al., 2012; Seo, 2014). The change from baseline to 2050 for each of the marine and terrestrial indicators can then be estimated. Since many coastal communities will also be engaged in other forms of economic activity such as agriculture a terrestrial exposure sub-component can also be estimated by comparing projected impacts of climate change on agricultural yields under different climate change scenarios. The LVI approach can then be used to collapse the marine and terrestrial sub-components into an exposure component. This can provide researchers with a modelled exposure component that can be examined in terms of the different climate change scenarios contained in the SRES/RCP.

The added benefit of the integrated framework is that the vulnerability analyses output can be integrated with ecological vulnerability analyses being conducted for each hotspot by the other GULLS working groups. This allows for integrated, interdisciplinary analyses to be conducted for each hotspot. It also provides the potential to compare social vulnerability and adaptive capacity across and within hotspots. The framework's flexibility also allows for the comparison of quantitative models as well as qualitative data from other studies in the same hotspot study regions. Some of the outputs of the social vulnerability analyses can be used as inputs to ecological models, but can then be used to test the efficacy of alternative adaptation options through simulation testing. This is achieved using locally available and developed models for each region, including models of intermediate complexity (MICE) (Plagányi et al., 2014), Ecosim (Christensen and Walters, 2004) and Atlantis (Fulton, 2010). For example, simple MICE models are being developed for each region, with a focus on a few key fishery species and the communities that rely on these resources, in order to dynamically simulate and test coupled climate-biological-human interactions and responses. The MICE models are validated by fitting to available data over the historic period and then projected forward using climate projections from a high resolution global ocean model with biogeochemistry run under RCP8.5 scenario (the highest IPCC AR5 CO_2 emission scenario) to year 2099.

A challenge for vulnerability analyses is ensuring an accurate in-depth assessment of vulnerability can be made at a scale that is relevant to decision makers. Although adaptation decision making occurs at many scales from national government down to individual households and this needs to be accounted for in vulnerability analyses (and in particular when designing adaptation options). Governance mapping has been undertaken in each hotspot which will subsequently be linked to the social ecological vulnerability data at different scales. Governance mapping is done through collection of formal laws, rules and regulations which map the top-down centralised maritime governance in each country. The social vulnerability survey and our

506 engagement with marine-dependent communities provides the data to map the informal rules and governance of the marine resources and coastal areas in the study sites

508 There are various analyses potentials and a key question in the analysis of data from vulnerability surveys is that of the appropriate weighting of indicators. The LVI framework provides a set of detailed guidelines for calculating a balanced weighted average composite index (Hahn et al., 2009; Mohan and Sinha, 2015). In the LVI approach, each indicator variable is standardized using the maximum and minimum values for the study population prior to being merged with all other indicators that contribute to a sub-component. The next step merges each of the sub-components that contribute to the relevant component using a consistent/standardized approach prior to using the components in the LVI equation. The approach used for the LVI means however that the estimates of vulnerability can only be compared to other estimates if they use the same method (Vincent, 2007). As highlighted earlier, the surveys conducted in each hotspot collected some consistent variables but others were adapted or removed from certain surveys. Furthermore, some surveys have had considerably larger numbers of respondents than others. Thus, the construction of vulnerability indices for each hotspot will have to be carefully considered to ensure that consistent and comparable results are derived. Indicators, sub-components and components may have to be weighted differently to the equal weighting used by Hahn et al. (2009) in order to estimate vulnerability in a consistent manner across hotspots.

524 The addition of terrestrial exposure to climate change is an important component for this analysis for two reasons. First, many of the coastal communities currently relying on fisheries are likely to have a series of livelihood strategies in which the household engages. Thus, whilst fisheries are an important aspect of livelihoods in the hotspots the impact of climate change on terrestrial food production may also play an important part in the vulnerability of the

communities. Thus, using the exposure components of land and marine will allow us to identify double hotspot regions (those that are projected to have high levels of exposure to negative marine and terrestrial change). Second, terrestrial agricultural production may provide an important adaptation option for some communities/hotspots. If this is not considered within the study in some way it is difficult to fully ascertain which communities/hotspots are likely to be the most vulnerable to climate-induced changes. The terrestrial projections of yield are based on different water supply options (rain-fed, irrigated) and different management options (High, intermediate and low intensity farming). Thus, providing a scenario system whereby the team can examine how a hotspot's vulnerability may change with a given development in agricultural input level or water supply system. The next stage will be to conduct group adaptation pathway development with each community to link with the outputs of the ecological and oceanographic GULLS models.

7. CONCLUSION

To develop a common methodology to compare social vulnerability across different communities, spanning multiple countries and ocean basins, an integrated yet flexible vulnerability framework has been developed. Not only it allows for robust comparisons of current and future vulnerabilities of coastal communities in different contexts to be made, but it avoids some of the typical shortcomings of social vulnerability research. It incorporates the social livelihood approach where other studies have only focused on the precepts of exposure, sensitivity and adaptive capacity which are not always easy to determine alone. Incorporating a flexibility component to the framework provides a greater sense of potential adaptability of individuals, occupations and institutions within the coastal and marine realm. The framework allows for future cross-scale comparisons, where instead of relying upon low resolution global datasets, data can be collected intensively at the local household level and can be analysed at that level but also integrated through indicators to allow for comparison to regional or national levels through Census data and even to the global level by integration with global indicators that map to the indicators from the surveys.

Most importantly, the presented framework allows for seamless integration with the marine ecological system and the dynamics within. For instance, the value and relative importance of some of the indicators the ecological models produce (like fish abundance and biodiversity) can be established in the social vulnerability framework. It is possible to assess the consequences of a change in these crucial ecological indicators on the coastal communities or stakeholder groups. Finally, it addresses another major criticism of vulnerability analyses, which is the provision of a vulnerability score, but where no further work is carried out. The vulnerability analyses conducted by the GULLS hotspot teams will assist in providing the baseline and predictions of future vulnerability to develop sustainable and well-informed adaptation options with the study communities and countries.

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Table 1 Comparison of vulnerability frameworks, their advantages, disadvantages, appropriate spatial scale and examples of their use in recent vulnerability studies.

Framework	**Advantage**	**Disadvantage**	**Spatial scale**	**Focus area**	**Study**
IPCC 2001*	Includes both ecological & social dimensions by using common concepts [exposure, sensitivity, adaptive capacity (AC)], Applicable to all spatial scales of vulnerability Comprehensive approach which is clear and understandable	Very broad level framework AC can be oversimplified into economic factors, disregarding social and ecological aspects	Global Regional Local	National fisheries Indian Ocean coral reefs & communities Northern Gulf of California, Mexico	Allison et al. 2009 Cinner et al. 2012 Morzaria-Luna et al. 2014
SLA/LVI	Multi-dimensioned view of poverty (economic and social) by using the 5 capitals Focused on aspects of sensitivity and AC Places high importance on policies and institutions	Provides no means to measure or integrate climate exposure or adaptation practices	Regional and Local National	West African countries Australia	Allison & Horemans 2006 Metcalf et al. 2015
Food Security (FS)	Multi-dimensioned view of food-based welfare (can include: availability, stability, access and utilization) Easy access of required data	Most studies work from national level FAO datasets Food availability and access often focus of studies, neglect of other two dimensions Estimating food security at local level is difficult or not always relevant	Global Local	Global food security Household food security	Godfray et al. 2010 Schmidhuber & Tubiello 2007 Pinstrup-Andersen 2009
IPCC_LVI	Focuses on social dimension of vulnerability Index can be constructed from household data alone Doesn’t depend on	Ecological vulnerability largely ignored	Regional Local	Mozambican regions Ganges River basin Urchin fishery, California	Hahn et al. 2009 Mohan & Sinha 2015 Chen et al. 2014

	climate models to assess risk				
IPCC_LVI_FS	Strong social and ecological foundation Flexible framework allows comparison of communities across different levels of development	Large range of indicators required makes framework unsuitable for rapid vulnerability assessments	Global and local	Southern Hemisphere hotspots	Howard et al.

*IPCC 2014 now utilises a different framework, where risk is central and vulnerability, hazards and exposure are three buttresses of risk that are then combined with climate and socio-economics (IPCC, 2014).

Table 2. Vulnerability assessment survey method and logistical differences among hotspots

Country	Researchers	Survey format	Pre-testing	Field team no.	Survey language	Translators used	Training received	Sample size	Number of refusals/ unusable surveys	% of sampled households
Australia	3	Web*	Yes	0	English	No	N/A	104	21	0.12%*
Brazil	2	Field	Yes	1	Portuguese	No	N/A	151	23	65%**
India	3	Field	Yes	30	Malayalam	Yes	Yes	800	0	48%
South Africa	3	Field	Yes	1	Afrikaans	Yes	Yes	65	1	58%#
Solomon Islands	2	Field	No	2	Pijin English	Yes	Yes	110	0	30%
Madagascar	2	Field	No	2	Malagasy	Yes	Yes	46	0	55%**

* In southern Australia approximately 1 in every 3 households partake in recreational fishing activities each year (Lyle, Stark and Tracey 2014). There are around 250,000 households which makes for a 0.12% sample.

** The total number of marine dependent households per community is an estimation made by the researches before the survey application, as the official number of marine dependent households in the area is not available. In Brazil the estimation is firstly based on the number of registered fishers per area and this number was cross checked with the local fishing association and community leadership in terms of their estimate of the number of active fishers. Lastly it was further verified through community site visits by the local researchers where visual estimates of the number of fishers were made.

In South Africa and Madagascar the estimation was based on the number of fishing rights allocated in the sector (see Gammage et al 2017), which was subsequently checked by the local researchers in field visits to the communities before the start of the survey.

Table 3: Correlation coefficients greater than 0.5 for country level vulnerability and different country characteristics.

Country characteristics	**Variable name**	**Correlation coefficient**	**Interpretation**
Size of the Exclusive Economic Zone	EEZ_size	-0.532	Smaller EEZ – greater vulnerability
Proportion of population who are undernourished	Undernourished	0.743	More people undernourished - greater vulnerability
Gross Domestic Product	GDP	-0.566	Lower GDP - greater vulnerability
Environment Protection Index	EPI_index	-0.632	Lower Environment Protection Index - greater vulnerability
Human Development Index	HDI_index	-0.575	Lower Human Development Index - greater vulnerability
Regulatory quality (score)	Regulatory_Quality	-0.599	Lower regulatory quality - greater vulnerability
Government effectiveness (score)	Govt_effectiveness	-0.823	Lower government effectiveness- greater vulnerability
Proportion of population for largest ethnic group	Majority_ethnicity	-0.744	Less ethnic diversity – greater vulnerability

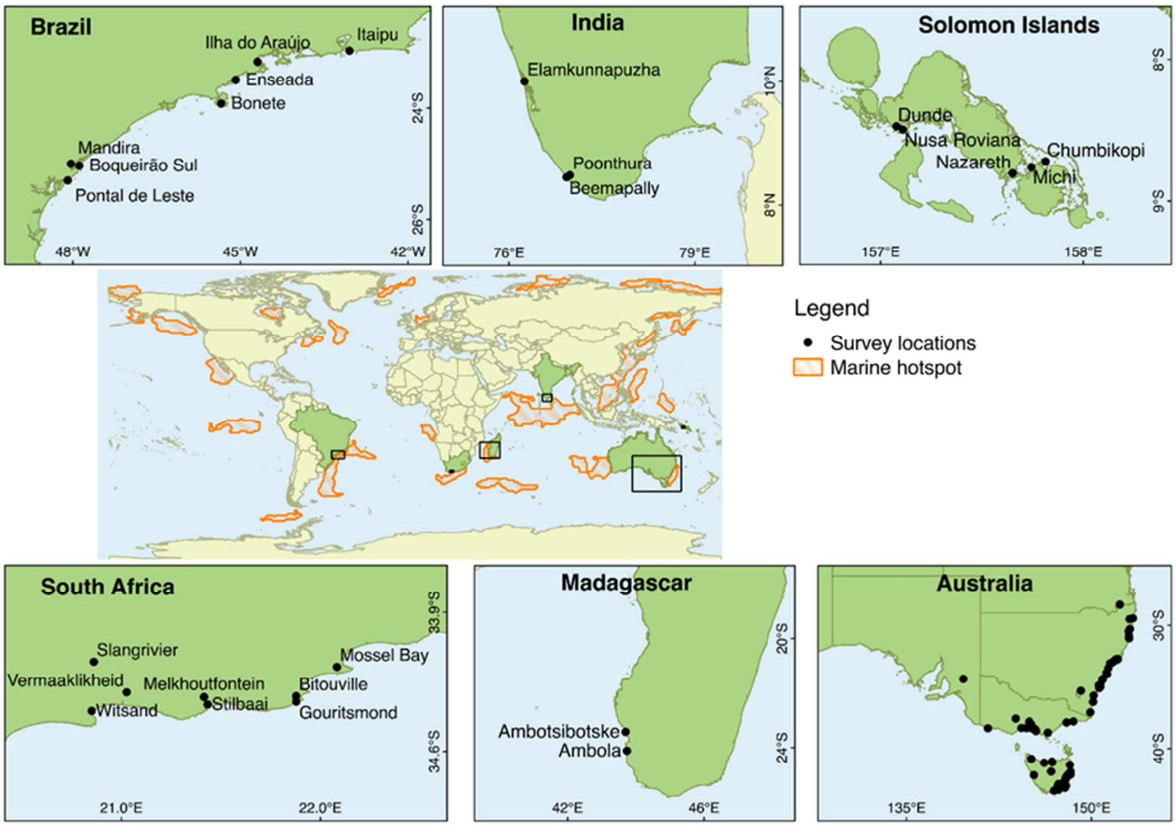


Figure 1. Countries where surveys were undertaken to assess human vulnerability to change in the marine environment. The survey locations are shown by black dots. In Australia the black dots represent the residence locations of individual respondents. The middle map shows the global marine hotspots.

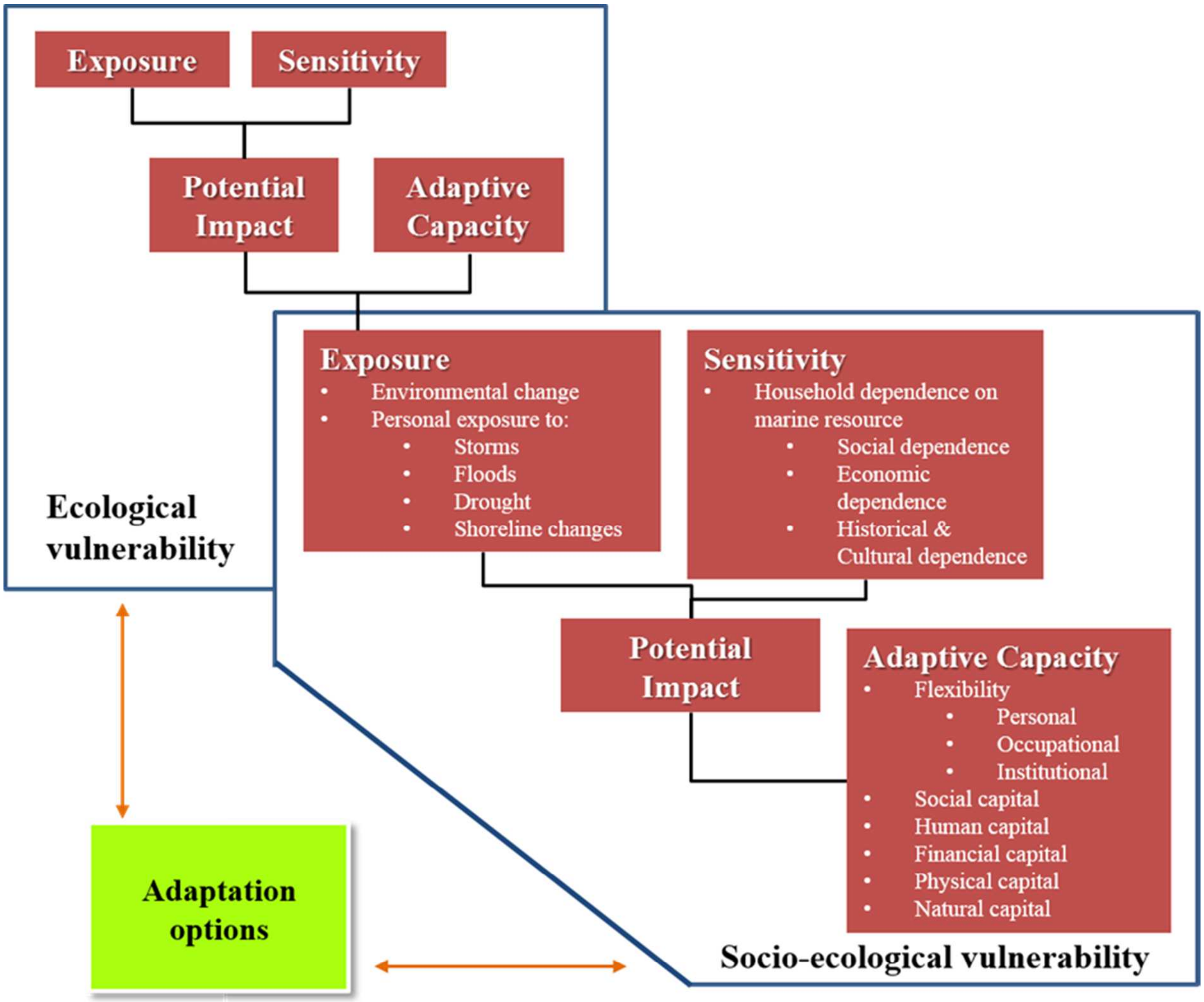
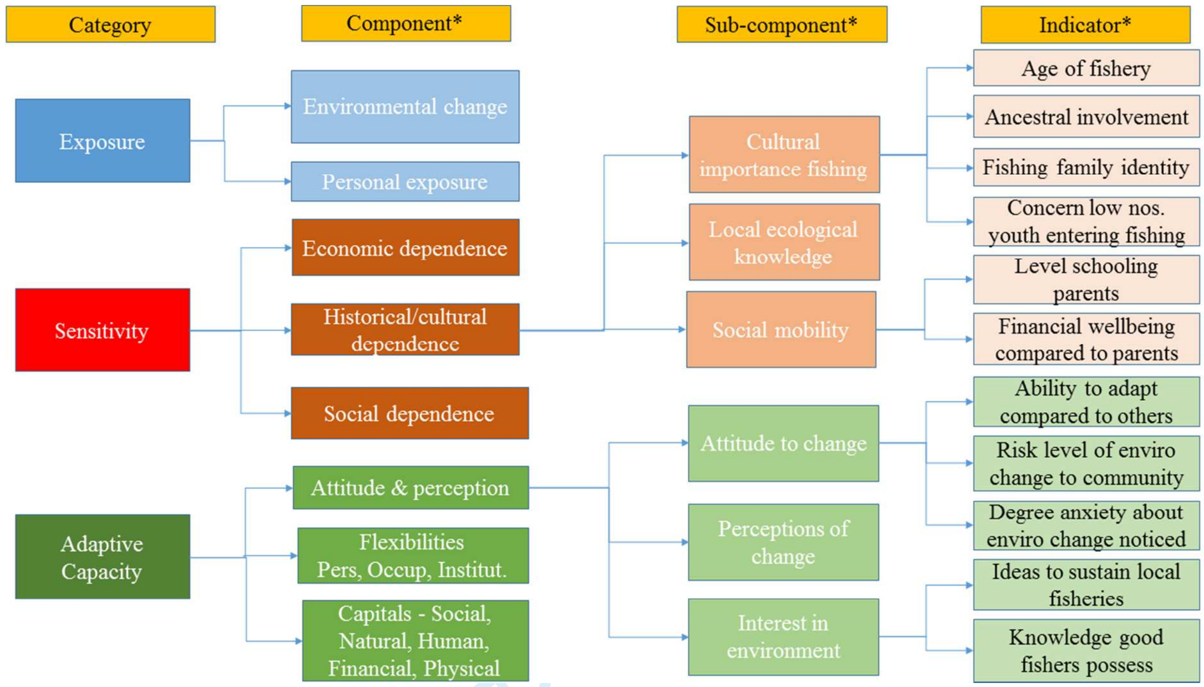


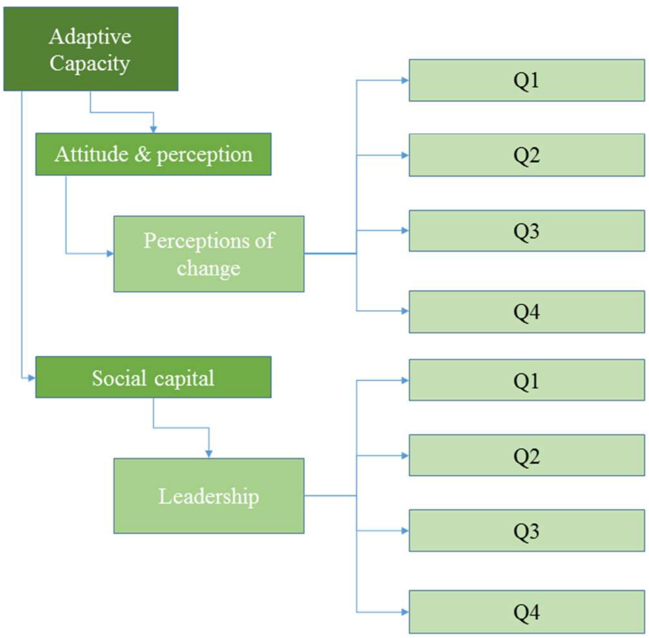
Figure 2. GULLS framework for assessing coastal community vulnerability by integrating approaches from: IPCC, (2001); Chambers and Conway, (1992); Allison and Horemans, (2006); Marshall et al., (2013) and Metcalf et al., (2015). Higher levels of complexity in the socio-economic subsystem are indicated showing different forms of dependencies, capitals and flexibilities.

841 

842 **Figure 3**. Structure of the integrated framework, demonstrating the multiple levels of complexity under each broad
843 scale component and category.

844 *To ensure clarity of the figure, only a few components for each category are depicted and only some of the sub-
845 components and indicators of each higher level are shown in this figure. Furthermore, due to space limitations,
846 exposure is only shown up to the component level but in the full framework exposure does have components, sub-
847 components and indicators.

848



Aus	Brazil	India	SA	Solomon Islands
Y	Y	Y	Y	Y
Y	Y	Y	Y	Y
Y	Y	N	Y	Y
Y	N	Y	N	N
Y	Y	Y	Y	Y
Y	N	N	N	N
Y	N	Y	N	N
Y	Y	Y	Y	Y

Figure 4. The relationship between the conceptual vulnerability framework and the local survey instrument. Up to four different questions feed data back to each sub-component of the framework (LHS). Question selection (Y = Yes; N = No) differed across hotspot countries depending on cultural and contextual relevance (RHS).

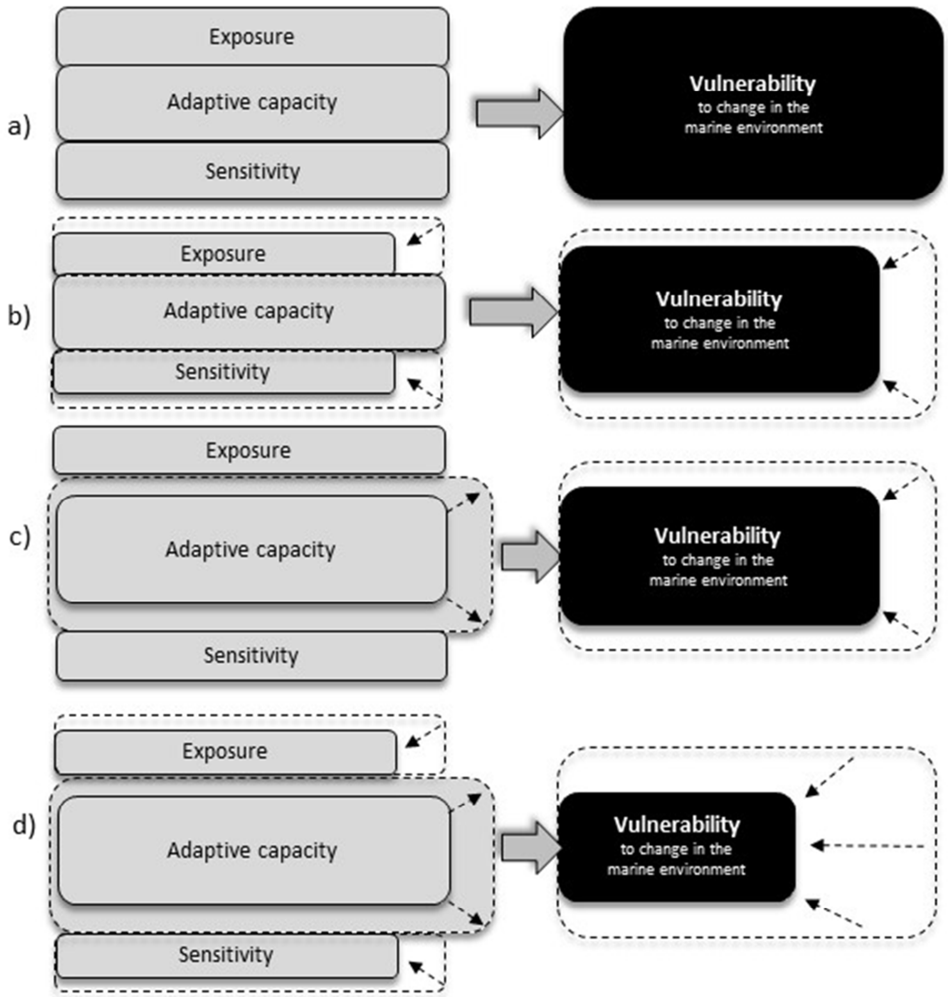


Figure 5. Relationship between reducing vulnerability and reducing sensitivity and/or exposure and increasing adaptive capacity (adapted from Engle 2011)

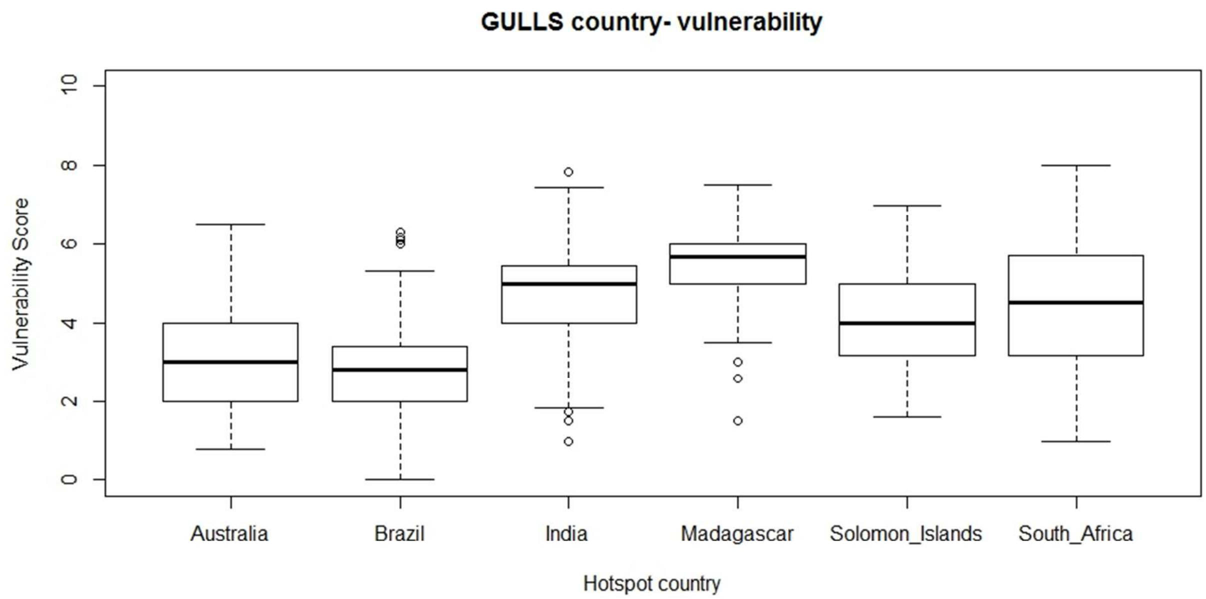
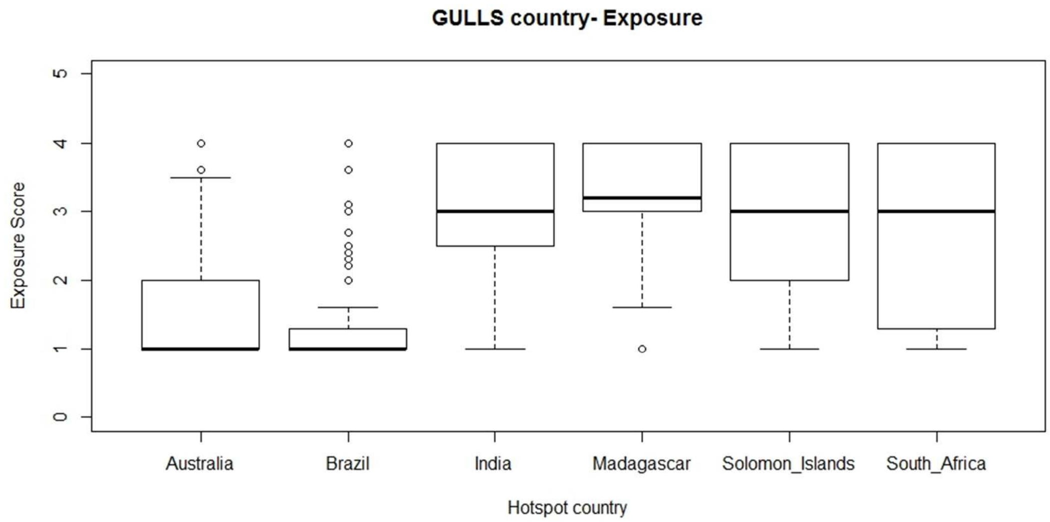
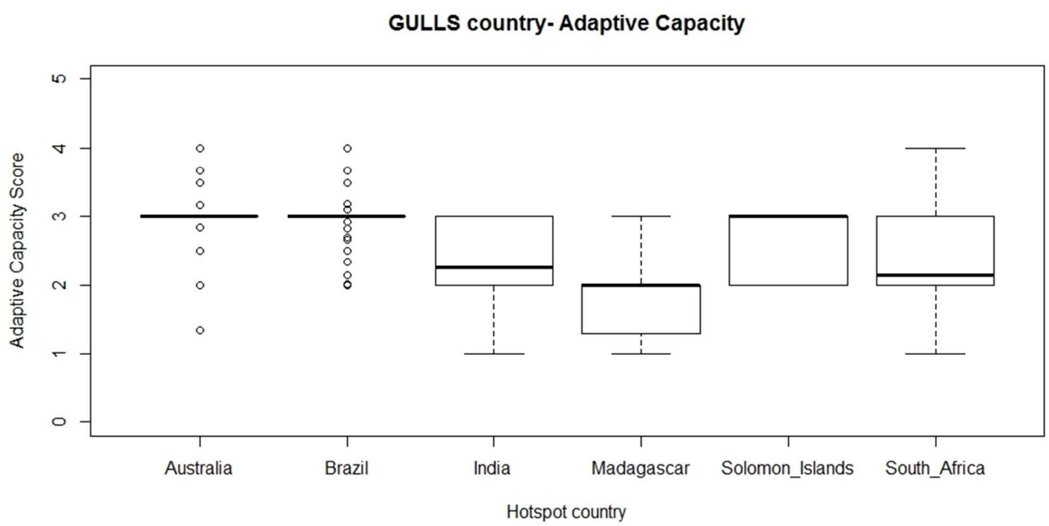


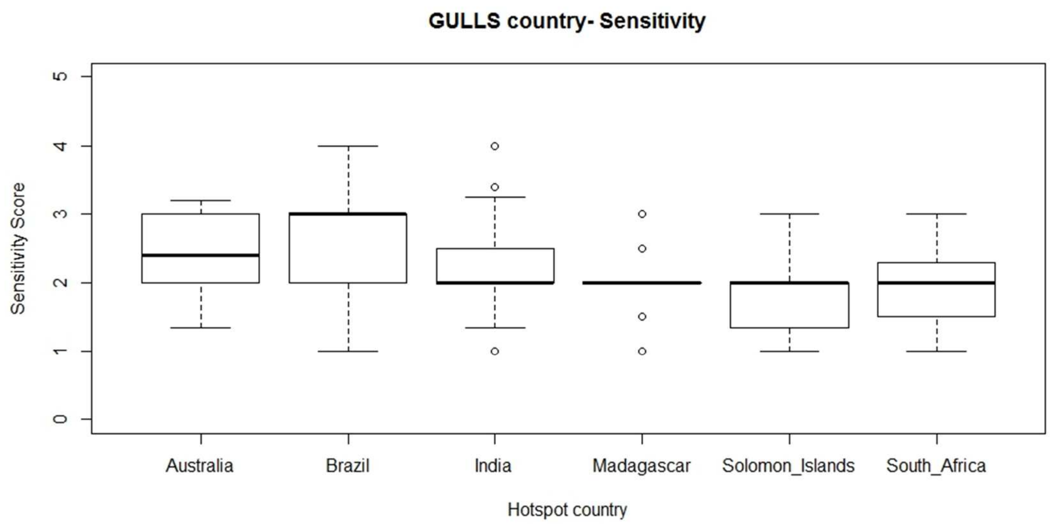
Figure 6. The vulnerability of hotspot countries to change in the marine environment. Scores range between 0 and 10 where scores greater than 4.5 are worse. Higher scores indicate *greater* vulnerability.


GULLS country- Exposure
Exposure Score
0
1
2
3
4
5
Australia
Brazil
India
Madagascar
Solomon_Islands
South_Africa
Hotspot country

873 a)


GULLS country- Adaptive Capacity
Adaptive Capacity Score
0
1
2
3
4
5
Australia
Brazil
India
Madagascar
Solomon_Islands
South_Africa
Hotspot country

874 b)



c)

Figure 7. The a) exposure b) adaptive capacity, and c) sensitivity of hotspot countries to change in the marine environment. Scores range between 0 and 5 where scores greater than 2.5 are worse. Higher scores indicate *greater* exposure and sensitivity (which is not beneficial), and higher scores also indicate greater adaptive capacity (which is beneficial).