



## Review

# The emerging threats of climate change on tropical coastal ecosystem services, public health, local economies and livelihood sustainability of small islands: Cumulative impacts and synergies



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## ABSTRACT

Climate change has significantly impacted tropical ecosystems critical for sustaining local economies and community livelihoods at global scales. Coastal ecosystems have largely declined, threatening the principal source of protein, building materials, tourism-based revenue, and the first line of defense against storm swells and sea level rise (SLR) for small tropical islands. Climate change has also impacted public health (i.e., altered distribution and increased prevalence of allergies, water-borne, and vector-borne diseases). Rapid human population growth has exacerbated pressure over coupled social–ecological systems, with concomitant non-sustainable impacts on natural resources, water availability, food security and sovereignty, public health, and quality of life, which should increase vulnerability and erode adaptation and mitigation capacity. This paper examines cumulative and synergistic impacts of climate change in the challenging context of highly vulnerable small tropical islands. Multiple adaptive strategies of coupled social–ecological ecosystems are discussed. Multi-level, multi-sectorial responses are necessary for adaptation to be successful.

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## 1. Introduction

*“Human influence on the climate system is clear, and recent anthropogenic emissions of greenhouse gases are the highest in history. Recent*

*climate changes have had widespread impacts on human and natural systems. Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, and sea level has risen. Anthropogenic greenhouse gas emissions have increased since the pre-industrial era, driven largely by economic and population growth, and are now higher than ever. This has led to atmospheric concentrations of carbon dioxide, methane and nitrous oxide that are unprecedented in at least the last*

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800,000 years. Their effects, together with those of other anthropogenic drivers, have been detected throughout the climate system and are extremely likely to have been the dominant cause of the observed warming since the mid-20th century. In recent decades, changes in climate have caused impacts on natural and human systems on all continents and across the oceans. Impacts are due to observed climate change, irrespective of its cause, indicating the sensitivity of natural and human systems to changing climate. Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of severe, pervasive and irreversible impacts for people and ecosystems. Surface temperature is projected to rise over the 21st century under all assessed emission scenarios. It is very likely that heat waves will occur more often and last longer, and that extreme precipitation events will become more intense and frequent in many regions. The ocean will continue to warm and acidify, and global mean sea level to rise. Climate change will amplify existing risks and create new risks for natural and human systems. Risks are unevenly distributed and are generally greater for disadvantaged people and communities in countries at all levels of development. Many aspects of climate change and associated impacts will continue for centuries, even if anthropogenic emissions of greenhouse gases are stopped. The risks of abrupt or irreversible changes increase as the magnitude of the warming increases".

[(Intergovernmental Panel on Climate Change, IPCC, 2014a)]

The above statement constitutes part of the most significant conclusions of the International Panel on Climate Change (IPCC) 5th Assessment Report, which explicitly defined the implications of climate change impacts in the near future. The report also concluded that warmer and/or fewer cold days and nights will occur over most land areas at the end of the 21st century, as well as warmer and/or more frequent hot days and nights. An increased frequency and/or duration of warm spells and/or heat waves will also be very likely to occur over most land areas. Heavy precipitation events and an increased frequency, intensity, and/or amount of heavy precipitation will also be very likely to occur, particularly along wet tropical regions. Other potential impacts very likely to occur at regional scales include the increased intensity and/or duration of drought conditions, increased intense tropical cyclone activity, increased sea surface warming and ocean acidification, and the increased incidence and/or magnitude of extreme high sea level. The combined impacts of these factors may affect multiple ecosystem functions, compromise food security and sovereignty, public health, local economies and people's livelihood sustainability in still largely unknown ways.

Current trends in changing climate, in combination with mathematical model predictions, have shown that anthropogenic-driven climate change has already had or will unequivocally have unprecedented impacts on biodiversity (Bellard et al., 2012), across multiple terrestrial (Shukla et al., 1990; Melillo et al., 1993; Still et al., 1999; Bonan, 2008) and marine ecosystems (Michener et al., 1997; Hoegh-Guldberg, 1999; Hoegh-Guldberg et al., 2007; Veron et al., 2009; NRC, 2010), with significant implications for human settlements (Mimura, 1999; Nicholls et al., 2008; Nicholls et al., 2010; Chindarkar, 2012), and variable but often negative and significant socio-economic consequences across regional scales (Tol, 2002; Parry et al., 2004; Stern, 2006; Lane et al., 2013). This is a particular concern for developing nations and small island nations, with rapidly growing human populations. Current impacts associated with SLR, altered patterns of tropical and extra-tropical cyclones, increasing air and sea surface temperatures (SST), and changing rainfall patterns confirm findings reported on small islands from the 4th Assessment Report and previous IPCC assessments. The future risks associated with these drivers include loss of adaptive capacity and ecosystem services critical to lives and livelihoods in small islands (IPCC, 2014b). Increasing population density may significantly reduce adaptive capacity in small islands.

Human population growth can have paramount impacts in the use and conservation of natural resources (Holdren and Ehrlich, 1974; Vitousek et al., 1997; Vörösmarty et al., 2000; McKee et al., 2003).

Such impacts could be significantly magnified by climate change. But potential long-term impacts of climate change in a human-dominated world still remain largely unknown (Karl and Trenberth, 2003). Some abrupt impacts on vulnerable coastal and marine ecosystems can occur rapidly beyond tolerance thresholds to changing environmental variables (NRC, 2013). Others may occur over very slow, often undetected, transient states between alternate stable states (Hughes et al., 2013a,b), implying a need to reevaluate the spatial and temporal scales of impacts and ecosystem conservation-oriented management strategies (Rau et al., 2012). This could have monumental long-term implications when analyzed in the combined and synergistic context of climate change impacts on environmental and public health, as well as that associated to SLR, declining biodiversity, water availability, food security and sovereignty, and on declining local economies and community-based livelihoods. Analyses of the combined and synergistic impacts of these factors are still largely missing.

The conservation of coastal ecosystem biodiversity, resilience, functions, benefits and services has acquired an unparalleled value in the context of projected trends of climate change impacts at a global scale. Mean atmospheric (ATM) carbon dioxide (CO<sub>2</sub>) concentration at the Mauna Loa Observatory, Hawaii, reached during July 2015 a maximum concentration of 401.3 ppm. There was a mean value of 404.4 ppm during early April 2015 (NOAA-ESRL data, 2015). Mean annual rates of change in ATM CO<sub>2</sub> have increased from 0.6 ppm/year during mid-20th century to 2.17 ppm/year over the last decade (Fig. 1), with an increase of 2.4 ppm between early 2014 and early 2015. This suggests that a sustained minimal global ATM CO<sub>2</sub> concentration of 400 ppm has been already reached, implying that global-scale measures to reduce atmospheric emissions of greenhouse gases (GHG) have not been effective enough to reduce accelerating ATM CO<sub>2</sub> build up. GHG emissions rates increased during 2000–2010 by a factor of 2.2%/year, in comparison to 1.3%/year during 1980–1990 (IPCC, 2014a). Under a continuing business-as-usual scenario, the unprecedented 600 ppm benchmark in ATM CO<sub>2</sub> concentration could be reached by 2082 or earlier, and the 800 ppm benchmark by 2130, if not earlier. This could result in an unprecedented increase in ATM CO<sub>2</sub> concentration and global temperature with yet unknown consequences across unprecedented rapid temporal and widespread biological scales.

SST rise itself is not unprecedented. What has no parallel in the geological record, at least over the last 800 Ky (Jouzel et al., 2007), is the current trend of change observed since mid-19th century. Current mean SST is 7 °C higher in comparison to the Pleistocene 130,000 years ago (McCulloch et al., 1999). It is also 6.5 °C higher in comparison to the

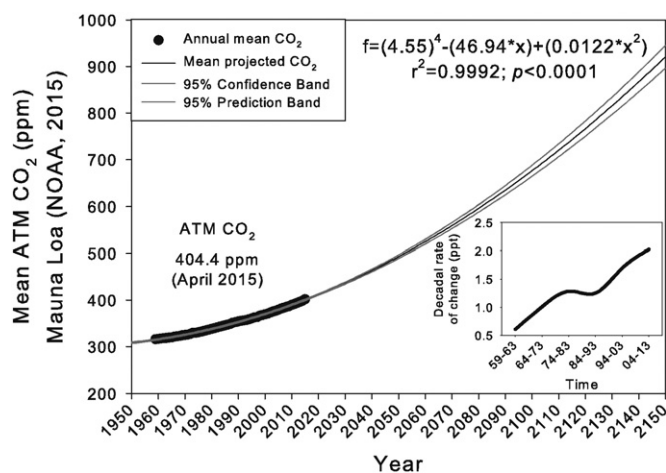
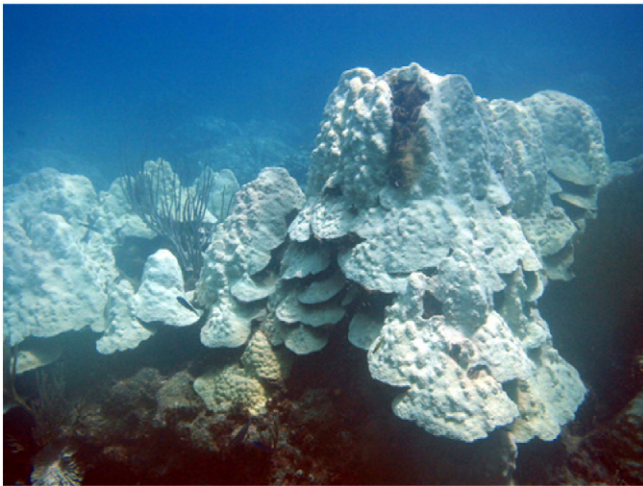


Fig. 1. Current and projected increases in atmospheric (ATM) carbon dioxide (CO<sub>2</sub>) concentrations at Mauna Loa, Hawaii, based on a non-linear regression analysis (1950–2150). Data source: ATM CO<sub>2</sub> concentrations from 1959 to 2015 (NOAA Earth System Research Laboratory, Global Monitoring Division, [http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo\\_data](http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_data)) (NOAA, 2015).

Holocene 10,350 years bp (Beck et al., 1997). Such changes, though relatively rapid on a geological time scale ( $\approx 1^\circ\text{C}/4483$  years since the Pleistocene;  $\approx 1^\circ\text{C}/2040$  years since the Holocene), do not even compare to the current escalating trend measured at  $0.4$  to  $0.8^\circ\text{C}$  only during the 20th century (Cane et al., 1997; Delworth and Knutson, 2000; Stock et al., 2011). A  $0.6^\circ\text{C}$  increase has also occurred over the last three decades (Hansen et al., 2006). Current trends have escalated up to  $0.2^\circ\text{C}/\text{decade}$ . So far the Earth is within  $\approx 1^\circ\text{C}$  of the warmest maximum during any interglacial period over the last 1.35 Ma (Medina-Elizalde and Lea, 2005; Hansen et al., 2006). Increasing temperature trends have scaled up after the global industrialization (Andronova and Schlesinger, 2000; Folland et al., 2001) at rates with no precedent in the geological record. There is also a projected SST increase of at least  $1\text{--}3^\circ\text{C}$  above current values by the end of 21st century (Hoegh-Guldberg, 1999; Kauffman et al., 2006), with potential to reach up to  $4.8^\circ\text{C}$  (IPCC, 2014a). This may trigger significant changes in tropical marine ecosystems, including recurrent massive coral bleaching episodes (Fig. 2) in the near future with potentially dramatic ecological (McWilliams et al., 2005; Buddemeier et al., 2008, 2010; Veron et al., 2009; Hoeke et al., 2011) and socio-economic (Lane et al., 2013) consequences for coral reefs and other coastal ecosystems. If no significant control on GHG emissions is implemented at a global scale, this would have irreversible environmental, ecological, health, and socio-economic consequences, particularly on small tropical island nations and low-lying coastal plains along developing nations. Insular states are often very low emitters of GHG, but yet are potentially the most vulnerable to the long-term effects of climate change.

There is also an increasing concern with climate change impacts on public health (Haines et al., 2000, 2006; Patz et al., 2005; Keim, 2008; Méndez-Lázaro, 2012) and how this could magnify human vulnerability to other climate-related impacts, including altered weather patterns, water availability, crops and fisheries productivity, food security and sovereignty, SLR, biodiversity loss, and ecosystem change, and their combined socio-economic and political consequences (Liverman, 1990). Climate change represents one of the greatest environmental and health equity challenges of our times (Patz and Kovatz, 2002).



**Fig. 2.** Coral reef ecosystems are highly vulnerable to climate change. Increased sea surface temperatures for periods of time over 1–2 months often result in massive coral bleaching events where reef-building corals expel their symbiotic zooxanthellae. In this example, laminar star corals (*Orbicella faveolata*), one of the most significant reef-building species of the Atlantic, bleached in Puerto Rico during the unprecedented sea surface warming event of 2005 across the wider Caribbean. Several large-sized reef-building species in the Atlantic are among the most vulnerable species to massive bleaching (Brandt, 2009; van Hooidonk et al., 2012). If bleaching extends for several weeks corals may become susceptible to microbial-borne diseases and suffer mass mortalities decimating entire populations with irreversible consequences for reef accretion, ecosystem functions, productivity, biodiversity, ecosystem resilience and services. The 2005 event resulted in a 60–80% loss in percent living coral cover across the northeastern Caribbean region (Miller et al., 2006, 2009; Hernández-Pacheco et al., 2011).

Wealthy, energy-consuming, GHG-emitter nations are most responsible for global warming, yet poor countries with significant socio-economic, environmental, public health, and hunger stresses are at most risk. This could further have meaningful political consequences as these factors may trigger massive migrations and potential invasions of adjacent countries. There is evidence that changes in the spatio-temporal distribution and prevalence of many diseases have occurred over recent years (Haines et al., 2000; Patz et al., 2000; Ziska et al., 2003; Horton et al., 2010), with major impacts on developing countries, but attempts to quantitatively link such changes to climate-driven ecosystem change are still largely lacking. There is also consensus that factors such as increased thermal stress, extreme weather events, future regional food yields, and infectious disease and hunger prevalence will become the major public health threats of climate change (Patz et al., 2005; McMichael et al., 2006). But there are still major concerns regarding health risks due to the social, demographic, and economic disruptions driven by climate change. Further, SLR has been forecasted to rapidly increase over the 21st century with increasing coastal erosion impacts (Gornitz, 1995; Wong, 2003), groundwater salinization (Ranjan et al., 2006), and major forecasted displacement of human populations from low-lying coastal areas (Jallow et al., 1996). SLR should flood substantial low-lying coastal urban and industrial areas with resulting chronic unprecedented levels of pollution of coastal waters. The combined cumulative impacts of climate change, human population growth, urban sprawling, and increased industrial and agricultural activities, in combination with SLR, will likely result in increased eutrophication of coastal waters (Rabalais et al., 2009). This may result in increased harmful algal bloom events, reduced water quality, hypoxia (oxygen depletion), and habitat loss. Poor island nations with high prevalence of hunger and endemic diseases, and that have undergone massive deforestation and a nearly total fisheries collapse, such as Haiti, are particularly vulnerable to such impacts. Nonetheless, the combined long-term ecological, environmental, public health impacts of SLR in increasing coastal pollution, and its concomitant impact on local economies and in declining people's livelihoods have still been poorly addressed. These factors are expected to have a permanent adverse impact on the local economy and livelihood sustainability of coastal human settlements, particularly on small tropical islands with limited alternative socio-economic and geographic resources, and due to their higher vulnerability to rapid changes and severely limited adaptive capacity. This would require challenging and unprecedented institutional processes focused in strengthening natural resource management, governance, economic efficiency and welfare maximization in an aim to successfully adapt to climate change (Adger et al., 2005a,b).

The objective of this paper is to explore the relationship between tropical coastal ecosystems decline as a result of climate change and SLR, and its implications on public health, food production, local economies and livelihood sustainability, with most emphasis on highly vulnerable small islands. Several possible feedback mechanisms are discussed to explain these interactions. Recommendations for the development of rapid climate change adaptation strategies are suggested.

## 2. Goods and services of coral reefs and other coastal ecosystems: how much could be at stake?

Coastal ecosystems such as coral reefs, seagrass meadows, mangroves and wetlands constitute the first line of defense against storm swells, coastal erosion and SLR, therefore, provide humans multiple goods, benefits and services (Moberg and Folke, 1999). However, their continuing decline will have significant adverse consequences for biodiversity and ecosystem functions, and may also imply multiple negative impacts on their socio-economic value and benefits such as food production, public health and people's livelihood sustainability. Therefore, their ecosystem services value should significantly increase as threats from SLR and climate change increase. Average global values of annual ecosystem services were estimated in 1997 to reach \$12.6 trillion U.S.



dollars (USD) for open oceans, \$8.4 trillion for open oceans, \$4.3 trillion for shelves, \$4.1 trillion for estuaries, \$3.8 trillion for seagrass and algal beds, and \$375 billion for coral reefs (Costanza et al., 1997). These totaled an annual value of over \$33.5 trillion back in 1997, and \$28.9 trillion converted to 2007 USD. But Costanza et al. (2014) estimated in 2011 the value of open oceans in \$60.5 trillion as of 2007 USD (+109%), \$5.2 trillion for estuaries (−9%), \$5.8 trillion for seagrass and algal beds (+10%), and over \$21.7 trillion for coral reefs (+3838%). The dramatic increase in the value of coral reefs shifted from a mean \$8384/ha/year in 1997 to \$352,249/ha/year in 2011, adjusted to 2007 USD values, a change that was largely related to an increased number of studies regarding their role in storm protection, erosion protection, and recreation (Costanza et al., 2014). Also, there has been a 55% loss of coral reef area due to a combination of natural and anthropogenic stressors.

The net benefits of coral reef ecosystems were also estimated at \$30 billion USD/year (Cesar et al., 2003), which based in the 47% U.S. cumulative inflation rate between January 1997 and December 2014 (data from the Consumer Price Index published by the U.S. Bureau of Labor Statistics), would represent about \$38.7 billion 2014 USD. The net benefits of coastal ecosystems in general were estimated in \$25.8 billion USD/year (Martínez et al., 2007). Burke and Spalding (2011) estimated Caribbean coral reef annual net benefits of \$2.7 billion USD for tourism, from \$944 million to \$2.8 billion USD for shoreline protection, and of \$395 million USD for coral reef fisheries. But alarming global inflationary trends (Krichene, 2008), as well as increased threats from different anthropogenic factors, in combination with climate change and SLR (Buddemeier et al., 2004; Meehl et al., 2005), have largely increased the significance and cost of conserving and rehabilitating coastal ecosystem services. Under current climate change projections, such values will become much higher particularly for small, low-lying, tropical island nations and developing countries, where most coral reef ecosystems are found, and where their local economies and livelihoods rely almost exclusively on the condition, goods and services of coral reefs and other associated coastal ecosystems (Barnett and Adger, 2003). Many of these vulnerable countries are often characterized by having large population densities, living under unsustainable poverty levels, weak natural resource governance, often having very limited access to technology, and lacking human and financial resources to manage and conserve their natural resources, which are frequently overexploited (i.e., massive tourism) and are highly vulnerable to climate change impacts (Hernández-Delgado et al., 2012).

Coral reefs represent one of the most critical resources for livelihood sustainability on small tropical island nations and developing countries. Examples of the goods and services provided by coral reef ecosystems include fisheries (source of protein), raw materials for construction, raw natural products for pharmaceutical, food and cosmetic industries, resources for jewelry and aquarium trade markets, tourism and recreation, aesthetic value, cultural, religious and spiritual values, shoreline protection from erosion, promote the development of seagrasses and mangroves on wave-protected zones, the generation of coralline sands, land-based waste assimilation, and climate regulation (Conservation International, 2008). Other ecological services include maintenance of biodiversity, genetic diversity and habitat diversity, regulation of ecosystem processes and functions, and the biological maintenance of resilience. There is also an intrinsic value through the connectivity between ecosystems through mobile links (Lundberg and Moberg, 2003) and through exporting of organic production to pelagic food webs. Reefs also provide important bio-geochemical services such as nitrogen fixation  $\text{CO}_2/\text{Ca}^{++}$  budget regulation, and land-based nutrient assimilation. Coral reefs and associated ecosystems also function as monitors and recorders of environmental change and historical pollution trends, and contribute to climate regulation. But coral reefs and other coastal ecosystems have rarely been considered part of the critical coastal infrastructure, a value which has been poorly documented (Emerton, 2006). Further, the natural protective functions and benefits of coastal ecosystems have often been undervalued or ignored in most economic

analyses. Undervaluing coastal ecosystem services has often resulted in a lack of adequate investment in their management and protection in proportion to their benefits. In consequence, their “real” value has been significantly underestimated and ecosystems are being rapidly degraded by a combination of human-driven factors across local to global scales without adequately addressing how much could be at stake through the “real” socio-economic loss.

Recent troubling evidence of global coral reef conditions presents a deeply concerning picture of these ecosystems. A recent glimpse of representative coral reefs from all oceans at a global scale show unequivocal evidence of major decline (Wilkinson, 2008; Sale and Szmant, 2012), and unprecedented regime shifts and disruption of ecosystems and climate (Hughes et al., 2013a,b). Multiple local human activities threaten the majority of reefs and associated coastal ecosystems at a global scale and the accelerating impacts of global factors, such as increasing ATM  $\text{CO}_2$  concentration (Veron et al., 2009), sea surface warming (Hoegh-Guldberg et al., 2007; Hoegh-Guldberg, 2009, 2011; Hoegh-Guldberg and Bruno, 2010), ocean acidification (Dupont et al., 2010; Pandolfi et al., 2011a, 2011b), and SLR (Meehl et al., 2005) are compounding these problems (Burke and Spalding, 2011) and driving many countries to an increased risk of vulnerability. Stoeckl et al. (2011) also suggested that rapid degradation of coral reef adjoining ecosystems may limit ecosystem services these provide to reefs, thus additionally contributing to their demise.

Degraded coral reefs yield limited goods and services, which is expected to have magnified negative socio-economic impacts on small tropical island communities with strong reliance on coral reefs, increasing the risk of poverty (Turner et al., 2007). Many of such communities often rely on massive tourism as their main source of economic revenue, but often at the expense of rapid environmental degradation, revenue leakage, and increased vulnerability to many socio-economic, environmental, and climate change-related threats (Hernández-Delgado et al., 2012). Countries with higher risks of coral reef degradation often due to poor land use and soil conservation practices, higher dependence on reef ecosystems, overexploited natural resources, scarce water supplies, poor economic and public health condition, limited food sustainability, weak political structure and governance, and low adaptive capacity, are the most vulnerable to projected trends of climate change-related impacts, including SLR. In the long run, such impacts may even act synergistically to enhance vulnerability and poverty. Poverty and food security and sovereignty are two of the most critical concerns associated to climate change (Sánchez, 2000), and these are directly linked to the degradation of coral reef ecosystems. Poverty and a lack of protein are directly linked to fisheries overexploitation which in turn could lead to coral reef decline due to reef food web shrinkage, to increased abundance of coral predators, and due to algal overgrowth. Reef degradation in turn could lead to increased levels of hunger, increased dependence on already overexploited reef resources, and in more desperate acts of destructive fishing (i.e., using poisons and explosives to fish). Food security, sovereignty and poverty must be immediately addressed to save coral reefs in the least developed countries. Equity and justice are also another concern as the poorest and most vulnerable nations often disproportionately experience adverse effects of climate change (Smit and Pilifosova, 2001; Thomas and Twyman, 2005; Mearns and Norton, 2010), particularly when poor nations have also been exposed to increasing impacts of economic globalization (O'Brien and Leichenko, 2000) and hunger. These combined factors may further lead to security concerns associated to climate change (Barnett, 2001).

Potential interactions and synergies among these factors still have poorly understood feedback mechanisms (Fig. 3). One of the critical aspects of such synergisms that still remain largely unexplored is that related to the potential accelerated impacts that coastal environmental degradation and climate change might have on public health and food security and sovereignty. Degraded coastal water quality as a result of SLR flooding of coastal urban centers and declining coastal ecosystem functions, benefits and services due to increased pollution could have

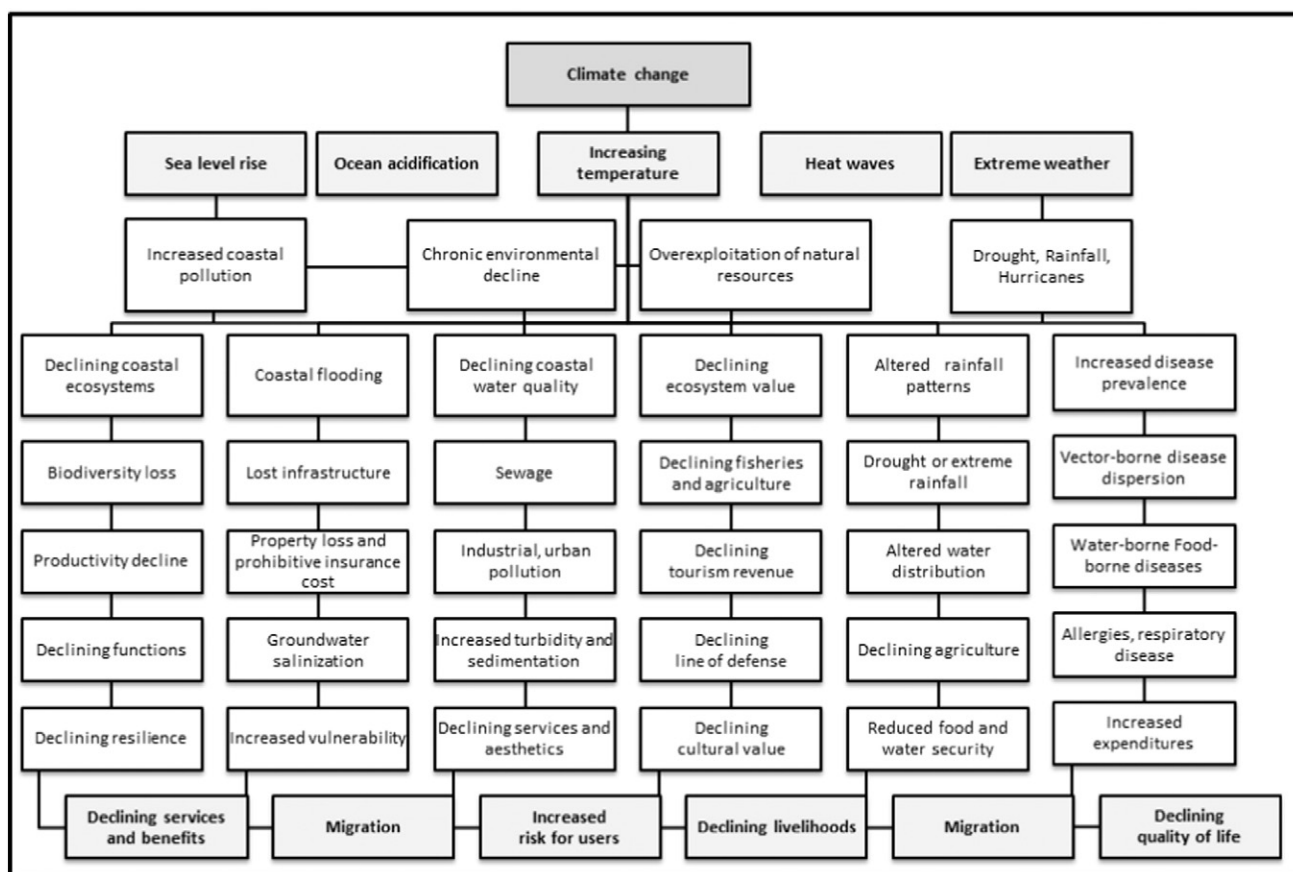


Fig. 3. Conceptual integrated model of climate change impacts on tropical coastal ecosystems, public health, local economies and on coastal community livelihoods.

potential permanent negative consequences on ecosystems, public health, local economies and livelihood sustainability. This may trigger impacts on coastal communities that can amplify change, i.e., via accelerated ecosystem decline, increasing fishing efforts and resource exploitation (Cinner et al., 2012), and increasing prevalence of water-borne diseases, which may permanently impair ecosystem resilience, uses and benefits, potentially collapsing regional tourism-based economy, local economies and people's livelihoods. The interdependence between human activities and the natural environment has also become a concern due to increasing stresses associated with the adverse impacts of overwhelming public debt and climate change. Protected areas development is one of the most cost-effective mechanisms to secure many ecosystem benefits, while simultaneously mitigating the impacts of climate change. To achieve this dual objective, protected areas development must be brought more centrally into land use planning process, ensuring that economic strategies and development plans recognize the critical contributions by protected areas to sustainable development. In the long run, this will contribute to the conservation of natural resources and to foster the sustainability of goods, benefits and services of coastal ecosystems.

### 3. The long-term cost of tropical coastal ecosystems decline

The current spatial scale, diversity, frequency, and severity of adverse impacts on tropical coastal ecosystems are unprecedented in the recent (Aronson and Precht, 2001; Aronson et al., 2002; Pandolfi et al., 2005) and past geological record (Mesoella, 1967; Pandolfi, 1996, 1999; Pandolfi and Jackson, 2001, 2006). Impacts by a diverse array of anthropogenic activities have increased in recent decades to the extent that tropical coastal ecosystems, particularly coral reefs, are threatened globally (Hughes et al., 2003). Human stressors such as poor land use patterns (DiDonato et al., 2009), massive deforestation (Ramos-

Scharrón, 2012), mangrove and wetland filling (McLeod and Salm, 2006), increased urban construction along coastal areas and watersheds (Hernández-Delgado et al., 2012; Ramos-Scharrón et al., 2012), eutrophication (Cloern, 2001; Díaz-Ortega and Hernández-Delgado, 2014), pollution (Hernández-Delgado et al., 2010, 2011), sedimentation and nutrients (Rogers, 1990; Meesters et al., 1998; Erftemeijer and Lewis, 2006; Risk, 2014), and historical overfishing over temporal scales of centuries to millennia (Jackson, 1997, 2001; Jackson et al., 2001; Pandolfi et al., 2003; Fitzpatrick and Donaldson, 2007) have largely contributed to a significant decline in species richness, biomass of target taxa, and on the resilience, functions, benefits and services of most tropical coastal ecosystems. These escalating threats may have a critical impact on existing coral species diversity (Huang, 2012) and on fisheries sustainability (Pauley et al., 2002; McClanahan et al., 2011; Pratchett et al., 2014). It may require challenging conservation-oriented management measures across unprecedented spatial and temporal scales (MacNeil and Graham, 2010; Rau et al., 2012), even beyond trans-national boundaries.

Losing coral reefs and associated ecosystems, such as seagrasses, in combination with continuing mangrove and coastal wetland filling, will have unprecedented impacts to existing coastal human settlements. Approximately, 500 million people depend on coral reefs at a global scale (Wilkinson, 2008). Any adverse impacts to these ecosystems, its adjoining terrestrial ecosystems and to coastal water quality may represent an increased risk in people's vulnerability to climate change as coral reefs, seagrasses, reef islands and mangrove systems constitute the first line of defense against storm tides, winter swells and SLR. A wide combination of factors such as shifting demands in the globalized economy, lack of socio-economic and political stability, shortage of local supplies of critical resources (i.e., water, food, fuel), or weather extremes could put the resilience of reef-dependent people on stake (Hughes et al., 2005). But coastal-based human settlements are

going to be challenged like never before as climate change will exert an unprecedented influence in societies (IPCC, 2007). The scale and rate of environmental change driven by increases in the concentration of GHG (Hönisch et al., 2009) and ocean acidification (Hönisch et al., 2012) is also unprecedented in the recent geological record beyond human history. The present rate of CO<sub>2</sub> emissions will produce an atmospheric concentration within less than 100 years not even experienced during the past 20 Ma and SST above those of the Pleistocene interglacial 130,000 years before present (McClanahan, 2002; IPCC, 2007). This may lead in the next few decades to significant – and in many cases dramatic – alterations in the availability and quality of tropical coastal ecosystem goods and services (McClanahan, 2002; Veron et al., 2009; Pratchett et al., 2014).

The ecological impacts of climate change on tropical marine ecosystems are also predicted to be diverse and long-lasting (Hoegh-Guldberg et al., 2007; Veron et al., 2009; Hughes et al., 2013a,b), with wide direct and indirect repercussions on different coastal ecosystems, including those occupied by human populations (Table 1). Climate change will affect weather patterns, riverine, estuarine, mangrove and wetland ecosystems, and their connectivity to coastal marine ecosystems, therefore affecting beaches and coral reefs, their biodiversity, resilience, productivity, benefits and services. SLR will particularly create significant problems to human settlements on low-lying coastal lands prone to flooding and beach erosion (Gornitz, 1995; Wong, 2003), with unprecedented property losses (CCSP, 2009), and increased insurance costs to compensate for weather extremes (Mills, 2005). This may result in increased vulnerability to extreme weather events (CCSP, 2009), declining coastal water quality and increased risks to public health as a result of increased pollution of coastal waters adjacent to large flooded urban areas (Hunter, 2003). There are multiple early warning signals pointing out at different factors which are showing unequivocal signs of change and distress. However, lack of technology and resources across many small island nations and developing countries can significantly limit their ability to timely detect, respond, mitigate, and/or adapt to forecasted changes.

#### 4. Early warning signals

Global scale observations have already evidenced multiple climate-related early warning signals. This has included unequivocal trends and projections of increasing sea and air temperatures across global scales (Hoerling et al., 2001, 2004; Hurrell et al., 2004; IPCC, 2007, 2014a), significant warming of the poles and rapid ice sheet melting (Jacobs and Hellmer, 1996; Oppenheimer, 1998; Johannessen et al., 2004; Krabill et al., 2004; Luthcke et al., 2006), increased anthropogenic GHG forcing (Hansen et al., 2007), increased recurrence of El Niño Southern Oscillation (ENSO) events connected with increasing temperature (Díaz et al., 2001), rising sea levels (Woodworth et al., 2009a, 2009b; Nicholls and Cazenave, 2010; Rignot et al., 2011), and increasing beach erosion rates from SLR (Wong, 2003; Ogston and Field, 2010). There is also a trend towards acidifying oceans (Orr et al., 2005; Pandolfi et al., 2011a, 2011b; Kaniewska et al., 2012), increased combined impacts of high SST and acidification in corals (Anthony et al., 2011), mass coral bleaching and post-bleaching coral mortality events (Miller et al., 2006, 2009; Eakin et al., 2010), and marine infectious disease outbreaks across multiple taxa (Burge et al., 2014). Hurricanes have increased in frequency (Knutson et al., 1998; Mann and Emanuel, 2006), severity (Elsner, 2006; Bender et al., 2010), duration (Webster et al., 2005), and have shown altered routes across the Atlantic under warming conditions (Pezza and Simmonds, 2005; Slater et al., 2005), with increased destructive potential (Lugo, 2000; Emanuel, 2005). There is also evidence of increased risks of hurricane intensity with increased ATM CO<sub>2</sub> (Knutson et al., 1998; Knutson and Tuleya, 1999, 2004; Anthes et al., 2006). Spatio-temporal shifts in atmospheric humidity (Manabe and Wetherald, 1980) and rainfall patterns have also been documented (Walther et al., 2002; Neelin et al., 2006), including an increase in the occurrence of extreme rainfall events across very large spatial scales (Easterling et al., 2000; Meehl et al., 2007), which may impact coral reef ecosystems (Hernández-Delgado et al., 2014). Such alterations may also trigger significant alterations in terrestrial ecosystems functioning and productivity. There is experimental

**Table 1**  
Most-likely impacts of climate change on coastal ecosystems, and local economies.

System	Summary of responses	
	Impact	Synergistic response
Weather	Increased frequency of extreme weather events (i.e., droughts, wildfires, storms, flash floods, landslides)	Altered freshwater availability; declining ecosystem productivity; declining crop production and food security; declining riverine, estuarine and coastal water quality; increased property loss and vulnerability to extreme weather events
Coastal lands	Sea level rise	Degradation of coastal aquifers by saline intrusion; increased vulnerability of adjacent human communities to recurrent coastal flooding events; flooding of urbanized areas (i.e., storm and sewage sewers; sewage treatment facilities, etc.); increased coastal pollution and turbidity due to mixing with polluted effluents
Beaches	Sea level rise Increased hurricane frequency	Increased beach erosion and property loss; irreversible damage to coastal amenities and infrastructure; declining aesthetical value of coastal ecosystems as a result of coastal erosion and water quality decline; ecosystem resilience decline; loss of goods and services
Mangroves, estuaries	Sea level rise	Altered spatial distribution of mangrove/wetland ecosystem functions and productivity; potential loss of buffering role of major flooding events and wave action during hurricanes, depending on location
Seagrasses	Sea level rise	Potential long-term invasion of flooded coastal plains; rapid declining condition of existing seagrasses due to declining water quality and pollution; declining ecosystem functions and productivity
Coral reefs	Sea surface warming Sea surface warming Ocean acidification Sea level rise	Recurrent massive coral bleaching and mass coral mortalities; declining fisheries and overall biodiversity; losing ecosystem resilience, functions, services and benefits; declining coastal water quality for sustainable reef growth; declining coral skeletal extension and calcification rates; increased bioerosion rates; shortening of reef-based food webs; declining productivity and availability of natural products of biomedical significance; declining aesthetic value for tourism industry; potentially declining role as CO <sub>2</sub> sinkhole
Local economy and sustainability	Multiple, across widespread socio-economic sectors	Declining sustainable productivity of crop and fisheries, food security, and coastal community livelihoods; declining environmental conditions, local economy, increased co-dependence in globalized economic models which may further negatively impact local economies; reduction in long-haul passengers due to ethical concerns associated to carbon footprint and regulatory taxes; changes in preferences of the tourism market; Increased vulnerability of beachfront properties and public infrastructure to hurricanes and SLR; increased costs of SLR mitigation; increased cost of insurance for beachfront properties; increased cost of treating deteriorated public health conditions



evidence that declining rainfall during ENSO resulted in declining vegetation species diversity in tropical forest ecosystems (Bunker and Carson, 2005). Further, declining rainfall could have adverse impacts on estuarine productivity in response to altered timing and availability of freshwater, nutrients and sediment delivery rates (Scavia et al., 2002). It may also represent a risk of declining coastal aquifer recharge, which in combination with increasing SLR may result in salt groundwater intrusion (Frederick and Major, 1997; Ranjan et al., 2006), a problem potentially exacerbated by the typical small island trends of rapid population growth and migration towards larger coastal cities (Mimura, 1999) which may increase water consumption demand.

Mathematical models have shown at least a 25% weakening in the North Atlantic thermohaline circulation (Schmittner et al., 2005), with regional and global alterations on ocean–atmosphere circulation (Trenberth, 1990; Deser and Blackmon, 1993; Visbeck, 2002; Rahmstorf, 2003). This could influence rainfall and hurricane patterns, as well as trade winds strength and spatial extent across regional to global spatial scales (Black et al., 1999; Taylor et al., 2012). Weaker trade winds and a negative North Atlantic Oscillation (NAO) oceanographic circulation index can alter salinity patterns across the Caribbean (Schmidt et al., 2004), produce increased sea surface warming of high latitudes due to increased latent heat transport from the equator (Schmittner and Stocker, 1999), as well as altered phytoplankton (Hays et al., 2005; Martínez et al., 2009; Boyce et al., 2010; Siegel and Franz, 2010; McQuatters-Gollop et al., 2011) and zooplankton (Brodeur et al., 1999; Richardson, 2008) dynamics and community composition due to declining nutrient upwelling effects, a drop in primary productivity (Barton et al., 2003; Behrenfeld et al., 2006; Taylor et al., 2012), and in shifting fisheries productivity (Taylor et al., 2012). It has also been estimated that alterations of the thermohaline circulation may contribute to increase sea level up to 1 m (Stocker and Schmittner, 1997; Knutti and Stocker, 2000; Levermann et al., 2005; Rahmstorf, 2006), with important consequences for coastal settlements. Transport of oxygen from the sea surface to the deep ocean would slow or cease, depriving the deep oceans of their supply of oxygen over scales of decades to centuries rendering them hypoxic or anoxic as happens now across many coastal regions (Justić et al., 1996, 1997; Rabalais et al., 2002). This may occur in combination with increasing primary production and consequent worldwide coastal eutrophication fueled by riverine runoff of fertilizers and the burning of fossil fuels (Rabalais et al., 2001; Díaz and Rosenberg, 2008), and a declining NAO, with potentially higher freshwater and dissolved nutrient inputs into coastal areas that may exacerbate the formation or expansion of dead zones. The combination of increasing SST and hypoxia may also foster significant alterations in the biogeographic distribution of multiple species (Pörtner, 2001), in part due to potentially increased stratification of the water column, surface freshening, and altered mixed-layer dynamics which may negatively impact the delivery of nutrients from the upper ocean where plant production occurs to dark deeper layers (Sarmiento et al., 1998; Stocker et al., 2001; Behrenfeld et al., 2006). In turn, this could affect deep-sea animals (i.e., commercial fish and squid species) and their communities in the water column and on the ocean floor. Deep water benthic ecosystems have already shown short-term responses to climate change (Glover et al., 2010). Nonetheless, links of these altered global-scale oceanic factors to declining coastal resources, and declining coastal economies and community-based livelihoods still remain poorly understood and should be a focus of future research.

Altered range shifts across terrestrial and marine species, as well as altered tree phenology, have also been documented among the most common early warning signals of climate change (Walther et al., 2002), in combination with major and often irreversible phase shifts in marine ecosystems (Hughes et al., 2013a,b). Widespread degradation of coral reef ecosystems has occurred as a combined result of recurrent hurricane impacts (Gardner et al., 2003), particularly following the Long-spine sea urchin (*Diadema antillarum*) mass mortality event

across the wider Caribbean region in 1983–84 (Jackson et al., 2014). Massive coral bleaching and consequential mortality (Miller et al., 2006, 2009; Baker et al., 2008; Hernández-Pacheco et al., 2011; De'ath et al., 2012; Alemu and Clement, 2014), recurrent infectious diseases across multiple taxa (Burge et al., 2014), and ocean acidification (Hoegh-Guldberg et al., 2007; Dupont et al., 2010), in combination with factors associated to human exploitation (Jackson et al., 2014), have further contributed to the observed coral reef decline. Recent evidence suggests that elevated SST, in combination with eutrophication, can magnify impacts of sedimentation on coral reefs (Weber et al., 2012). Also, chronic eutrophication has been shown to produce up to a 3.5-fold increase in the prevalence and severity of coral bleaching and diseases (Vega-Thurber et al., 2014). Large-scale studies have shown a disturbing impairment of the regeneration potential of Caribbean coral reefs following disturbance (Gardner et al., 2005), and projections of climate change impacts suggest further unavoidable decline under current trends (Graham et al., 2006; Buddemeier et al., 2008, 2010; Hernández-Pacheco et al., 2011; Lane et al., 2013).

Coral reef fish community declines have also been documented across moderate to very large spatial scales coinciding with habitat decline (Jones et al., 2004; Pratchett et al., 2008; Paddock et al., 2009), threatening the sustainability of reef fisheries, food security and sovereignty, and people's livelihoods across many countries (Pauley et al., 2002; Cinner et al., 2011, 2012; McClanahan and Cinner, 2012). Coral-dependent fishes can suffer the most rapid population declines as coral is lost (Munday et al., 2008; Pratchett et al., 2008, 2014). However, many other fish species may exhibit long-term declines due to the long-term loss of settlement habitats and erosion of habitat structural complexity (Pratchett et al., 2008). Increased SST may also affect the physiological performance and behavior of coral reef fishes, especially during their early life history (Roessig et al., 2004; Munday et al., 2008). Increased SST is expected to accelerate larval development, potentially leading to reduced pelagic duration and earlier reef-seeking behavior (Munday et al., 2009). Therefore, depending on the spatial arrangement of reefs, we would expect a reduction in dispersal distances and the spatial scale of connectivity. A small increase in SST might enhance the number of larvae surviving the pelagic phase, but larger increases are likely to reduce reproductive output and increase larval mortality (Munday et al., 2009). Changes to ocean currents could also alter the dynamics of fish larval supply, may alter larval dispersion routes and the scales necessary for effective dispersal for many species (Cowen et al., 2006), as well as the overall spatial distribution of global-scale fisheries (Cheung et al., 2010). How could these alteration affect people's livelihoods across local to regional spatial scales still remains largely unknown.

Combined factors such as chronic habitat decline, overfishing and declining herbivory rates may lead fish populations to fall below critical minimums and to a significant decline in fertilization success (Ogden, 1997; Elmhirst et al., 2009). It may also alter large-scale connectivity (Steneck, 2006) and could also impact planktonic productivity (Hays et al., 2005; Behrenfeld et al., 2006), which could affect the amount of larvae surviving the pelagic stage and their condition at settlement. Even high-latitude pelagic species exhibit significant changes in seasonal migration patterns related to climate-induced changes in zooplankton productivity, changes in species composition, altered geographic distribution, and climate-related changes in recruitment success stemming from either higher production or survival in the pelagic egg or larval stage, or owing to changes in the quality/quantity of nursery habitats (Rijnsdorp et al., 2009). Further, the demographic impacts of fishing could have substantial effects on the capacity of populations to buffer climate variability (i.e., changing demography, migration) and may reduce the capacity of populations to withstand climate variability and change (Planque et al., 2010). At the ecosystem level, such reduced complexity by elimination of species may be destabilizing and could lead to reduced resilience to disturbance. Fishing and climate change have also been pointed out as co-factors leading to a ten-fold increase in medusae biomass in the Bearing Sea (Brodeur et al., 1999). Combined

effects may modify ocean energy and material flows as well as biogeochemical cycles, eventually impacting the overall ecosystem functioning and services upon which people and societies depend (Doney et al., 2012). These combined factors could have long-term negative impacts for fisheries productivity across regional to global spatial scales, and if combined with overall nursery grounds habitat degradation associated to increased pollution and SLR, could have unprecedented permanent impacts on coastal community livelihoods, particularly along the tropics.

Extreme weather events, mostly in the form of major rainfall episodes, could have significant impacts on watershed, estuarine and coastal dynamics and productivity. Although little is known about the effects of flooding on coral or reef fish recruitment, extreme rainfall and increased recurrence of flood events could potentially influence temporal patterns of coral reef connectivity on nearshore reefs, especially if increased freshwater runoff pulses differentially affect the survival and dispersal pattern of larvae or the production of the planktonic food that larvae need during their pelagic phase across coastal waters. For example, significant storm runoff can result in localized coral mortality (Nowlis et al., 1997), and chronic sediment deposition and nutrient inputs can smother reef benthic communities and impair reef growth (Rogers, 1990; Meesters et al., 1998; Ramos-Scharrón et al., 2012; Risk, 2014). It may also cause a decline in coral recruitment rates (Goh and Lee, 2010). Changes in nutrient availability associated with runoff can change the composition of plankton communities that are food for larvae (McKinnon et al., 2007) and changes in salinity can alter the direction of currents or cause larvae to modify their vertical position in the water column (Paris et al., 2002; Cowen et al., 2003). Also, there could be alterations at individual-level behavior, such as the avoidance of unfavorable conditions and, if possible, movement into suitable areas, population-level changes via changes in the balance between rates of mortality, growth and reproduction, and ecosystem-level changes in productivity and food web interactions (Pörtner and Peck, 2010). These factors will threaten the sustainability of food production in coral reefs, in the long run impacting reef-based fisheries and local community livelihoods.

### 5. The consequences of climate change on public health, vulnerability and adaptive capacity

Large-scale alterations in temperature, rainfall, atmospheric circulation patterns and soil moisture can influence the spatio-temporal distribution and prevalence of human diseases and their vectors (Patz et al., 1998; Craig et al., 2004; Griffin, 2007). They can also influence the ability of humans to resist and recover from disturbance, which in the long term may influence their capacity to adapt to changes. Under such conditions the productivity of coupled social–ecological systems may be severely eroded, which may perpetuate vulnerability and poverty. Climate is a major factor controlling the potential for outbreaks of certain diseases with major negative economic impacts on societies (Greenough et al., 2001; Alley et al., 2005), though the economic impact of climate change effects on public health has still remained obscure. One particular vulnerability concern that has still been poorly addressed is the adverse economic effects associated to declining health on government expenditures on public health and education (Bosello et al., 2005). Yet, the concept of vulnerability to disease risk will depend not only on the environmental exposure, but also on the sensitivity and adaptive capacity of the group and place experiencing it (Comrie, 2007). Children (Hosking et al., 2010), older citizens (Horton et al., 2010) and women (Cannon, 2002; Terry, 2009) are the most vulnerable groups, particularly the poor and those from remote regions (McGeehin and Mirabelli, 2001). Cultural factors and poverty can further enhance women's vulnerability (Cannon, 2002). Vulnerability to climate change can be further enhanced by globalization and other local geographic, socio-economic, political, cultural and health factors (O'Brien et al., 2004). Small low-lying islands are in a more vulnerable situation than

large continental areas. Vulnerability reduction programs reduce susceptibility and increase resilience, and susceptibility to disasters can be largely reduced by prevention and mitigation of emergencies (Keim, 2008). Emergency preparedness and response and recovery activities—including those that address climate change—increase disaster resilience. But this will ultimately depend on the socio-economic condition, governance weakness, and adaptive capacity of each individual place, and socio-economically compromised developing countries might have a very limited ability to prepare and respond to climate-related emergencies.

The interactions between environment and society are highlighted through multiple climate-related diseases, ranging from direct to complex relationships, including impacts from extreme heat, air pollution, aeroallergens, fungi, water- and food-borne diseases, influenza, and from rodent- and insect-borne diseases (Haines et al., 2000; Patz et al., 2000; Levett, 2001; Shiff, 2002; Craig et al., 2004; Comrie, 2007; Hurtado-Díaz et al., 2007; Gamble et al., 2008; Graves et al., 2008; Kearney et al., 2009; Keiser and Utzinger, 2009; Koelle, 2009; McManus et al., 2010). Vector-borne diseases will expand their geographic distribution and death tolls, especially among elderly people, because of heat waves, the indirect effects of climate change on water quality and availability, declining food security and sovereignty, and extreme climatic events (Costello et al., 2009). There is also a major concern of an increased prevalence of skin cancer associated to ozone depletion and increased UV radiation (Martens, 1998; de Vries et al., 2005). Further, interactions between ozone depletion and climate change might result in an increased incidence of cataracts and skin cancer, plus alterations in the patterns of certain categories of infectious and other diseases, and in potential suppression of immunological responses to diseases (de Gruijl et al., 2003). There is also increasing evidence of altered geographic distributions of some infectious disease vectors (ticks at high latitudes, malaria mosquitoes at high altitudes), fungi and bacteria transported through clouds of desert dust, and an uptrend in extreme weather events and associated deaths, injuries and other health outcomes (Reiter, 2001; Griffin, 2007; McMichael and Lindgren, 2011). Also, recently spreading maladies transmitted by mosquitoes, such as the chikungunya virus, have rapidly spread at global scales and have been associated to global warming trends (Epstein, 2007; Powers and Logue, 2007; Gould and Higgs, 2009; Rosenthal, 2009; Omarjee et al., 2014). Such altered patterns could trigger massive human migrations with largely unknown environmental, public health and socio-economic consequences (McLeman and Smit, 2006).

Policy makers often perceive human migration as a problem, but migration has always been a key response to environmental and non-environmental transformations and pressures, including plague and disease outbreaks (see review by Miki, 2010), and should be a central element of strategies of adaptation to climate change (Tacoli, 2009). Migration has a long history, with droughts, floods, food shortages, and other climate-related changes forcing the resettlement of populations since early hominids first spread out from Africa nearly 2 Ma ago (Barrett, 2012). Later, massive migrations occurred through the late Pleistocene and Holocene due to altered climate, glaciation and sea level changes (Núñez et al., 2002; Goebel et al., 2008; Pope and Terrell, 2008; Cruciani et al., 2010). More recent migrations have occurred through Europe over the last 2500 years due to climate variability (Büntgen et al., 2011), followed by the collapse of the Mayan civilization as a result of 200-year long decline in rainfall (Haug et al., 2003; Medina-Elizalde and Rohling, 2012). There was also a significant migration in the United States during the agriculture crisis of the 1930s following drought and flooding cycles (McLeman and Smit, 2006), and across Africa due to seasonal variation in rainfall cycles (Guilmoto, 1998), seasonal hunger cycles (Ogbu, 1973), poverty and desertification (Brauch, 2006; Jónsson, 2010; Bettini and Andersson, 2014), or a combination of poverty, hunger and war (Toole and Waldman, 1993; Jonsson and Durkee, 2011). Human-induced climate change is expected to contribute to even greater population movements in the coming decades, with perhaps as many as 250 million people expected to become



“environmental refugees” by 2050 (McMichael et al., 2012). This could even be more concerning to low-lying island nations where entire populations will inevitably be forced to migrate to another country due to flooding by SLR.

Climate-change-related migration is very likely to result in adverse socio-economic, cultural and health outcomes, both for displaced and for host populations, particularly in situations of forced migration, and in small island scenarios, affecting overall coupled social–ecological systems (Fig. 4). Migration, in combination with increasing population growth is likely to result in an increased demand for goods and services, in the potential perpetuation of non-sustainable globalized economic models, increased impacts to natural resources, cost of food production/importation and pollution, and in a declining productivity of coupled social–ecological systems. In the long run, this could adversely affect human resistance and resilience, community livelihoods, and adaptive capacity, resulting in a permanent poverty trap. In the other hand, increasing populations and the perpetuation of a globalized economic model may often lead to further exploitation of natural resources, which may typically lead to increased deforestation for crops and human settlements, increased soil erosion and runoff, and to further increased cost of food production/importation. Further, increased degradation of soil productivity may lead to declining soil fertility and food production capacity, which will increase the use of chemical fertilizers and pesticides. This will often result in significant chronic eutrophication and pollution of groundwater, surface water and coastal waters, which could further lead to declining productivity of coupled social–

ecological systems. Resource misuse and overexploitation may also lead into a net erosion of human resilience and resistance, into declining adaptive capacity and livelihoods, and to increased vulnerability and poverty.

Among the vulnerable groups, women are likely to be disproportionately affected because on average women tend to be poorer, less educated, have a lower health status and have limited direct access to or ownership of natural resources (Chindarkar, 2012). These direct and indirect impacts of climate change on human security may in turn increase the risk of violent conflict (Barnett and Adger, 2007), which may further trigger migration, social transformation and poverty.

Humans can be exposed to climate change-related impacts through variable pathways (Haines et al., 2006), including changing weather patterns and indirectly through changes in water, air and food quality and availability, and through changing ecosystems, agriculture, fisheries, economy and health (Table 2). In one hand, declining coupled social–ecological systems may result in a net simultaneous erosion of human and ecosystem resilience, which in one hand may result in a net loss of ecosystem goods and services, and socio-economic value (Fig. 5). In turn, this may result in a net decline in livelihoods, socio-economic and political stability, and in declining governance. If these conditions occur in combination with declining rainfall trends and SLR, it may also result in declining groundwater recharge, in combination with long-term salinization of groundwater and in declining food webs associated to coastal pollution and overexploitation. These combined factors may further result in declining food security/sovereignty,

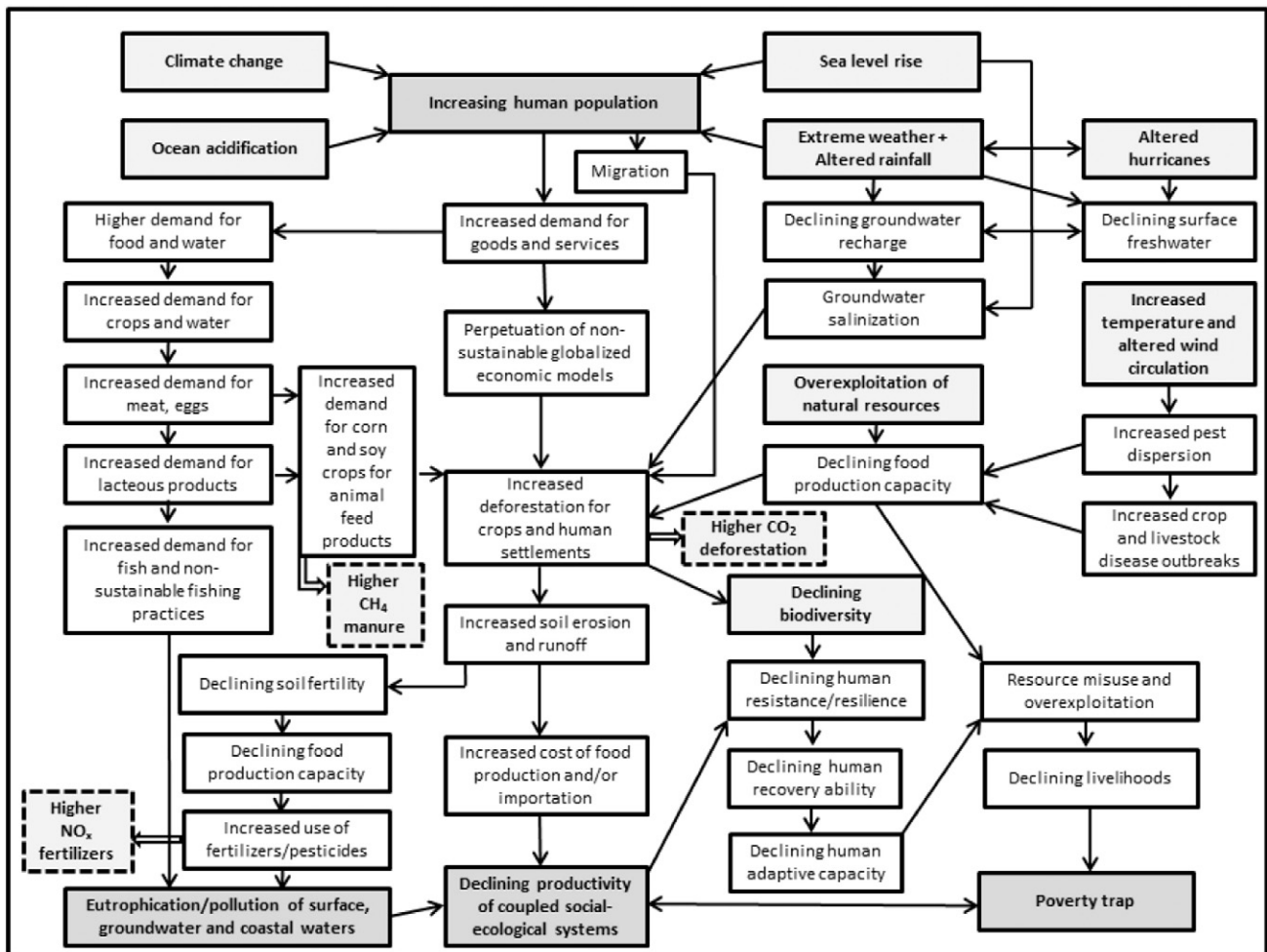


Fig. 4. Conceptual integrated model of declining productivity of coupled social–ecological systems as a combined result of increasing human population and climate change.

**Table 2**

Most-likely impacts of climate change on coastal human settlements public health.

Weather event	Summary of responses	
	Health effects	Adaptation measures
Heat waves	Heat stress, mostly on children, old citizens, women, the poor, those with respiratory disease	Early warning systems; architecture; air conditioning; community response; massive reforestation campaigns; migration
Extreme weather events	Injuries from storms; drowning from coastal or watershed flooding; mostly on coastal, low-lying land dwellers, the poor	Early warning systems; zoning and land use policies; architecture; engineering; massive reforestation campaigns; migration
Sea level rise	Injuries; drowning; water and soil salinization; ecosystem and economic disruption; mostly on coastal dwellers, the poor	Engineering; architecture; zoning and land use policies; abandonment and migration
Drought and increased temperature	This may result in increased respiratory disease exacerbation, asthma, mental health problems, food and water shortages, malnutrition, food- and water-borne diseases, mass population displacement and potential international conflicts	Technological advances; enhanced delivery systems; public education; water treatment; medical treatment; watershed management; zoning and land use policies; vector control; negotiation and conflict mediation; post-disaster response; migration
Allergenic responses	Increases in temperature, CO <sub>2</sub> , and precipitation tend to foster the proliferation of weedy plant species that are known producers of allergenic pollen; higher levels of CO <sub>2</sub> in the atmosphere act as a fertilizer for plant growth; warmer temperatures and increased precipitation cause some plants to grow faster, bloom earlier, and produce more pollen; temperature changes are expected to alter allergy seasons to begin earlier and last longer and the distribution of allergenic plant varieties to change over time	Increased expenses in health care; improved technologies aimed at improving indoor air quality; air conditioning; migration
Coastal water pollution	Increased prevalence of waterborne, foodborne, and/or vector-transmitted diseases; declining coastal water quality due to pollution may increase human vulnerability to waterborne diseases; consumption of polluted fish or invertebrates can increase the vulnerability to foodborne diseases; exposure by bathers and swimmers; affected distribution and prevalence of vector-transmitted diseases; affected tourism and revenues; most vulnerable are old citizens, children, women, the poor	Improved technologies aimed at reducing pollution; altered agricultural and fishery practices; abandonment and migration
Coastal land inundation	Sea level rise causing saline intrusion into coastal aquifers; increased vulnerability of adjacent human communities to recurrent coastal flooding events; degraded aquifers; flooding of urbanized areas (i.e., storm and sewage sewers, sewage treatment facilities, etc.); increased coastal pollution and turbidity; declining food production and food security	Highly expensive engineering solutions (i.e., sea walls and levees); improved technologies aimed at reducing pollution; altered agricultural practices; abandonment and migration

increased risk of starvation, declining public health, and increased social vulnerability. These factors may further affect human resilience and resistance, further impacting recovery ability and adaptive capacity, which in the long run may also lead to a poverty trap.

Effects are projected to progressively increase across many countries and regions, having direct and indirect impacts on the health of people. More extreme weather events (Relman et al., 2008), heat waves (Epstein, 2008), drought (Horton et al., 2010), spread of infective parasites (Colwell, 2008) and detrimental impacts on air (Bernard et al., 2001) and water quality (Hunter, 2003; Patz et al., 2008) all have impacts on our health and will impose significant challenges to society (Costa, 2011). Further, the combination of malnutrition from drought-induced crop failures and impaired immunity from UV irradiation could increase epidemics of measles, mumps, rubella, polio, influenza, and pertussis in unimmunized populations across developing nations and refugee camps (Díaz, 2006).

A particular concern regarding spreading diseases is related to progressive flooding of coastal cities due to SLR and the potential impact of mixing polluted storm waters and sewage with coastal waters which may result in increased water-borne microbial loads. The food-, water-, and vector-borne microbial agents that will cause climate change-induced infectious disease outbreaks are often characterized by having low infective doses and high virulence, and being environmentally stable, and salt-, chlorine-, and iodine-resistant (Díaz, 2006). Water and food-borne diseases may include gastroenteritis caused by coccidian protozoans (*Cryptosporidium parvum*, *Cyclospora cayetanensis*, *Isospora belli*), hepatitis A virus, astroviruses, caliciviruses, *Giardia lamblia*, the non-cholera marine vibrios (*Vibrio vulnificus*, *Vibrio parahaemolyticus*), *Campylobacter jejuni*, *Shigella* spp., and the typhoidal and nontyphoidal *Salmonella* species (Díaz, 2006). Humans may be exposed to these bacteria following the consumption of contaminated drinking water or food exposed to animal or human carriers or by direct exposure of swimmers (Frumkin et al., 2008). The potential increase in

such conditions may suggest an increased demand on emergency medicine responses particularly on highly vulnerable areas where resources and technology could be severely limited (Hess et al., 2009).

Climate change could also have multiple indirect impacts on public health. Warming trends favors the spread of disease, particularly under polluted conditions, as prolonged extreme weather events create conditions conducive to disease outbreaks, not only in humans, but also in wildlife, livestock, agricultural systems, forests and marine life (Epstein et al., 2005). There is evidence of microbiological water quality decline during warm ENSO episodes (Lipp et al., 2001). Diarrheal disease has been significantly correlated with increased temperature in Pacific islands (Singh et al., 2001). Fecal pollution has also been correlated with watershed population increases, and even more strongly correlated with the percentage of developed land within the watershed (Mallin et al., 2000; Méndez-Lázaro et al., 2012; Norat-Ramírez et al., 2013). Fecal pollution is also significantly higher under degraded turbid coastal waters with higher risks for coastal coral reef health (Fabricius and McCorry, 2006; Hernández-Delgado et al., 2010, 2011; Díaz-Ortega and Hernández-Delgado, 2014) and for recreational users (Shuval, 2003; Bonkosky et al., 2009). Climate change can also foster increasing disease incidence in waterfowl (Traill et al., 2009; Garamszegi, 2011), livestock (Gale et al., 2009), and on plants (Chakraborty and Newton, 2011), which may compromise the ability to harvest stocks, affecting human food security.

Climate-related temperature changes are also expected to increase the potency of airborne allergens due to spatial displacement and invasions (latitudinal, altitudinal) of multiple plant species, increasing pollen concentration in the air, length of the allergy season, strength of airborne allergens, and the resulting increases in allergy symptoms (Frumkin et al., 2008; Gamble et al., 2008) and asthma incidence (Beggs and Bambrick, 2006). There is substantial evidence in pollen paleo-records of long-term, range shifts and adaptive responses across large spatial and latitudinal scales in plant communities as a result of

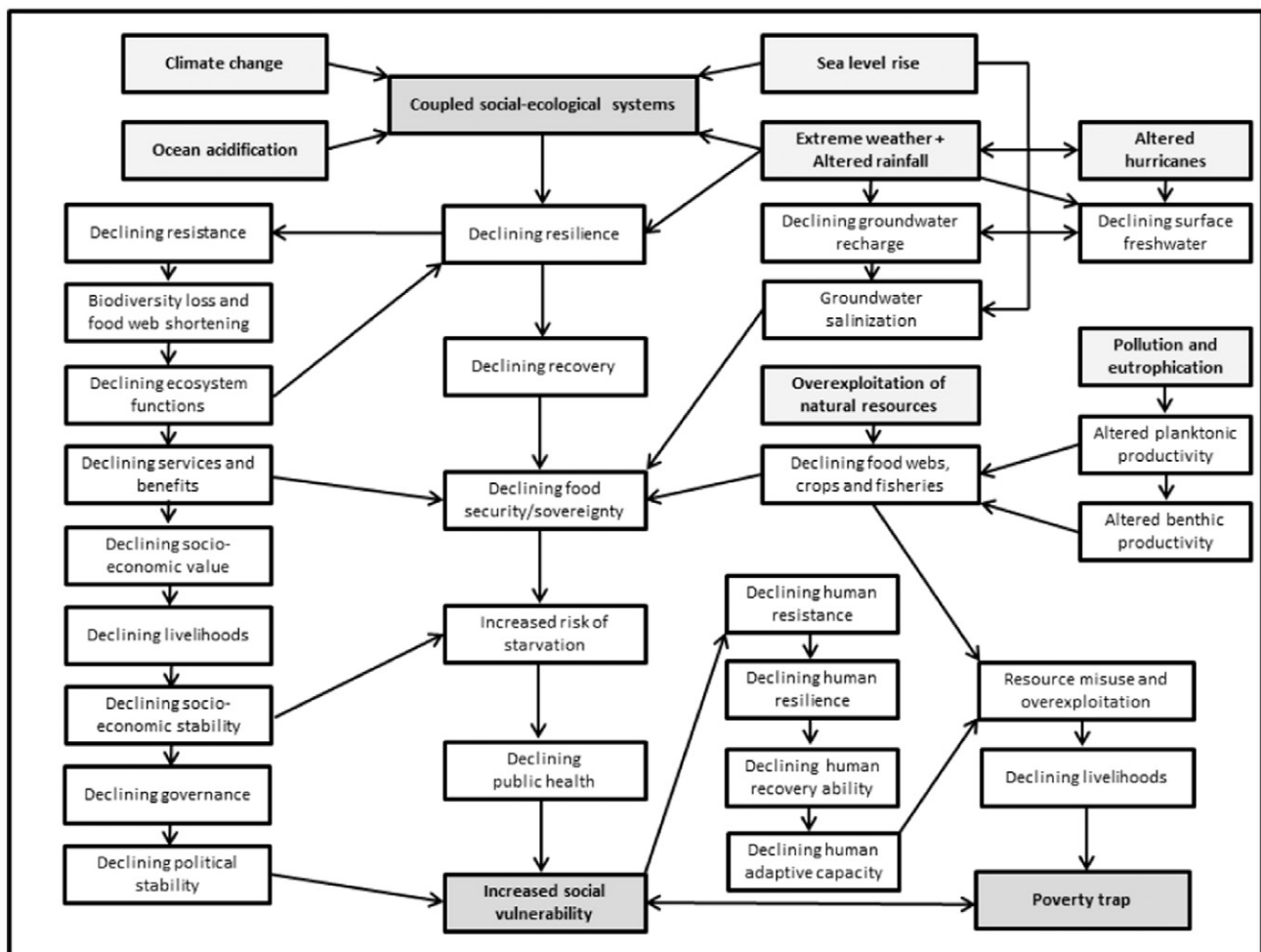


Fig. 5. Conceptual integrated model of declining productivity of increased social vulnerability as a result of declining coupled social-ecological systems and climate change.

climate change (Huntley, 1991; Davis and Shaw, 2001). Climate change, in combination with shifting wind patterns, will allow certain allergen-producing plant species to migrate into novel habitats, and wind-blown dust, carrying pollen and molds from different regions at global scales could expose people to allergens they had not previously contacted. There is also evidence of prolonged pollen seasons in multiple plant species coinciding with increasing temperature (van Vliet et al., 2002; Galán et al., 2005; García-Mozo et al., 2006). Exposure to increased concentrations of pollen and mold may make current non-sufferers more likely to develop allergic symptoms and may increase the risk to those chronically affected by allergies. Respiratory illness could have more pronounced impacts across large urban centers which have already showed increased respiratory disease prevalence due to air pollution from high energy consumption and heavy traffic (D'Amato et al., 2010). This could have notorious economic impacts as public health impacts increase. Further research is needed to understand the response of aeroallergens to climate change, to characterize their role in allergic disease development, and to estimate the costs to avoid or minimize the health impacts of allergic diseases. Long-term data on aeroallergens are also needed to document changes in aeroallergen production, to characterize their distribution, content, and potency, to model future potential impacts and to identify potential high risk zones given current and forecasted climate change trends.

In summary, there are several key elements of research priorities regarding the public health impacts of climate change that still need to be addressed at the scale of individual nations: (1) identify and characterize communities and population sectors at greatest risk to climate change and air pollution, including potential alterations in societal and behavioral

responses; (2) assess the individual and synergistic impacts of air quality and climate change on human health of sensitive sub-populations (i.e., children, older citizens, women, immune-compromised persons); (3) develop approaches to improve multi-disciplinary assessments of the likelihood and effects of extreme weather events on human health; and (4) identify and characterize what would be the most likely impacts to coastal water quality and coastal community public health of SLR and coastal flooding.

## 6. Threats to local economies and livelihood sustainability

Unlike any other disturbance experienced by contemporary societies, climate change has the potential to produce significant impacts across very large temporal and spatial scales (Shea and Dyoulgerov, 1997; Fankhauser et al., 1999; Marshall and Johnson, 2007), with significant adverse consequences on local economies and livelihoods, particularly, in small islands (Mills, 2005; Lane et al., 2013). Many coastal communities and reef-based industries are likely to struggle to cope with a challenge of this magnitude, with a very likely adverse impact to local economies and livelihood sustainability. Climate change might have a significant impact on Caribbean tourism economy through the alteration of condition and scenic value of environmental features important to destination selection (Uyarra et al., 2005; Hernández-Delgado et al., 2012). Vulnerable people will need guidance and support to anticipate the impacts of climate change and implement adaptation strategies if they are to sustain their livelihoods and quality of life into the future.

The combined long-term impacts of climate change, chronic coastal environmental degradation and ecosystem decline, and increased



human vulnerability to diseases could have deleterious consequences for local economies as a result of coastal flooding, chronic declining coastal water quality, groundwater salinization, threatened food production, and collapsing tourism industry (Fig. 3). SLR, in combination with declining rainfall trends, has been shown to foster saline intrusion in groundwater, altering coastal vegetation (Greaver and Sternberg, 2010). This could result in an irreversible decline of goods and services of coastal vegetation barriers (i.e., vegetation role as buffer against coastal erosion, shoreline protection against SLR itself) and freshwater table (i.e., supporting other inland vegetation non-adapted to saltwater intrusion, crops). Declining coastal terrestrial and marine ecosystem benefits and services may also result in declining food production and starvation. This could be a critical concern in small islands which might largely depend upon food importation. The inability to feed the population, in combination with the prohibitive costs of engineering alternatives for shoreline erosion protection of urban areas, tourism facilities, and critical infrastructure along low-lying coastal areas (i.e., seaports, airports, highways, electric power stations, sewage treatment facilities, hospitals, schools, etc.) due to SLR, and in combination with expected increases in coastal pollution, in disease prevalence and in the cost of disease prevention or treatments could be unsustainable for many island nations. This could result in a major ecological collapse, combined with an unavoidable public health problem of unprecedented scale, and a potential unprecedented risk in food security (resulting in increased expenses in food importation) could also lead to an economic collapse, particularly in small islands with limited resources that may largely depend on tourism revenues. Magnified economic costs associated to increased health treatments to people, property insurance, migration from coastal to upland areas, if viable, or evacuation of the entire population from low-lying islands to adjacent larger islands or continents will also be a major source of socio-economic and political challenges and conflicts. Climate change adaptation planning must be completed as soon as possible and must consider long-term economic and livelihood impacts of all available alternatives, including the cost of migration, as well as the cost of doing nothing to abate impacts.

The recovery and sustainability of livelihoods will rely in six basic elements, according to Plummer and Armitage (2007), including: (1) increased well-being (i.e., improved socio-economic conditions at the individual/household level); (2) decreased poverty; (3) increased income; (4) decreased vulnerability; (5) increased food security; and (6) sustainable resource use. Managing these factors will require an integrated, multi-sectorial, participatory approach, and will represent a key challenge to small island states and developing nations.

## 7. The enhanced vulnerability of small tropical islands: case studies from the Caribbean and the Indo-Pacific

By nature, small tropical islands are highly vulnerable to climate change, SLR, and both to chronic and stochastic disturbances. Islands are often small, have limited human, economic and technical resources, and limited socio-economic resilience, but often constitute a significant tourism attraction (Jędrusik, 2004). Multiple islands, such as Puerto Rico, in the Caribbean (Hernández-Delgado et al., 2012) and the Maldives, in the Indian Ocean (Brown et al., 1997), are being also overexploited by massive tourism and non-sustainable development practices which have the potential to put on stake their limited natural resources, and putting on risk local economies and livelihoods due to revenue leakage (Hernández-Delgado et al., 2012). Such islands share a very fragile ecology and a high dependence on non-sustainable tourism, which often results in adverse environmental impacts (De Albuquerque and McElroy, 1992). Small Caribbean island states such as Bonaire and Barbados, which are strongly dependent on massive tourism, are much more vulnerable to climate change-related habitat decline, which are a strong factor attracting tourists (Uyarra et al., 2005). Therefore, special attention must be paid to reduce rapid environmental decline of small islands' natural resources by reducing

overexploitation and pollution, and by establishing sustainable development strategies.

Sustainable development across small islands can be constrained by the scarcity of natural resources, and by the quality and quantity of available human resources (Soliani and Rossi, 1992). Small islands are often significantly impacted by non-sustainable urban sprawling, which often results in tourism and residential construction on vulnerable habitats, and on the construction of steep unpaved roads which result in extensive soil erosion and sediment delivery to adjacent coastal waters. Examples of this have been documented across both, the U.S. Virgin Islands (MacDonald et al., 1997; Ramos-Scharrón, 2012) and Puerto Rico (Ramos-Scharrón et al., 2012, 2015). In addition, many Pacific tropical islands, such as Tonga, Fiji, Samoa, and Tuvalu are low-lying (<10 m above sea level), therefore entire populations can be at risk to rising seas during Spring tides and hurricanes, and to SLR (Mimura, 1999). Indo-Pacific islands across the Maldives, Tuvalu and the Marshall Islands which are mostly composed by coral sands are particularly vulnerable to SLR (Perry et al., 2011). These require immediate adaptive responses. The same can be said about multiple low lying islands in the Atlantic, including the Bahamas, a significant portion of Cuba and even the U.S. state of Florida. Multiple Caribbean small islands are also rapidly losing their first lines of defense against storm swells and SLR, their coral reefs (Hughes, 1994; Gardner et al., 2003, 2005; Coelho and Manfrino, 2007; Miller et al., 2009; Hernández-Pacheco et al., 2011). This could have significant long-term implications on ecosystem resilience, functions, benefits and services, and in the long-run could affect governance.

Governance is a key component of the capacity of social-ecological systems to adapt and mitigate potential climate change impacts, in particular across small islands. Resilience, adaptability, and transformability determine the future trajectories of social-ecological systems. Also, institutional (Young, 2010) and migration dynamics as a result increasing environmental pressures (Warner, 2010) can significantly influence resilience, vulnerability and adaptation capacity. This is largely related to governance weakness and the challenges associated to migration conflicts. Walker et al. (2004) defined adaptability as the capacity of key players in the system to influence resilience, which in the context of a social-ecological system, is essentially the capacity to manage it. Transformability is the capacity to create a fundamentally new system when ecological, economic, or social structures make the existing system untenable (Walker et al., 2004). Trust and leadership were suggested as key elements for successful adaptability and transformability (Gunderson et al., 2006). But Abel et al. (2006) argued that excessive subsidization of local social-ecological systems can reduce their capacity to self-organize under changing conditions (i.e., climate change). Therefore, economic dependence on external resources may also become a major roadblock for successful adaptation and mitigation. On this context, Olsson et al. (2006) suggested important strategies to achieve change in social-ecological systems: (1) reconceptualize issues (i.e., change strategies to address problems); (2) generate and integrate a diversity of ideas (i.e., provide multi-stakeholder, multi-sectorial participatory opportunities to share viewpoints and solutions); (3) communicate and engage with key individuals in different sectors (i.e., participatory processes engaging multiple sectors of society, including marginalized communities, are critical); (4) move across levels of governance and politics (i.e., there is a need to expand the organizational scale of actions, from individual/household to regional/trans-national); (5) promote and steward experimentation at smaller scales (i.e., test alternative adaptive and mitigation solution on local scales to show success); and (6) promote novelty by combining different networks, experiences and social memories (i.e., improving participation to the widest number of society sectors possible will allow to address different strategies and solutions).

Small islands' economy can also be significantly susceptible to environmental disasters (Adrianto and Matsuda, 2002) and extreme weather events such as hurricanes (Scavia et al., 2002). This can be potentially exacerbated by a combination of geographic, socio-economic and

environmental factors. Also, lack of governance flexibility and stability can be a roadblock to adaptation (Duit et al., 2010). Small island development states (41 in total) have made only a modest progress towards having all necessary tools to manage their coastal zone, land uses and resource management across a global scale (Walker, 2006). Tompkins et al. (2005) analyzed the vulnerability of the Caribbean Island of Anguilla to climate change. The following characteristics made Anguilla vulnerable to natural extreme hazards: (1) reliance on primary exports (lack of food security); (2) wide disparities on economic well-being among society sectors; (3) limited development of physical and social infrastructure; (4) poor land planning; and (5) weak governance and public administration. Vulnerability to climate-related hazards is also related to (1) small physical size (i.e., land use conflicts and intensity, limited natural resources); (2) remoteness (i.e., high costs of importation, geopolitical dependence); (3) environmental factors (i.e., vulnerability of coastal zone, exposed interior); (4) poor disaster mitigation capacity (i.e., limited hazard forecasting ability); (5) demographic limitations (i.e., limited human capital, high per capita cost of infrastructure); and (6) small economy (i.e., high dependence on external finance, small internal market, high dependence on natural resources, limited production capacity). These factors need to be targeted through a combination of adaptation and mitigation strategies. But several factors can potentially prevent many poor countries and small islands to achieve such goals. According to Sachs (2006), there are four critical factors that need to be assessed: (1) extreme poverty (approximately 1 billion people still live in the planet struggling for their daily survival which often results in extreme environmental degradation and resource depletion); (2) powerful vested interests (private for-profit interest outcompeting public sustainable interests; i.e., fisheries agreements made between islands such as Antigua, in the Caribbean Lesser Antilles, and Japan); (3) global economic pressures (disproportionate economic growth of developed nations create unprecedented environmental pressures on poor countries and small island nations; massive tourism pressures on small islands; revenue leakage; lack of food security and sovereignty); and (4) lack of scientific knowledge in the poorest countries (lack of governance, struggle to achieve the basic socio-economic growth; limited or lack of understanding complex interactions of climate change, environmental pollution, economic drivers, public health, and sustainable livelihoods). Together, these could become overwhelming factors that can severely limit the ability for successfully achieving adaptation and mitigation goals, which may require a combination of multi-level and multi-sectorial strategies, particularly on small island nations.

Moreno and Becken (2009) developed an assessment model for the vulnerability to hurricanes to beach ecosystems in Fiji, in the Southern Pacific, which focused on three different elements: (1) dimensions of vulnerability (i.e., exposure, sensitivity, adaptive capacity); (2) components of dimensions (i.e., exposure will depend on hurricane risk and severity, local and tourism population, infrastructure vulnerability; sensitivity will depend on beach characteristics, infrastructure conditions, tourist perceptions; adaptive capacity will depend on management capacity, institutional support, access to financing); and (3) measures of components. In this last context, exposure will depend in the intensity and frequency of hurricanes, location, population number, number of tourists, and the value of affected infrastructure and resources. Sensitivity will depend on topography, current coastal erosion rates, hurricane-proof infrastructure, and public perceptions. Adaptive capacity will depend on the effectiveness of early warning systems, investment into adaptation, technology deployed, marketing, and diversification. Moreno and Becken (2009) also developed a similar assessment model for the vulnerability to massive coral bleaching in Fiji. Exposure will depend on ocean conditions (i.e., SST, SLR), reef conditions (i.e., location), and storms (i.e. frequency, intensity). Sensitivity will depend on reef conditions (i.e., protection of the reef, percent healthy reef, species present, diversity and extension) and tourist perceptions (i.e., tourists' densities and types, and reef preferences). Adaptive capacity will depend on institutional support (i.e., MPAs, conservation projects, research and

monitoring projects), on managerial capacity (i.e., education, diversification of activities, carrying capacity, limits of acceptable change), and technological capacity (i.e., artificial reefs). This suggests that adaptation and mitigation strategies for small tropical islands may also require target-specific approaches based on targeted and prioritized economic activities in order to maintain diversified livelihoods.

A final key element highly critical in small islands scenarios is community-based engagement. Under most marginalized islands and communities, top-down approaches can be perceived by local communities as outside impositions, often leading to rejection. But if communities are properly engaged in problem assessment, planning, decision-making processes, and implementation there would be a higher probability of success for adaptation and mitigation goals. Tompkins et al. (2005) listed six steps that were necessary in the Cayman Islands, Caribbean Sea, for successful adaptation to tropical storm risk. These included: (1) making the mental link in citizens between hazard events, vulnerability and impacts; (2) having important respected individuals taking responsibility for the issue; (3) having respected individuals in the community persuading others to engage for the issue; (4) forming small community-based groups of concerned individuals; (5) pushing community-based groups for preparedness action in their areas; and (6) forming a National Hurricane Committee. Key persons are fundamental as they provide leadership, trust, vision, meaning, and they help transform management organizations toward a learning environment (Folke et al., 2005). Community-based participation has been proved a key element necessary to gain local support for changes in public policy and management (McConney et al., 2003; Berkes, 2004), and would be fundamental for adaptation and mitigation strategies to be successful on small islands. Also, community-based management in Trinidad and Tobago was shown to enhance adaptive capacity in two ways: by building networks that are important for coping with extreme events and by retaining the resilience of the underpinning resources and ecological systems (Tompkins and Adger, 2004).

## 8. Recommendations for adaptation and mitigation strategies on small tropical islands

Multiple strategies have been identified that can help improve governance, as well as the understanding of multiple thresholds and improving the likelihood of implementing successful adaptation and mitigation strategies to sustain and increase coastal ecosystem and human resilience. But adaptive capacity will largely depend on the level of wealth, needs, education level, infrastructure status, and vulnerability to hazards. In this context, most small tropical island nations are characterized by poor wealth, very high needs, limited to poor education, weak infrastructure conditions, and moderate to high vulnerability to climate-related hazards. The sustainable adaptability of coupled social-ecological systems will need to target multiple organizational levels of societies, including: (1) individual/household; (2) tribal/municipal; (3) national; and (4) regional/trans-national levels, and strategies need to be interconnected among all levels (Fig. 6). Individual and household socio-economic conditions can play an important role in influencing people's potential adaptation ability (Cinner et al., 2009). This may become particularly critical in island nations with poor governance. Challenges that need to be addressed at the individual/household level include improving the socio-economic condition, maintenance of flexibility and assets, and of the ability to relocate, prevent the declining of livelihoods and socio-economic stability, avoid poverty traps, and establish a balance between short-term benefits and declining long-term resilience of couple social-ecological systems. Poverty traps are particularly critical as chronic declining socio-economic conditions may prevent poor people to maintain sufficient resources to overcome natural disaster, declining livelihoods and low income (Carter and Barrett, 2006).

Strategies are also needed at the tribal/municipal level, including the provision of local needs and services, fostering community-based

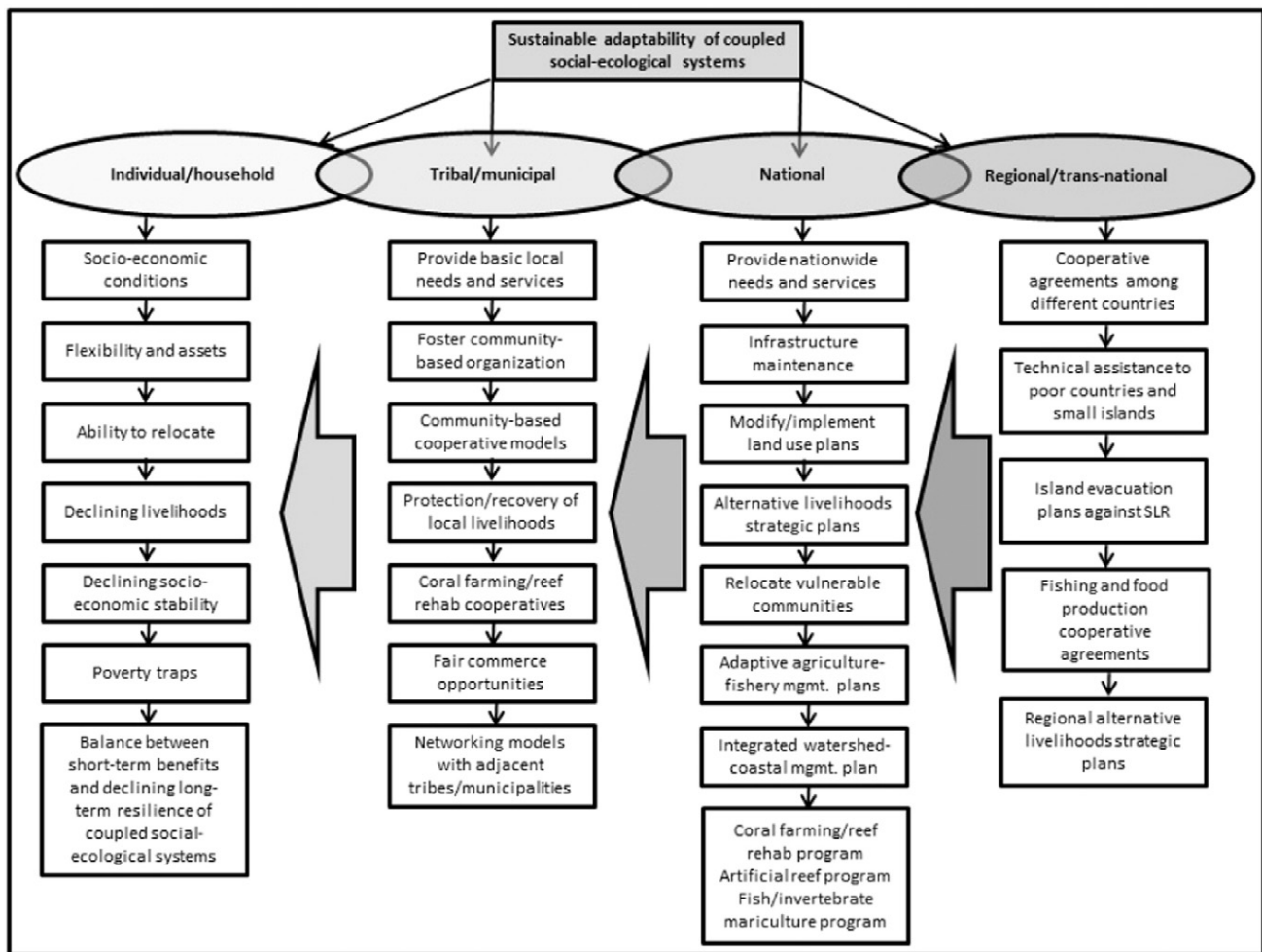


Fig. 6. Conceptual model of sustainable adaptability of coupled social-ecological systems.

organization and cooperative models, fostering the protection/recovery of livelihoods, the development and support of community-based coral farming and reef rehabilitation cooperatives, the establishment and support of fair commerce opportunities, and networking models with adjacent tribes/ municipalities (Fig. 6). Efforts would also be required at the national level in order to provide nationwide needs and services, infrastructure maintenance, modification and implement land use plans, establish alternative livelihood strategic plans, relocate vulnerable communities, implement adaptive agriculture and fishery management plans, integrated watershed-coastal management plans, and implement national programs to foster coral farming and reef rehabilitation, artificial reefs, and commercial fish and invertebrate mariculture. Efforts at the regional/trans-national level may include cooperative agreements among different countries, technical assistance to poor countries and small islands, low islands evacuation plans against SLR, fishing and food production cooperative agreements, and the development of regional alternative livelihoods strategic plans.

Adaptation can provide short-term benefits, but it may have adverse long-term effects that may affect the resilience of social-ecological systems if chronic human-driven degradation of coastal ecosystems that function as first line of defense against storm swells and SLR is not reduced. In this context, the sustainable adaptability of the first line of defense and ecosystem services will need to focus on five interactive components: (1) SLR; (2) maintain coastal setbacks; (3) reforest coastal barriers; (4) rehabilitate shallow reef ecological functions and services; and (5) implement a strong management and marketing of perceived risks (Fig. 7). SLR adaptive strategies can be subdivided into retreat, adapt, and defend (Boko et al., 2007). Retreat may imply the relocation

of vulnerable human communities and infrastructure, and the change and management of land uses. Adaptation may imply management of multiple components such as saltwater intrusion, reducing or eliminating sand and coral mining for construction material, delineating flood and erosion hazardous areas, rehabilitating sand dunes, and implementing strict controls on the overexploitation of coastal resources, population growth, and pollution. Defend imply the implementation of highly-expensive engineering solutions such as building seawalls, breakwaters, pillar housing, and raised foundations.

Maintaining coastal setbacks changing and managing land uses to protect buffer zones, preserving areas for the expansion of wetlands under SLR, and the elimination of vulnerable structures (Fig. 7). Reforesting coastal barriers will imply restoring coastal forests and buffer zones, and the overall rehabilitation of coastal barrier ecosystems services. The rehabilitation of shallow coastal coral reefs will require the restoration of rapidly-growing coral populations, coral reef functions and services, the restoration of shallow reef net accretion rates, and the rehabilitation of reef landscapes and tourism attractiveness. The overall objective of these efforts would be to increase resilience to disturbance (i.e., recurrent or more intense hurricanes, SLR). The component of stronger management and marketing of perceived risk will require a “damage control” approach of public perceptions and will require public outreach through mass media, a stronger tourism management response, “damage control” perception management, a wider diversification of tourism products and market segments that may also diversify local livelihoods, adaptive pricing policies and adaptive regulatory structure, including taxes, subsidies, and economic incentives to businesses (McClanahan and Cinner, 2012). The integration of



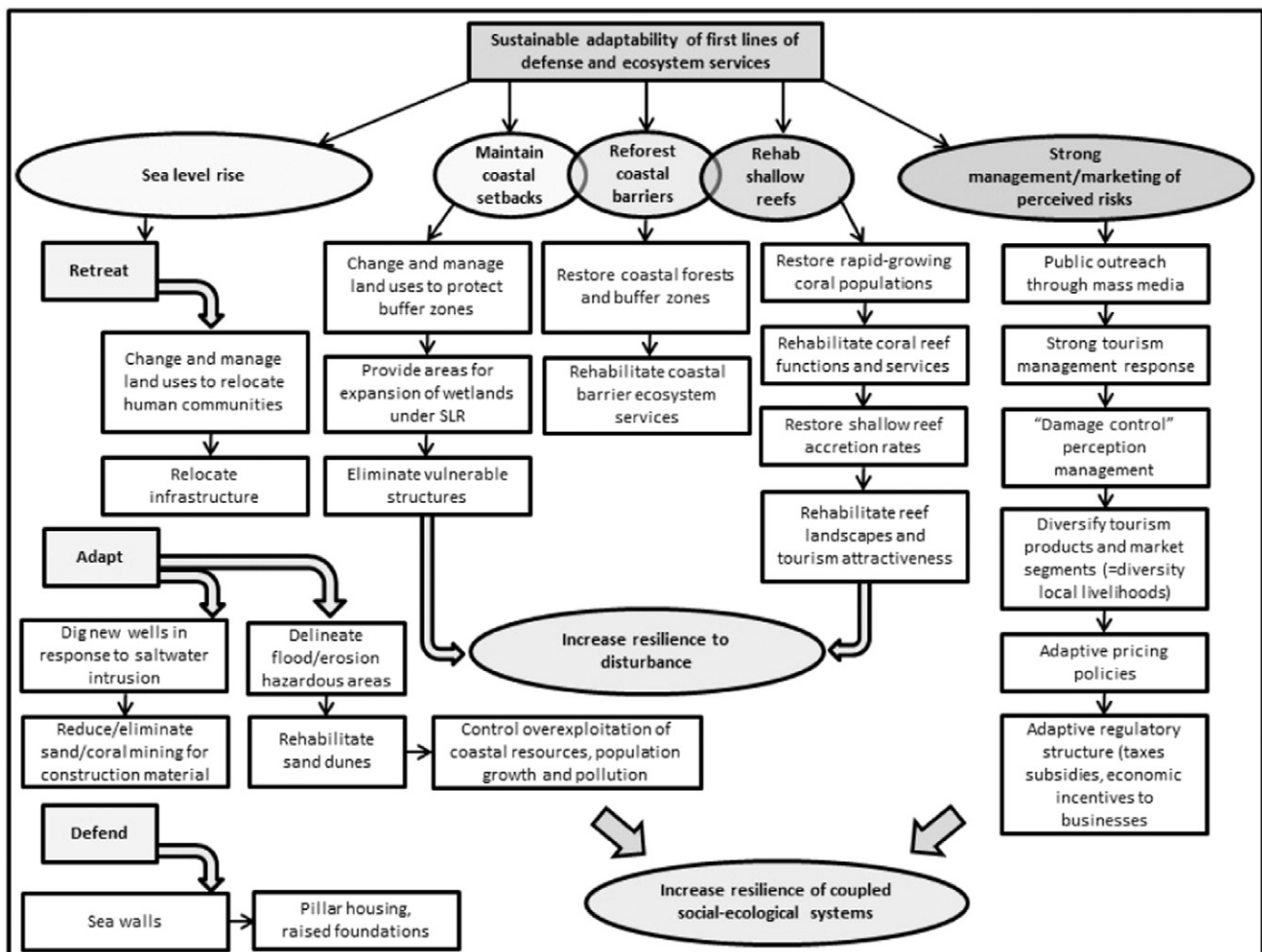


Fig. 7. Conceptual model of sustainable adaptability of first lines of defense and ecosystem services.

efforts to protect and restore the first line of defense against storm swells and SLR will be fundamental to foster enhanced benefits of adaptive strategies of coupled social–ecological systems across all of its organizational levels.

One of the most critical elements for small island nations that require adaptive management strategies are fisheries. According to McClanahan and Cinner (2012), the sustainable adaptability of fisheries may require addressing seven key elements, including: (1) essential fish habitat (EFH) degradation; (2) changes in the spatio-temporal distribution of fisheries; (3) changes to yield; (4) damage to coastal infrastructure; (5) change to profitability; (6) influx of fishers from other areas; and (7) health and safety (Fig. 8). Small islands have limited surface areas for agriculture and livestock, and mostly rely on fishing and on expensive importation of food. Therefore, fishing should be a key component of climate change adaptation strategies. But special care must be taken to prevent short-term benefits to have adverse long-term effects that may affect the resilience of social–ecological systems. Under current scenarios of ecosystem overexploitation, climate change and SLR, fishers may rapidly benefit from the establishment of no-take marine protected areas (MPAs), shifting fishing grounds, changing gears and target species, increasing fishing efforts, but in combination with predicted climate change and SLR scenarios, in the long-term these strategies may have the potential to magnify depletion and magnify the tragedy of the commons effect, leading to major conflicts. Therefore, adaptive strategies need to incorporate social–ecological systems across all of its organizational levels, ecosystems that function as first line of defense along coastlines, and fisheries.

Adaptive strategies to cope with chronic EFH degradation may include reducing the loss of EFH due to chronic pollution, and managing habitat decline due to climate change and SLR by reducing other local anthropogenic stressors (i.e., fishing pressure, water quality decline, sedimentation). It will also require managing shallow coastal habitats decline due to *Sargassum* mats massive arrivals (i.e., Caribbean Sea), and rehabilitating EFH (i.e., water quality, coral reefs, seagrass, mangroves, estuaries) to recover ecosystem resilience, functions and services. Changes in the spatio-temporal distribution of fisheries will require designating no-take MPA networks, changing and/or rotating the location of fishing activities, and the development of marine fish open ocean cage aquaculture. Changes to yield will also require reducing fishing efforts across overexploited ecosystems, diversification of livelihoods, reducing costs and increasing the efficiency of operations, changing fishing gears, fishery targets or habitats, implementing fish aggregation devices (FADs) and artificial reefs, and protecting fish spawning aggregation sites. Adaptive management of fisheries will require managing damage to coastal infrastructure. This will imply the rehabilitation and response to disasters, implementing integrated coastal management strategies, the development of early warning systems, and education across multiple levels. Changes to profitability from declining fisheries need to be managed by diversifying market products and livelihoods, and by fostering aquaculture cooperative models. The influx of fishers from other areas may need to be managed through the implementation of property rights to reduce potential social and political conflicts. Health and safety challenges will require managing human communities retreat, establishing or downscaling weather warning

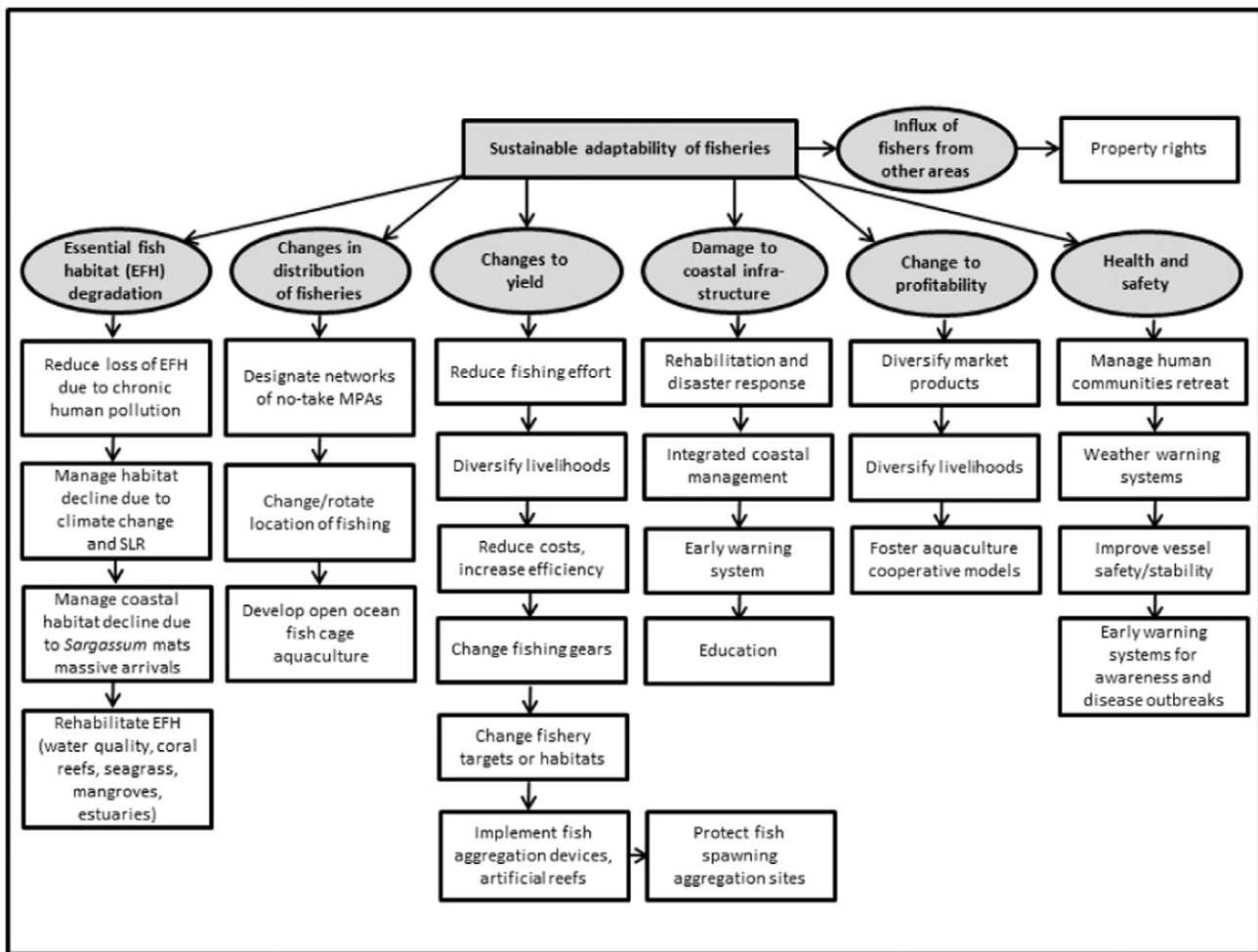


Fig. 8. Conceptual model of sustainable adaptability of fisheries.

systems, improving vessel safety and stability, and by establishing early warning systems for awareness and disease outbreaks.

Variable strategies need to be implemented either before, during or after ecosystem thresholds are crossed. The most critical challenge is to identify early warning signals of any major threshold change. But this might be one of the most complex challenges as most ecosystem changes unfold at very slowly rates, rarely detectable to science, particularly in places which lack appropriate technology and resources. It is also fundamental to rehabilitate coastal ecosystem resilience to slow down progressive degradation and reducing the probability of rapidly crossing any threshold. This may require the designation of no-take MPAs and the need to incorporate base communities and other local stakeholders into a participatory management or co-management model of resource extractive activities (Cinner *et al.*, 2009). Examples of such engagement already include successful coral farming and coral reef rehabilitation efforts in support of local MPA management (Hernández-Delgado and Suleimán-Ramos, 2014; Hernández-Delgado *et al.*, 2014). This would virtually provide more time to coastal ecosystems to recover from climate-related disturbance (Hughes *et al.*, 2013a). But if strategies are to be implemented during or after ecosystem thresholds are crossed it would be important to implement novel, alternative, and adaptive management strategies to deal with alternate conditions, transient successional trajectories, and with cumulative and synergistic impacts on coastal and marine ecosystems. This may imply further challenges such as unprecedented spatial, temporal and political scales of management.

Natural resource conservation needs also to pay fundamental attention to critically threatened and endangered species, endemic species,

indicator/sentinel species, species that aggregate for reproduction, and highly migratory species that might require conservation efforts on global scales (Barber, 2004). There is also a need to conserve and restore viable representations of interconnected terrestrial, freshwater and marine ecosystems, habitats that constitute a source of freshwater, large non-fragmented landscapes, natural landscapes under major threats by urban sprawl and development, fish spawning aggregation sites, and critical habitats for sustaining viable populations of highly migratory species. Adaptive strategies for the conservation of biodiversity also need to be implemented, particularly in the form of ecosystem services and benefits (i.e., fish nursery grounds, natural coastal barriers, forest hydrological functions, wetlands buffering role, genetic diversity, food production, sources of natural products). There is also a need to protect and manage important socio-economic resources, such as fisheries, coastal croplands (i.e., coconut), grasslands (i.e., cattle farms), groundwater and other freshwater reservoirs. Further, there is a need to down-scale climate models to provide more realistic simulations and prediction of basin-scale hydrology (Wilby *et al.*, 2000) and to address the impacts of climate change on the small-scale spatial distribution of biodiversity, species, crop yields, and water resources (Tabor and Williams, 2010). These approaches may require integrating new information from climate models, sensitivity analyses, and vulnerability assessments for species and ecosystems (Mawdsley, 2011), and the development of spatial planning policies and policy guidance which take account of climate change (Nadarajah and Rankin, 2005).

Heller and Zavaleta (2009) thoroughly reviewed recommendations for biodiversity adaptive management in face of climate change and suggested that adaptation requires improved regional institutional

coordination, expanded spatial and temporal perspective, incorporation of climate change scenarios into all planning and action, and greater effort to address multiple threats and global change drivers simultaneously in ways that are responsive to and inclusive of human communities. On that sense, adaptation will have to deal with unavoidable uncertainty about the future, always based on precautionary principles, and integrating multiple spatial scales of planning and management. It will also need to integrate into existing policies and programs, and will need to incorporate social sciences as the approach should be focused on managing coupled social–ecological ecosystems. This means, biodiversity conservation strategies need to stem out from community-based integrative and participatory processes. But the reality is that lack of proper human and economic resources may prevent multiple small tropical island nations to achieve such objectives. This is a major concern as it may potentially increase long-term climate risks for biodiversity and for the highly vulnerable groups that depend on it. Recent evidence has also shown unequivocal signs of global freshwater reservoir declines (Famiglietti, 2014). Therefore, strategies to improve water management efficiency (i.e., catchment, storage, distribution, leakages, wastewater treatment, water reclamation), natural groundwater recharge, and an improved ability to intercept and store rainfall at the household level are important adaptive measures, with particular urgency in small islands, arid environments, and across large geographic areas. This has become a critical element across the wider Caribbean region, where data suggest a steady decline in daily rainfall (Peterson et al., 2002), and where models suggest will become much drier in the near future (Neelin et al., 2006). It is also fundamental to include the ecological capital as part of socio-economic evaluations as it is usually poorly understood, difficult to measure and tends to be undervalued (Barbier, 2014). Therefore, the rapid depletion and degradation of natural resources need to be incorporated into economic indicators. This could allow improving socio-economic indicators of climate change impacts and improving estimates of climate change adaptation cost.

However, there are still other major, complex and highly challenging adaptive strategies which might require the need to relocate coastal communities highly vulnerable to SLR, develop and implement a food security and sovereignty plan, a plan to reduce, reuse and recycle solid wastes, and a multi-disciplinary educational plan for base communities regarding the environmental, socio-economic and public health implications of climate change. In addition, there is still a need to improve energy efficiency and to foster the development of renewable energy sources, improve and incentive public transportation, and to implement urban sustainability strategies. Such approaches might likely be unrealistic for many island nations with severe socio-economic limitations which may deem them to poverty traps, unless larger-scale, trans-boundary adaptive approaches are taken.

There are also multiple mitigation strategies that need to be rapidly implemented, in particularly those that reduce carbon emissions or that naturally offset emissions. Nutrient and sediment loadings to estuarine and coastal waters need to be reduced now so that further water quality degradation is prevented. This would be a fundamental measure to reduce two of the most significant sources of anthropogenic stress on coastal ecosystems and should help maintaining coastal ecosystems productivity resilience, functions (i.e., carbon sequestration, nursery ground, buffer against wave action and coastal erosion), benefits, goods and services for a longer period of time. There is also a need to reforest natural and urban catchment areas, and to improve the sustainability of urban areas, including the conversion to green buildings, and to improve the management of water resources (i.e., improve interception, retention and infiltration, reduce runoff). Also, coral farming and reef rehabilitation will help not only to replenish depleted corals, but to rehabilitate shallow reef nursery grounds, restore reef value for tourism and recreation, its ability to produce fish protein, its role to protect shorelines, and offset carbon emissions.

Climate change adaptation and mitigation strategies need also to be implemented in the context of public health at the base community

level. Human vulnerability to any disaster, including those climate-related, has complex social, economic, health, and cultural dimensions. Simultaneous steps taken in agriculture, urban planning, water and civil defense, will have implications for prevention of illness and injury (Woodward et al., 2011). There is a definite major need to foster increased food security and sovereignty to reduce vulnerability to extreme events and poverty in the topics (Sánchez, 2000; Ziervogel and Ericksen, 2010; Chakraborty and Newton, 2011). Vulnerability to natural disasters has two sides: (1) susceptibility – the degree of exposure to dangerous hazards; and (2) resilience – the capacity to cope with or recover from disaster consequences (Keim, 2008). According to this author, vulnerability reduction programs are important to reduce susceptibility and increase resilience. Susceptibility to disasters can be largely reduced by prevention and mitigation of emergencies, and emergency preparedness, response and recovery activities to increase disaster resilience. This means that local public health agencies have the direct responsibility to build human health resilience to climate-related disasters. But this requires ongoing, progressive assessment and action, not a one-time assessment of risks and interventions (Ebi and Semenza, 2008). Further, it will require integrated approaches, from regional or trans-national to individual/household level.

But maybe the most critical concern regarding climate change adaptation and mitigation in small tropical developing nations is largely economic (Stage, 2010). Those countries least causally responsible for climate change, such as small island nations, are predicted to suffer the most from climate impacts (Hartzell-Nicholls, 2011). Costs and benefits of climate change adaptation in developing nations, beyond economic and climate science, need to incorporate behavioral science, and legal and moral aspects (Stage, 2010). Lack of government capacity or their unwillingness to address the infrastructure and service needs of their low-income populations would also represent another roadblock to adaptation (Satterthwaite, 2011). Finally, there is still a view in many government institutions that biodiversity conservation contradicts socio-economic development. Nonetheless, there is a paramount need to link biodiversity conservation, community-based livelihoods, and food security to foster climate change adaptation (Mainka and Trivedi, 2002), and sustainable socio-economic growth.

To achieve these and many other strategies there is still a need to build awareness across different sectors of society. There is also a need to translate information about research on climate change impact needs into language and time scales relevant for high-level and sectorial policy makers, planners and managers (Huq et al., 2003). It is fundamental to educate and engage all relevant stakeholders, particularly the most vulnerable sectors of society (i.e., marginal communities, human settlements along coastal areas and floodplains, women), and to connect national and international experts and researchers with decision makers on the ground (Marshall et al., 2010). Special attention must be paid to the most vulnerable regions and populations within each country (i.e., indigenous people, older citizens, women and children) to strengthen strategies for improving negotiating capacities and seeking major funders, and to build long-term national adaptive or mitigating capacity. This implies the integration of global climate change into bottom-up and place-based efforts to engage base communities into adaptive practices (van Aalsts et al., 2008). Community-based participation is crucial to foster engagement of vulnerable groups in assessing temporal trends in climate risks, to address vulnerability reduction, and to discuss, plan, design and implement solutions. This suggests the need to translate climate information to the community level, to incorporate traditional ecological knowledge and cultural heritage, and address community-based risks and needs. However, to be effective, outsiders must first gain the trust of the communities they want to help (Huq and Reid, 2007). It is also fundamental to respect indigenous people's rights and traditions (ILRC, 2014). Such information should then be incorporated to national, regional and global strategies.



## 9. Conclusions

Climate change has caused major unprecedented impacts across many coastal tropical ecosystems, on public health, and on local economies and community livelihoods. The magnitude of such impacts may become more pronounced for developing nations in the near future. Preparing and adapting for climate change can be challenging, particularly for small island nations. The nature and severity of impacts are likely to vary from place to place and across economic sectors, and also across society organizational scales, from individual/household to regional/trans-national scales. In addition to the effects on depleted tropical marine resources, coastal resource users will also be subjected to institutional and regulatory changes and challenges. For example, regulations to reduce fishing effort (such as gear restrictions, temporary closures, fishing quotas, and the designation of no-take MPAs have already been introduced specifically to increase reef resilience to climate change (Salm and Coles, 2001; Miththapala, 2008). But even though no-take MPAs support higher fish biomass than adjacent areas open to fishing, they have no significant effect on the ecosystem response to large-scale climate-related disturbance, further suggesting that adaptive management of climate change-related impacts will have to occur on unprecedented spatial, multi-national scales (Graham et al., 2008).

Best case scenarios may arise if we can keep ATM CO<sub>2</sub> concentration below 450 ppm and increase our efforts to build the ecological resilience of coral reefs and other associated coastal ecosystems which function as first lines of defense against storm swells and SLR, as well as motors of community-based livelihoods and local economies. There is absolutely a need to reduce the impact of other environmental stresses, such as pollution, sedimentation, overexploitation, destructive fishing practices, and non-sustainable land uses. Worst-case scenarios may arise if we do not take immediate and imperative stern action on emissions. Even under scenarios way beyond 450 ppm, extensive coral reef ecosystems are being lost in the rapidly warming and acidifying seas. Similarly, marine-based food webs are being impacted by ocean acidification and fishing exploitation, with a resulting loss in biodiversity, biomass, food web shrinking, and declining productivity. Also, major ecological changes are occurring across terrestrial landscapes and freshwater ecosystems with paramount direct and indirect effects on biodiversity, ecosystem functions, resilience, water availability, and on food security and sovereignty. But even under such an obscure panorama, there are still plenty of opportunities for adaptation.

There are multiple fundamental strategies for the sustainable adaptability of coupled social–ecological systems across multiple societal organizational scales, of coastal ecosystems that function as first lines of defense against storm swells and SLR, and fisheries that can still be implemented to gain extra time to reduce potential impacts by climate change and SLR. There are also opportunities to foster a reduction in public health risks and to improve food security and sovereignty. This has to pay particular emphasis on the most vulnerable sectors of society. Given the trend of increasing global stress on tropical coastal ecosystems, it has become increasingly important to reduce the impact of other human stresses on coastal ecosystems, freshwater and groundwater resources, and on food production. But this alone, will not be enough to save small tropical island ecosystems, their resilience, productivity and tourism economic value if we do not reduce our greenhouse gas emissions, particularly that of CO<sub>2</sub>. If adaptive action is not rapidly taken, the future of small tropical island nations might be at a very high risk in the near future.

Our generation has the unprecedented challenge of lifting people out of poverty, advancing economic growth through sustainable socio-economic models, and conserving and rehabilitating rapidly declining natural resources. To achieve this we must connect the links among declining natural resources, biodiversity, productivity, natural resources value, food security and sovereignty, public health, local economy, the long-term erosion of traditional livelihoods, water scarcity, energy shortages, increased globalized economic pressures, women's empowerment,

and the combined impacts of local human stressors and climate change. Solutions must transcend the typical focus on individual problems and must be solutions for all. There is still time to take action before it becomes too late.

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