Mapping the vulnerability and exposure of communities in coral reef endowed areas

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Abstract

Marine ecosystem is adversely affected by anthropogenic and natural stressors hence the need for proactive actions to protect them. Indeed, the human related pressures on such ecosystem such as coral reefs increase the vulnerability of communities both inland and coastal who depend on coral reefs for welfare purposes. Moreover, the need to address coping strategies with appropriate mitigation and adaptation strategies for such communities is required when threats are global such as climate change. Indeed, mapping these areas by constructing vulnerability index and comparing three approaches in indices construction is essential to understand the sensitivity of such methods under complex socio-economic as well as ecological dimensions for countries. The results from the overall vulnerability study shows that adaptive capacity is increasing for developed countries whereas for emerging/developing countries which are economically growing faster at this time are however vulnerable with time. In sum, matching the policy actions required in mitigation for such ecosystem and simultaneously economically growing suggest that developing and/or emerging nations require coordinated governance efforts matched with socio-economic and ecological considerations at to broaden consensus at the national levels to meet the global climate change impacts.

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Key words: vulnerability index, coral reef, exposure, mapping, climate change

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1. Introduction

Human subsistence depends on marine ecosystems for use and non-use values in various socio-economic and cultural sectors. However, such ecosystems are sensitive to human/anthropogenic stressors as well as natural disasters. Recent initiatives/agreements to protect biodiversity/ecosystem have highlighted the importance to protect such ecosystem from the threats of overfishing, coastal development pressures, pollution and climatic change. From all these threats the most challenging one is related to climatic change as it involves not only local effort but also global one. According to the 2007 IPCC report, human induced climate change is expected to cause and increase of global temperature between1.8° and 4.0° C by the end of this century. (IPCC, 2007a).Coral reefs ecosystem which are site specific are considered as one of the most sensitive biomes to respond adversely to climate change. Two effects of climate change on such ecosystem include bleaching and acidification. For the former, asmall increases (1°-2°C) in sea temperature, above the long-term summer maxima, destabilizes the relationship between host corals and their symbiotic algae (Strong et al., 1998) resulting in bleaching. The latter is related to calcification process for corals where the global rise in CO_2 levels increases the ocean's absorption of CO_2, resulting in a high concentration of carbonic acid and bicarbonate ions, hence lowering the carbonate ions, which in effect decreases the coral's growth rates and other calcareous ecosystems (Grimsditch and Salm, 2006). The rate of calcium carbonate removal matters, particularly when it exceeds the calcification rate leading to decreased coral sizes which are susceptible to further breakage and bio-erosion (Buddemeiret al, 2004). In this paper we refrain from examining this factor but future studies may shed light when analyzed with climate change effects (see McNeil et al. 2004).All types of threats whether local or global impact directly and indirectly the sustenance of nations or states. Indeed, the degradation of marine and/or coastal ecosystems results in the loss of goods and/or services not only to coastal but also inland communities (UNEP, 2006).

The afore-mentioned coral reef states referred to this study include nations and territories identified by the World Atlas of Coral Reefs who are ranked by their reef area (Spalding et al, 2001). What is more is that most coral ecosystems are sited in developing countries showing once more how poorer nations are highly dependent on such ecosystems for fishing, shoreline protection, recreation as well as aesthetic services and are more exposed and sensitive to climatic impacts.Accounting available indicators that are vital to vulnerability of such nations amidst of climate change exposure on coral reef ecosystem cannot be ignored.In other words, these states and/or territories need to recover from negative effects of climate change in a way the chain-linked effects from the coral reef ecosystem to their daily lives and/or activities requires resilience. However, to address resilience and recovery relies on the vulnerability measurements focusing on the socio-economic, political, ecological and climatic variables which thispaper aims to explore and assess.

Significantly the mapping of coral reef endowed areas and ecosystem at global levels is relevant. As reported by the IPCC (2007b),increases of sea surface temperature of around 1-3° C would result to frequent coral bleaching incidents. Consequently, this may intensify other existing human activities threats such as overfishing, pollution and coastal development on coral reef ecosystem. Identifying such threats is essential step in examining the vulnerabilities spill over effects from the ecosystem to local communities. Nevertheless, recognizing the interactions of public institutions as well as communities and government involvement with biodiversity/ecosystems requires problem-solving at the local, regional and international levels.

For decision makers, institutes and planners may consider this step useful in planning adaptation strategies to cope with the effects at both local as well as global levels. Nevertheless in recent years climatic change science have shifted from scientist to political decision makers where negotiations and policy actions and discussions require a comprehensive vulnerability basis to better capture the overall dependency of nations and territories and devise adaptation responses to in times of uncertainties. Significantly, the revised strategic plan for biodiversity 2011-2020 as recommended by the Conference of Parties to CBD (about 188signatories' members) highlighted the reduction of pressures faced by coral reefs in the Aichi biodiversity target (CBD, 2010). Indeed such pressures (directly and indirectly) may implicitly refer to climate change as well as anthropogenic stress. Consequently, the urgency of estimating vulnerability of people as well as nature provides greater insights on how these pressures and/or threats can adversely affect man and nature. Our aim is to provide a standardized measurable vulnerable index that is comparable among coral reef endowed nations and/or territories over time following to some extent the CBD aspects of biodiversity indicators.

Several key research questions are illustrated in this paper: first, what socio-economic, institutional and ecological variables affect vulnerability of nations/territories? Secondly, to what extend does exposure in this case temperature variability affect vulnerability? The first question can be addressed by creating a vulnerability index and the latter, by examining the temperature variations among several coral reef endowed countries. These two predicaments are important at this time as adaptation planning requires stakeholder to examine the vulnerability and temperature changes for surrounding populations under climate change. However the challenge with regards to adaptation from climate change is locally based whereas the adverse effect of climate change may appear globally.

Indeed, where and when the next threats are coming from are uncertain hence adaptation to the exposures and impacts is essential for coral reef dependent states as they can manage and conserve at local levels .A fact is that for poor countries that are heavily dependent on these ecosystems economically; are caught between economic developments on one hand and on the other hand the climate change. The balancing act of securing economic development of nation's livelihood with adaptation requires the assessment of such vulnerable communities. Indeed, past studies like Burke et al 2011, Cinner et al 2012 and Cheung et al 2012 have investigated such a relationship and concluded that climate change threats will accelerate the coral reef loss globally. Similarly, this study investigates the climate change inquiry though focussing more on the vulnerability trends among several countries when temperature variability is considered. The idea of examining the trends of vulnerability at different time periods can assist countries globally to understand how the climate change threats accentuate vulnerability with time. For instance for exposure like global temperature where increased temperature likely to occur in warmer regions where local people are highly dependent on recreational tourism can benefit from adaptation policies like creating or increasing marine protected areas and zoning of the areas to assist the natural recovery process of corals.

The next sections of this paper are organized as follows: conceptual model and (section 2), data and comparisons with other previous studies, selection of variables from a databases and methodology (section 3) and discussion of the results (section 4) and conclusion (section 5)

2. Conceptual model of vulnerability indices as related to coral reef areas

In environmental economics, the concept of vulnerability is well established as initially defined by the IPCC 2001report where the three components of vulnerability are identified: exposure, sensitivity and adaptive capacity.[1] Consequently, several conceptual frameworks in environmental economics have explored vulnerability for communities depending on coral related ecosystems as a source of welfare potential. Three such publications related to vulnerability index include: the World Resource Institute (WRI) (see under Burke et al, 2011),Cinner et al (2012) and Cheung et al (2012). Shown in Table 1 is the summary of the key sub-components with their respective indicators as found in the three conceptual frameworks.

Table 1: Summary of VIs categories and related indicators

VI category /Author(s)	**Burke et al (2011)**	**Cinner et al (2012)**	**Cheung et al (2012)**
Exposure description	Two threats: local and global	Two threats: coral bleaching (CB) and climate variable (CV)	Two threats: climate change (CC) and ocean acidification (OA)
variables	Local: 1. coastal development 2. watershed and marine pollution 3. overfishing and destructive fishing. Global: 1. sea surface temperature 2. coral bleaching incidents 3. ocean acidification.	CB: 1.Coral bleaching incidents CV: 1. sea surface temperature 2. photosynthetically active radiation 3.ultraviolet radiation chlorophyll 4.surface currents 5. wind velocity	CC: 1. percentage loss of fisheries catch potential OA: 1. amount of aragonite saturation state
Sensitivity description	dependency on corals	dependency on fisheries	dependency on fish and seafood consumption

[1]According to the IPCC 2001 (Technical summary: climate change 2001: impacts, adaptation and vulnerability), exposure is defined as sensitivity refers to the extent the system is affected adversely by climate change stimuli whether directly or indirectly. For instance, the extent what the climate change elements are such as the frequency and magnitude of extreme events impact livelihood of individuals/society etc. Adaptive capacity is the ability for the system to cope with the climate change variability, extremes and damages.

variables	1. reef associated population (number of coastal people within 30 km of the reef, coastal population within 30 km as proportion of national population) 2.reef fisheries employment (number of reef fishers 3.reef fishers as proportion of national population) 4.reef-associated exports (value of reef-associated exports as proportion of total export value) 5.nutritional dependence on fish and seafood (per capita annual consumption of fish and seafood) 6.reef associated tourism (ratio of registered dive shops for tourist arrivals) 7.shoreline protection (index of coastal protection of reefs).	sensitivity score: 1. fraction of households engaged in fishery activity 2. ratio of total number of households to total of households engage in either fishery or non-fishery sector 3. ranking of non-fishery related occupation to fishery related occupation	CC: 1.percentage of available protein OA: 1. coral reef fishers as a proportion of the national population 2.mollusk consumption as a percentage of available protein.
Adaptive capacity description	ability to cope with coral reef degradation	social adaptive capacity index	ability to cope with seafood security
variables	1. economic resources (GDP and remittances) 2. education (adult literacy rate 3.combined ratio of enrolment in varied education levels) 4. health (average life expectancy) 5.governance (average of worldwide governance indicators 6.fisheries subsidies) 7.access to markets (proportion of population within 25 km of market centres) 8.agricultural resources (agricultural land area per agricultural worker).	1. causal agents affecting marine fish 2. capacity to anticipate change in fish decline 3. occupational mobility 4. occupational multiplicity (number of changed jobs by respondent in past five years) 5.social capital (total community groups respondent belongs to) 6. material asset (indicator for about 15 material possessions) 7. technology (fishing gears used) 8. infrastructure (20 items such roads, medical clinic).	CC & OA: 1. GDP per capita 2. population growth rate 3.percentage of population undernourished.
Number of countries/territories	27	5	50
Cross-sectional	Yes	Yes	Yes

In the case of Burke et al. (2011) they had considered 27 countries and territories at national levels when computing the vulnerability index. All the indicators in each component were normalized and averaged and , all the three sub-components were multiplied to form the vulnerability index (VI). Their selection of a multiplicative index over additive (averaging) model is the former assigned high VI on all the three components whereas the latter was skewed to one of the component. Also, both models were highly correlated at r=0.84. Moreover, two additional threats from climate change variables namely: past thermal stress events in this case coral bleaching between 1998 and 2007 and future ocean acidification in 2030 and 2050, were integrated in the final model. In conclusion, their study showed that when local threats are considered there are more than 60 percent of the world's coral reefs (about 150,000 sq km of reef) threatened however this increases to 75 percent when past thermal stress is included. Moreover, that thermal stress will play an active partin advancing the threat levels compared to acidification by 2030, though nearlyhalf of all reefs globally will be threatened by both conditions. One key limitation of this studyisall the data was compiled from secondary sources at the national levels.

One study that overcomes such data difficulty at the local level is Cinner et al. (2012) where the vulnerability scores using socio-economic from a primary survey collected from 42 coastal communities in 29 sites for Kenya, Tanzania, Seychelles, Madagascar and Mauritius. Data for exposure was obtained from remote sensing information model whilst the sensitivity and adaptive capacity were based on local socio-economic surveys collected in the selected sites. The approach considered in constructing the vulnerability include the sensitivity analysis using additive cases based on previous work done by Adger and Vincent (2005) and Allison et al., (2009) as shown in equation 1 and 2 respectively, where:

Vulnerability=(exposure + sensitivity)- adaptive capacity equation (1)

Vulnerability=exposure + sensitivity/ adaptive capacity equation (2)

In their results, they concluded both approaches were highly correlated at r=0.9and at the end selected the former one than the latter as the VI spread within and across the countries was reasonable. Significant differences were found in overall VIs particularly for some sites for instance Mauritius had a negative score. A closer examination of these sites had lower exposure score and higher adaptive capacity relative to other sites. In general, their finding the vulnerability measures varied from one country to another and also within a country suggesting that focussed policy tools are required to address the varied dimensions of vulnerability within country and across countries. With regards to climate change and vulnerability, they suggested mitigation policy interventions on international level though with limited coral reef linkages such as: funding efforts for relief efforts, conservation, infrastructure, adaptation as well as environment governance and global negotiation on climate change. In sum, this study differs from Burke et al (2011) in two major counts: more local specific variables were accounted for and aggregation method using additive approach. For the former it means not only local data is useful but also national ones to account for a larger-scale analysis of vulnerability. With respect to the aggregation approach, the additive may suggest that three components are independent unlike the multiplicative one in Burke et al (2011).

Cheung et al (2012) also estimated two vulnerability indices for climate change and ocean acidification where exposure, dependence on and consumption of fish and seafood and adaptive capacity for over 50 countries and territories were ranked. However, this study considered vulnerability based on seafood security where most of the data variables were obtained from secondary sources such as Food and Agriculture Organization (FAO) and World Resource Institute (WRI). Moreover, the numbers of indicators identified in this study were fewer than the two previous studies . Their vulnerability were ranked and the additive approach with equal weights to the three sub-components was examined. Every indicator was normalized and averaged, in other words, equal weights for each indicator in each of three sub-categories or sub-components. Nevertheless, the estimated vulnerability was calculated by combining both climate change and ocean acidification. Overall, their final results showed that the combined vulnerability index of both climate change and ocean acidification resulted to high vulnerability for coastal and small islands located in tropics and low latitudes.

Our study differs from other vulnerability index in three major avenues: the vulnerability components being assessed is as suggested by the Conference of Parties to the Convention of Biodiversity Development (CBD) where it bridges the vulnerability closer to the policy relevance debate. Indeed, building on some biodiversity indicators and respective focal areas as identified by CBD to meet the previous Biodiversity 2010 Target (Parliamentary office of Science and Technology, 2008)suggest that these indicators are essential and as result the present indicators have been revised slightly to meet the 2020 targets considering the climate change scenarios. The key seven focal areas identified include: status and trend; threats; ecosystem integrity and ecosystem goods and services; sustainable use; access and benefits sharing; status of resource transfer and use and public opinion/status of traditional knowledge, innovation and practise.

Secondly, the mixed aggregation method proposed in this study has the joint advantage over those used singly namely the additive case of Cinner et al (2012) which assumes independency and full substitutability and the multiplicative one of Burke et al (2011) which assumes full dependency across vulnerability components. Hence, for the sensitivity analysis we compare and calculate the three approaches simultaneously.

Thirdly, this study explores the global data set by considering the temporal where the time variation may significantly change the evolution of vulnerability particularly when social-economic-political events among nations are also coupled with additional pressure from climate change at a global scale. Additionally, we consider the national scale like the case of Burke et al (2011) and Cheung et al (2012) studies because we can identify the key policy actions particularly related to mitigation of climate change where global actions are required to mitigate vulnerability for those poorly funded countries endowed with coral reef ecosystem.

3. Indicators, selection of variables and index calculation

In the construction of the vulnerability index we refer to the OECD handbook (2008) where the recommended steps from theoretical framework suggest the useful steps in the creating the indices are: data selection, normalisation, weighting and aggregation (see *Table 1A* in the Appendix). For the data selection and compilation, these were obtained from at least ten diverse sources ranging from World Bank World Development Indicators (WDI), Food and Agricultural Organization (FAO) to ReefBase as well as World Resource Institute (WRI). The merged database included ecological and socio-economic, political and climatic variables to compute the overall index. The conceptual framework identified and implemented was formulated with two major contributions: the IPCC definition of vulnerability in three components (exposure, sensitivity and adaptive capacity) and the Convention on Biological Diversity (CBD)/EU/UK biodiversity target 2010 where even focal areas (trends, threats, ecosystem integrity, sustainable use, access, status of use and public opinion) with their respective indicators were highlighted.[2]

Significantly, the inclusion of human interaction with nature (in this case biodiversity) was considered essential in computing the index thereby the original conceptual framework under CBD indicators were enriched by other social and economic indicators like: GDP per capita, food supply quantity, number of those employed in agriculture, life expectancy at birth, age dependency, health expenditures and population within 100 kilometres of the coast. The importance of including these national indicators is a broader consensus as found in other previous studies suggesting that these indicators match the comparison of nations and/or territories according to socio-economic context as well as the political and climate variables.

Figure 1 illustrates the respective the vulnerability sub-components and the classified focal areas and headliner indicators as suggested by the CBD report. In other instances, some headline indicators were dropped from the original CBD listing such as linguistic diversity,

[2]Subsequently, the European Environment Agency (EEA) has implemented EU indicators comparable to CBD one, commonly referred to Streamlining European Biodiversity Indicators (SEBI) see this: http://www.eea.europa.eu/publications/technical_report_2007_11

nitrogen depositions and red list index as they were insufficient observations to estimate the VI.[3]

Vulnerability sub-components	Focal areas[1]	Headliner indicator	Selected indicators
Exposure	Threats to biodiversity	extreme weather related incidents	• number of droughts • number of extreme temperature • number of flooding
		temperature[2]	• monthly mean temperature
Sensitivity	Status and trends of biodiversity	coverage of protected area	• coverage of coral to MPA
	Sustainable use	area under sustainable management	• employment(agriculture) • food supply quantity • populationwithin 100 km of coast
		ecological footprint (ef)	• ef/biocapacity
Adaptive capacity	Access and benefits sharing	institution[3]	• corruption perceptions index
	Ecosystem integrity and ecosystem goods and services	health and well - beingcommunities	• health expenditure p.c. • life expectancy at birth • age dependency ratio
		marine trophic index	• mean trophic level
		economic well being[3]	• GDP per capita (p.c.)

Notes:
[1]Revised focal area from the original of seven to five
[2]Re-calculated exposure including temperature variability
[3]Added new headliner from previous framework

Figure 1: Conceptual framework of the selected variables for vulnerable index according to CBD indicators

[3]All these databases were important in computing the vulnerable index for coral reef communities, however, the arrangements and aggregation of the varied sources resulted to a few observations than the original sources. For instance, for some databases like IUCN Redlist (flora and fauna), available sources were restricted to 40 countries for only 2007 and thereby merging this with the final merged of years 2000-2006 was challenging. Consequently, in the selection of the IUCN Redlist were not included because of limited data availability for the required time-frame. Similarly for the case of public opinions/status of traditional knowledge, innovations and practises we excluded this as the ratio of indigenous language to total language were fewer observations than expected.

3.1 The exposure index

For the first vulnerability sub-component namely exposure, this index was based on the previous monthly mean temperatures combined with the number of events i.e. drought, floods and extreme temperatures that occurred between 2000 and 2006, which were relevant to examine the adverse impact of such risks on coral reef ecosystem. [4]

3.2 Sensitivity

For the second, sensitivity, two focal areas identified namely: status and trends of biodiversity and sustainable use were relevant in increasing the impact of climate change effects on coral reef ecosystem. In the case for the status we considered the ratio of coral reef coverage to the marine protected areas and the overshoot ratio which is the ecological footprint over the biocapacity. Other variables considered useful include: the number of people employed in the agriculture sector, nutrition value per capita and population along the coast.

3.3 The adaptive capacity

For the third, adaptive capacity, the main focal areas were: ecosystem integrity and access and benefit sharing.[5]We combined the economic factors including the GDP per capita as well as variables related to health and well-being of communities: health expenditure per capita, age dependency ratio and life expectancy at birth and ecosystem: marine trophic levels. Moreover for access of resources in this case we considered the corruption index was relevant as a proxy to access and/or property rights. Shown in *Table 1*, are the descriptive statistics of these normalized variables (except for country and year) as well as standard deviation of monthly temperatures.

[4]Unfortunately for the precipitation for all countries was limited as well as the computed number of hot and cold months were limited.

[5] For the resource transfer as related to financial assistance in support of biodiversity and/or financing management for the coral reef ecosystems we considered another proxy variable namely funds committed to International Development Association (IDA) for funding sustainable projects. However we later excluded it as high income countries do not have IDA allocated in their national budgets.

Table 1: Descriptive statistics for selected variables used in calculating vulnerable index (VI)

Variable	Description	OBEs	Mean	Std. Dev.	Min	Max
nor_coral_~o	Normalized coral coverage over marine protected area (km2)	80	0.033	0.142	0	1
nor_pop~2000	Normalized Population within 100 km of coast at year 2000	80	0.582	0.313	0	1
nor_oversh~t	Normalized overshoot=ecological footprint over biocapacity	80	0.241	0.268	0	1
nor_employ~u	Normalized Employment in agriculture (% of total employment)	80	0.314	0.192	0	1
nor_foodsu~t	Normalized food supply quantity (kg/capita/yr)	80	0.243	0.242	0	1
nor_evt_f~09	Normalized Number of floods 2000-2009	80	0.257	0.260	0	1
nor_evt_t~09	Normalized Number of extreme temperatures 2000-2009	80	0.102	0.173	0	1
nor_evtdr~09	Normalized Number of drought 2000-2009	80	0.167	0.244	0	1
nor_meantr~l	Normalized Marine trophic levels	80	0.509	0.173	0	1
nor_c2orru~x	Normalized Corruption index	80	0.356	0.233	0	1
nor_gdperc~t	Normalized GDP per capita constant	80	0.271	0.270	0	1
nor_a3gede~k	Normalized Age dependency ratio, % of working-age population	80	0.291	0.174	0	1
nor_h3lthe~t	Normalized Health expenditure per capita (constant)	80	0.188	0.252	0	1
nor_lifexp~h	Normalized Life expectancy at birth total (years)	80	0.679	0.199	0	1
dev_jantemp	std. deviation of jantemp	62	-1.749	9.102	-25	10
dev_febtemp	std. deviation of febtemp	66	-1.832	8.597	-23	9
dev_martemp	std. deviation of martemp	62	-1.523	7.693	-17	7
dev_aprtemp	std. deviation of aprtemp	63	-1.174	6.096	-13	7
dev_maytemp	std. deviation of maytemp	62	-1.870	5.437	-11	9
dev_juntemp	std. deviation of juntemp	64	-1.156	5.717	-12	12
dev_jultemp	std. deviation of jultemp	61	-0.868	5.856	-13	12
dev_augtemp	std. deviation of augtemp	61	-0.741	5.519	-12	12
dev_septemp	std. deviation of septemp	64	-0.725	4.927	-12	8
dev_octemp	std. deviation of octemp	62	-0.969	5.345	-13	6
dev_novtemp	std. deviation of novtemp	61	-1.270	6.521	-17	8
dev_dectemp	std. deviation of dectemp	62	-1.808	8.644	-21	10

3.4 Normalization

The normalization was using a linear transformation where the selected variable was considered with the overall minimum and maximum across all countries and/territories and years.A linear transformation of say corruption index was calculated as follows: (corruption index- minimum of corruption of index all countries in all years)/(maximum of corruption index across all countries and years- minimum of corruption of index across all countries and years). For each of the selected variables the normalization was in the interval [0, 1]where 1 represents extremely unsustainable value conversely to 0, fully sustainable. However, caution should be taken that the most sustainable say the best performer when VI is at zero does not mean there are no vulnerabilities in the system. For benchmarking, each selected variable were identified with the value 1 as the highest bound and 0 lowest bound after the normalization. These targets were fixed according to arbitrary information about the relation of each indicator to overall VI and what is commonly identified in the literature. Additionally, we cross-examined this consistency in the early stages of index construction.

3.5 Weighting and aggregation

Equal weighting were assigned to all the headliner indicators. For inter-temporal comparison the normalization of VI variables was done for all the data available then sorted by year and country. Additionally, the estimated vulnerability index was developed by weighted aggregation of three sub-indices (exposure, sensitivity and adaptive capacity) where each of the sub-indices is composite of headliner indicators associated with the seven focal areas. That is to say, each headliner indicator (see Figure 1) had an equal weight to the sub-indices, say for the case of the exposure, the headline indicators and/or associated variables were averaged equally. Similarly this was the case for sensitivity as well as adaptive capacity. Moreover, all variables found in one headliner were averaged prior final averaging with other headliners. Take the case of AC where the headliner indicator such as health and well being communities had three variables i.e. health expenditure per capita, life expectancy at birth and age dependency ratio. These three were first added and averaged before final averaging with the rest of the headliners like marine trophic index, economic well being etc.

With regards to the overall aggregation of the VIs three distinct linear approaches were considered: a) multiplicative b) additive c) mixed (or combination). The first two approaches as mentioned earlier relate to two vulnerability studies associated with coral reef, Burke et al

(2011) and Cinner et al (2012) (see equation 3 and 4 respectively). For the third approach, we suggest a mixed one where we combine both the additive and multiplicative one as shown in equation 5. Specifically, we evaluate this mixed one where we assign equal weight for additive and multiplicative set at 0.5.

VI_I:(Cinner et al.) =((EX)+SE)+(1-AC) equation (3)

VI_2: (Burke et al.)=((1-AC)*SE*EX) equation (4)

VI_3: (combination) = 0.5*(Burke et al)+ 0.5*(Cinner et al) equation (5)

We acknowledge the advantage of multiplicative aggregation as suggested by Herrero et al (2007) that it avoids the constant rates of the substitution among variables as found in the additive case. Moreover, this framework provides robust way to minimize the difficultness of direction and dimension of errors as found in additive one (OECD, 2008). For this study we maintain the additive cases for sensitivity analysis despite the shortcoming. Moreover, the additive is commonly used in other previous studies like Cinner et al (2012), Adger and Vincent (2005) as well as Allison et al (2009) suggests that this approach is worth keeping for comparison purposes against other approaches. Consequently, in estimating a mixed approach we attempt to examine whether there are differences and/or similarities in all the three approaches. Indeed, the correlation of these approaches when compared to one another shows that the VI_1 (Cinner et al.) and VI_3 (combination) is nearly perfect correlated at r=0.99 compared toVI_2 (Burke et al.) and VI_3(combination) at r=0.91; and VI_I (Cinner et al.) and VI_2 (Burke et al) at r=0.89.

Moreover, irrespective of the aggregation approaches, the correlation matrix of each of the three sub-component to the overall vulnerability performance shows that adaptive capacity and sensitivity are positively and slightly correlated at 0.4734. Conversely, the correlation between adaptive capacity and exposure as well as correlation between sensitivity and exposure were negatively correlated at -0.2806 and -0.1612 respectively. As expected there is a negative relationship between adaptive capacity and exposure also between sensitivity and exposure as both of them reduce the overall vulnerability.

Take the case of the weighting for the additive case where each sub-component and associated indicator were identified by calculating the Shapley's value. This value shows the relative importance of each indicator against the three sub-components. Shown in *Table* 2, the contribution of exposure to overall VI contributes to nearly 54% of the weight, whereas for the other two, namely sensitivity is 7% and adaptive capacity about 40%. With regards to weights of each selected indicators for the three sub-components the results varied. For instance the contribution of say number of flood events to exposure is represented by nearly 43% compared to temperature at 20% and droughts 37%. Similarly the highest contributing indicator to sensitivity is the overcapacity in this case the ratio of ecological footprint to bio-capacity and for adaptive capacity was the GDP per capita as well as health expenditure per capita both nearly at 30%.

Table 2: Shapley's value of criteria

Sub-component	**selected indicator**	**Shapley value**
Exposure		53.69%
	number of floods	42.93%
	number of extreme temperature	20.04%
	number of droughts	37.03%
Sensitivity		7.30%
	ecological footprint/biocapacity	51.72%
	coverage of coral to MPA	11.49%
	population within 100 km of coast	12.51%
	employment(agriculture)	1.22%
	food supply quantity	23.07%
Adaptive capacity		39.01%
	mean trophic level	4.68%
	corruption perceptions index	26.57%
	GDP per capita (p.c.)	29.77%
	age dependency ratio	3.45%
	health expenditure p.c	29.75%
	life expectancy at birth	5.77%

4. Results and discussion

Shown in *Table 3* is the breakdown of selected countries and years according to the vulnerability index (VI) for three types: Cinner et al (2012), the additive version where all the three components having equal weight where sensitivity and exposure were added and adaptive capacity subtracted. The multiplicative one as suggested by Burke et al (2011) – the WRI approach where all the three components were multiplied. For the last one, the intermediate one (or combination)had equal weighted of the additive and multiplicative as mentioned previously. .

Using a paired t-test for each approach for the years 2002 and 2006 shows that the mean difference of one approach against the other is different from 0, in other words the three approaches differ from each other. This should be taken with caution as the 2002 included some countries with 2003 estimations like Ecuador, Honduras, Nicaragua and Pakistan. All in all, in all models the higher the cumulative VI score the higher vulnerability in contrast to lower VI scores which corresponds to lower vulnerability. In sum, the top ranks were assigned to highest VI like China as opposed to lowest VI in Australia.

These estimations suggest that there is a decrease trend in vulnerability for the selected countries particularly with regards to rich economies such as Australia and Japan as opposed to say Colombia and Pakistan when all three approaches are considered. One plausible explanation could be that such high income countries have adapted better with time after events, in other words, through years their learning curve in adaptation efforts from the previous years has increased. This stresses the importance of low income and/or emerging countries need to emphasize on adaptation plans and strategies when assessing vulnerability of communities in anticipation of future climate change effects.

Among the most vulnerable nations is China where the VIs is the highest compared to nearly all countries. In the case of China, the proportion of their coral coverage to the world total is 0.5%greater than Brazil (0.4%), Ecuador (0.02%), Honduras (0.3%), Jamaica (0.3%), Mexico (0.4%), Nicaragua (0.02%), Pakistan (0.02%) and South Africa (0.02%). Moreover, most China's coral reef ecosystem are in the South China Sea and Hainan, Guangdong, and Guangxi coastal waters. According to Wu and Zhang (2012) the coral reef ecosystems in China are in crises and are attributed to a compound of factors namely: coral bleaching, overfishing and destructive fishing methods, large-scale coral exploitation, marine environmental pollution, carbon dioxide increase, sedimentation as well as eutrophication. Specifically, the winter cold flow from north China as well as anthropogenic activities has resulted to over 70% coral bleaching among fringing reefs in Sanya.

Table 3: Vulnerability indices according to three aggregation types (normalized by year)

Approach	**Country**	**2002 VI**	**2002 rank**	**2006 VI**	**2006 rank**	**rank change 2002-2006**
Cinner et al	Australia	0.000	15	0.000	15	↔
	Brazil	0.257	8	0.463	7	↑
	China	1.000	1	1.000	1	↔
	Colombia	0.077	14	0.299	13	↑
	Ecuador*	0.359	6	0.367	11	↓
	Honduras*	0.304	7	0.453	8	↓
	Indonesia	0.508	2	0.620	3	↓
	Jamaica	0.180	10	0.675	2	↑
	Japan	0.093	13	0.280	14	↓
	Malaysia	0.137	11	0.440	9	↑
	Mexico	0.450	3	0.463	6	↓
	Nicaragua*	0.198	9	0.370	10	↓
	Pakistan*	0.399	4	0.571	4	↔
	South Africa	0.114	12	0.357	12	↔
	Thailand	0.396	5	0.535	5	↔
Burke et al	Australia	0.004	13	0.000	15	↓
	Brazil	0.095	6	0.120	7	↓
	China	1.000	1	1.000	1	↔
	Colombia	0.000	15	0.036	12	↑
	Ecuador*	0.023	10	0.022	14	↓
	Honduras*	0.094	7	0.121	6	↑
	Indonesia	0.340	3	0.329	2	↑
	Jamaica	0.003	14	0.090	9	↑
	Japan	0.019	11	0.033	13	↓
	Malaysia	0.047	8	0.110	8	↔
	Mexico	0.357	2	0.159	5	↓
	Nicaragua*	0.025	9	0.053	11	↓
	Pakistan*	0.184	5	0.248	3	↑
	South Africa	0.018	12	0.055	10	↑
	Thailand	0.215	4	0.219	4	↔
Combination	Australia	0.000	15	0.000	15	↔
	Brazil	0.242	8	0.437	7	↑
	China	1.000	1	1.000	1	↔
	Colombia	0.069	14	0.280	13	↑
	Ecuador*	0.328	6	0.341	11	↓
	Honduras*	0.285	7	0.428	8	↓
	Indonesia	0.492	2	0.598	3	↓
	Jamaica	0.163	10	0.631	2	↑
	Japan	0.086	13	0.261	14	↓
	Malaysia	0.128	11	0.415	9	↑
	Mexico	0.441	3	0.440	6	↓
	Nicaragua*	0.182	9	0.346	10	↓
	Pakistan*	0.379	5	0.547	4	↑
	South Africa	0.105	12	0.334	12	↔
	Thailand	0.379	4	0.511	5	↓

Notes: * denotes 2003

Closer examination of the scatter plot of vulnerability index (from the combined aggregation)against GDP per capita as illustrated in *Figure 1* and *2* shows that the position of China relative to the others is highly vulnerable both in year 2002 and 2006. For Australia and Japan these countries suggests they are outliers and is attributed to high income economies with greater adaptive capacity compared to others. Moreover, the relationship between GDP per capita and vulnerability as illustrated by these negative slopes suggest as GDP per capita increases (decreases) the vulnerability index among countries decreases (increases) the low (or high).

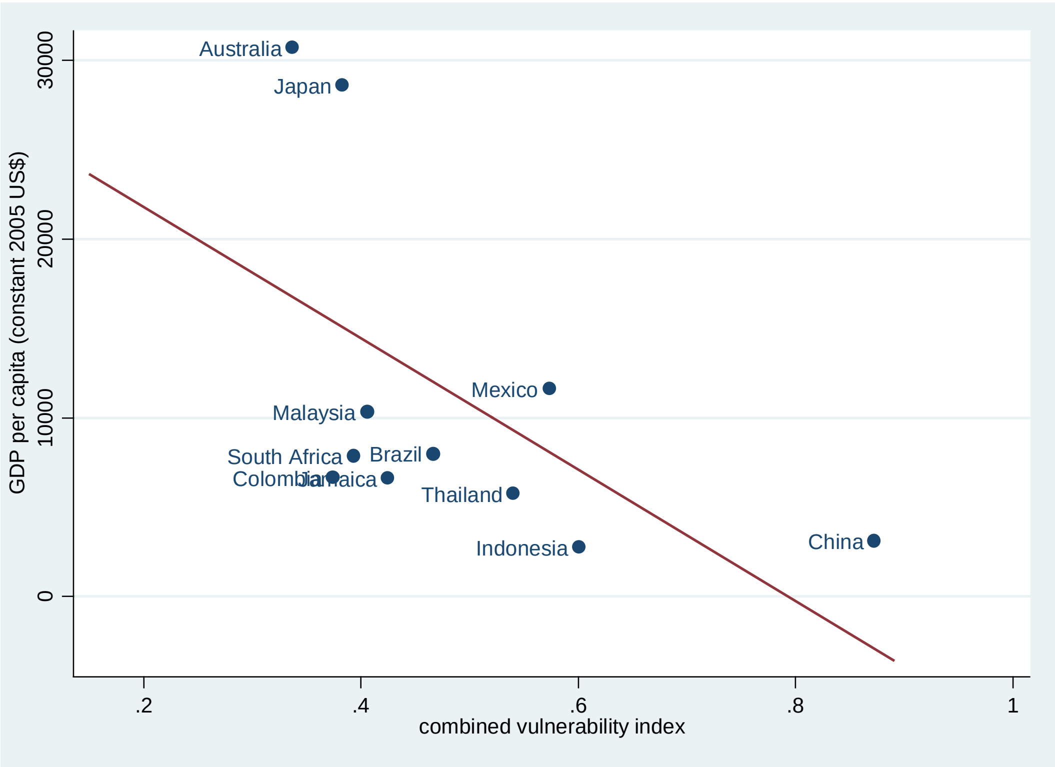

Figure 1: Link of combined aggregated index and GDP per capita in 2002 (excluding temperature variation)

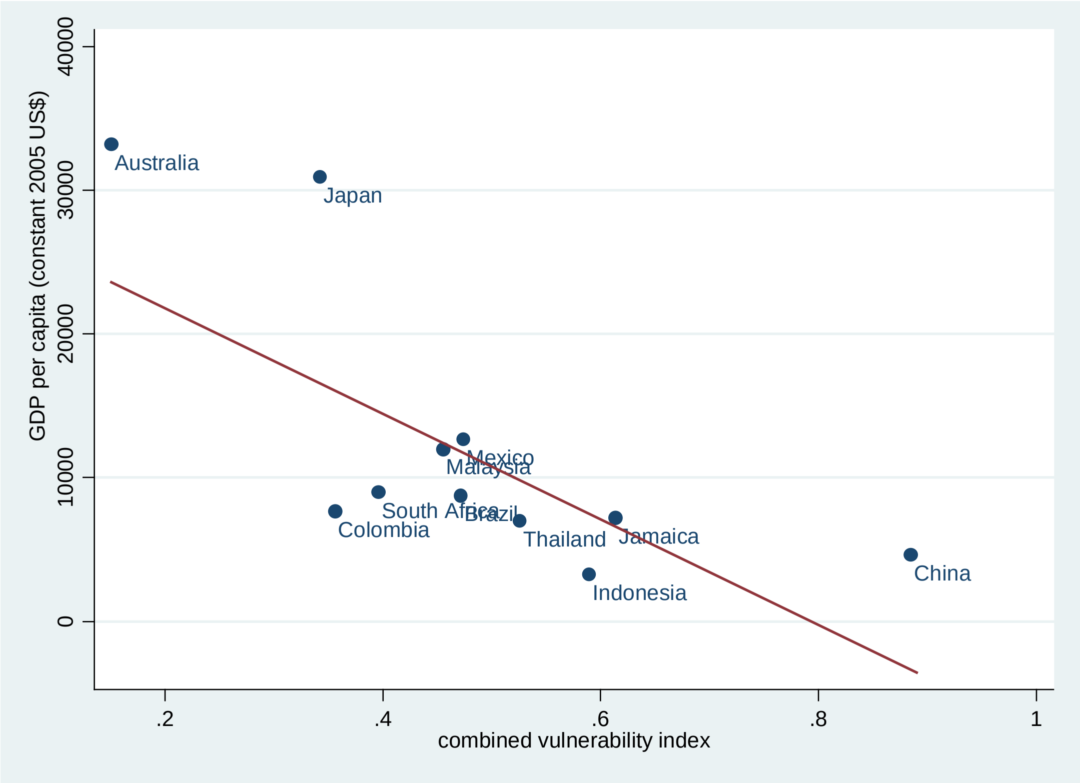

Figure 2: Link of combined aggregated index and GDP per capita in 2006 (excluding temperature variation)

Despite the country variation among all the vulnerability studies the ranking results found in this study are consistent with the previous studies (i.e. Burke et al (2011), Cinner et al (2012) and Cheung et al (2012)) confirming the conclusion that at regional/national-scale index the most vulnerable nations are primarily located in developing and/or emerging countries. In fact, the top five countries highly vulnerable as ranked accordingly by: Burke et al (2011) include Philippines, Indonesia, Cuba, Madagascar and Solomon Islands; whereas for Cinner et al (2012): Madagascar, Kenya and Tanzania and Cheung et al (2012) include: Comoros, Togo, Cook Islands, Kiribati and Eritrea. In our case, the top ones were: China, Jamaica, Indonesia, Pakistan and Thailand.

The vulnerability indices computed should be taken with caution as other exposure factors may play a major role in the index calculation. Importantly, are local factors as well as national accounts of coral bleaching (linked to increased surface sea temperature), nitrogen depositions, marine pollution and overfishing data. In this case, *Table 4*, depicts another set of VIs by including additional component to exposure namely temperature variability as an external risk to coral reef dependent areas. . Moreover, the sensitivity of this variable to the exposure index is relevant as the temperature variability induces coral bleaching incidents particularly at high temperatures. However, the limited data availability on temperature led to fewer countries from the previous *Table 3*. Our attempt to use coral bleaching events instead of temperature variation resulted to fewer countries than the temperature one, however, the vulnerability patterns showed a similar trend between the coral bleaching and temperature variations for countries.

Table 4: Vulnerability indices including temperature variation in exposure

	Country	**2002 VI**	**2002 rank**	**2006 VI**	**2006 rank**	**change in rank 2002-2006**
Cinner et al	Australia	0.306	5	0.000	6	↓
	Brazil	0.447	3	0.529	3	↔
	China	1.000	1	1.000	1	↔
	Japan	0.172	6	0.230	5	↑
	South Africa	0.342	4	0.467	4	↔
	Thailand	0.907	2	0.862	2	↔
Burke et al	Australia	0.154	5	0.000	6	↓
	Brazil	0.223	3	0.227	4	↓
	China	1.000	1	1.000	1	↔
	Japan	0.140	6	0.099	5	↑
	South Africa	0.213	4	0.249	3	↑
	Thailand	0.911	2	0.802	2	↔
Combination	Australia	0.291	5	0.000	6	↓
	Brazil	0.426	3	0.504	3	↔
	China	1.000	1	1.000	1	↔
	Japan	0.169	6	0.219	5	↑
	South Africa	0.330	4	0.449	4	↔
	Thailand	0.907	2	0.856	2	↔

Note: 1. These results were based on Cinner et al (2012) framework

What is emerging from this estimation is the exposure index has increased for most countries except for China than in the previous table and the overall VI is slightly higher than the other estimations. Similar to the previous tables, the change of the rank of VI is slight compared to*Table*3. Again, this trend could be attributed to increased adaptive capacity by countries in period 2002-2006 except for Japan which shows an anomaly increase of VI unlike the VI without temperature in 2006. One plausible reason can be explained by major catastrophe in the pacific area related to earthquakes hence decreasing adaptive capacity in the area. Nevertheless, due to limited temperature data we are unable to examine further trends of increased temperature effects as well as coral bleaching incidents for other countries.

5. Conclusion

Irrespective of the aggregation methods proposed this study has illustrated like other previous studies that exposure, adaptive capacity and sensitivity varies among nations and there are no cookie-cut approaches in adaptation and mitigation efforts for these states. Therefore for policy relevance, stakeholders need to plan, manage and allocate resources effectively and efficiently in distinct regions to protect fragile ecosystems under climate change. Moreover, the various linear aggregate approaches of multiplicative, additive and combination indicate that the three are different from each other hence the computation of such aggregation of indices do matter in vulnerability.

Similarly, variables found in exposure component are a major concern. For instance, coral bleaching incidents which are related to increased temperature are uncertain and their effect on fisheries nurseries, food security and livelihood of local people and businesses is pernicious. Consequently, future works should attempt to examine coral bleaching incidents along with the diverse coral reef types and quality to determine the resilience and recovery levels for the distinct reef types in all regions. Indeed, what has emerged from this work is that biophysical processes and the biological nature of coral reef ecosystem are complex and requires more specific data in examining vulnerability. Hence, an inter-disciplinary approach among economists, ecologists and biologists in determining measurable pathways are vital to help create better management options in mitigation and/or adaption against climate change.

Significantly, the creation of aggregated portal that include open data related to vulnerability is essential as most present databases are scattered and fragmented. Indeed, limited data access to essential indicators may endanger the meaningful research of vulnerability for individuals and/or states when such information is restricted for researchers as well as planners. One way forward is for researchers and planners to establish a portal particularly related to marine resources to reduce the complexity and subjectivity of indices construction.

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Appendix 1

***Table 1A*: Checklist for construction of vulnerability indices**

	Step	Why and how carried out
1	Theoretical framework	Vulnerability is relevant in the case of coral reef communities where the linkage of exposure, sensitivity and adaptive capacity of communities is essential in adaptation and mitigation efforts against climate changes.
2	Data selection	The selection and combination of variables were related to ecological as well as social and economic factors. The use of proxies variables were considered as option when data was unavailable. The strength of these variables were commonly used in other vulnerability construction in previous literature such as Cinner et al (2012), Burke et al (2011), However, the weakness is that data is across countries and over time hence, there are no local or regional specific data on coral reef communities.
3	Imputation of missing data	In some cases there were missing data among countries however no imputationof these missing values were carried out.
4	Multivariate analysis	A principal component analysis for the three components of vulnerability namely exposure, sensitivity and adaptive capacityshowed the results on the weights of each of the component were mixed. Also, each sub-component varies with time where adaptive capacity increases and the exposure as well as sensitivity are decreasing.
5	Normalisation	The normalization was carried out based on the data properties namely using the min-max method in all cases across countries and years.
6	Weighting and aggregation	The weighting for three aggregation types was linear, simple and equal weight however the third one namely the combination consisted of the inter-mediate option of multiplicative and additive aggregation. Also, rankings to confirm with the VI aggregations.
7	Uncertainty and sensitivity analysis	In comparison with previous studies conducted by Burke et al (2011) and Cinner et al (2012) the variables and the weight used in those studies.
8	Back to the data	Attempted to examine why the vulnerability trends were high in countries such as China or low in the case of Australia. Also, our attempt to identify the effect of increased exposure particularly related to inclusion of temperature variation.
9	Links to other indicators	The comparison combined (intermediate) index comparedto GDP per capita.
10	Visualisation of the results	Plotted the distinct vulnerability indices to illustrate the differences found on three aggregation methods.