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REVIEW ARTICLE

Communities and change in the anthropocene: understanding social-ecological vulnerability and planning adaptations to multiple interacting exposures

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Abstract The majority of vulnerability and adaptation scholarship, policies and programs focus exclusively on climate change or global environmental change. Yet, individuals, communities and sectors experience a broad array of multi-scalar and multi-temporal, social, political, economic and environmental changes to which they are vulnerable and must adapt. While extensive theoretical—and increasingly empirical—work suggests the need to explore multiple exposures, a clear conceptual framework which would facilitate analysis of vulnerability and adaptation to multiple interacting socioeconomic and biophysical changes is lacking. This review and synthesis paper aims to fill this gap through presenting a conceptual framework for integrating multiple exposures into vulnerability analysis and adaptation planning. To support applications of the framework and facilitate assessments and comparative analyses of community vulnerability, we develop a comprehensive typology of drivers and exposures experienced by coastal communities. Our results reveal essential elements of a pragmatic approach for local-scale vulnerability analysis and for planning appropriate adaptations within the context of multiple interacting exposures. We also identify methodologies for characterizing exposures and impacts, exploring interactions and identifying and prioritizing responses. This review focuses on coastal communities; however, we believe the framework, typology and approach will be useful for understanding vulnerability and planning adaptation to multiple exposures in various social-ecological contexts.

Keywords Social-ecological systems · Vulnerability · Adaptation · Exposure · Adaptive capacity · Coastal communities · Drivers of change

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> The complexity, unpredictability and pace of events in our world, and the severity of global environmental stress, are soaring….Many societies, groups, and people adapt reasonably well to our swiftly changing world, but others have fallen behind and risk being overwhelmed by converging pressures. Thomas Homer-Dixon, The Ingenuity Gap, 2000.

Introduction

"Change is the only constant…", Heraclitus might have been talking about communities when he said this in ancient Greece. For contemporary communities around the world, each situated in a distinct social-ecological context and each with their own histories and visions for the future, anthropogenic change is occurring with increasing rapidity, complexity and uncontrollability (IPCC 2014; Steffen et al.

2015). The drivers of these changes occur at different scales and speeds and include environmental, climatic, economic, technological, sociocultural, demographic and governance factors (Millenium Ecosystem Assessment 2005; Zou and Wei 2010; Bennett et al. 2014b). Communities are exposed to these exogenous changes through direct and indirect impacts on the interrelated components of social-ecological systems (Turner et al. 2003; Perry et al. 2010). Multiple socioeconomic and biophysical changes occurring simultaneously at different scales and speeds interact to produce drastically different outcomes for communities in different places (O'Brien and Leichenko 2003; O'Brien et al. 2004; Tuler et al. 2008; Brklacich et al. 2009). Yet, the predominant focus of vulnerability and adaptation research, policy and practice has been solely on climate change or global environmental change. This focus on a single driver of change is often the result of a problem-centered, rather than community-centered, approach.

Understanding the multiple, interacting drivers and impacts of these changes on social-ecological systems is paramount for ecological sustainability and for human well-being. Authors from various disciplines, including social-ecological systems and resilience (Berkes et al. 2003; Turner et al. 2003; Walker et al. 2004), sustainable livelihoods (Ellis 2000; Scoones 2009), hazards research (Berkes 2007; Smith 2013), fisheries (Tuler et al. 2008; Perry et al. 2010; Kittinger et al. 2013), agriculture (Eakin 2005; Paavola 2008) and climate change vulnerability and adaptation (Adger 2006; Marshall et al. 2010; Eriksen et al. 2011; Roiko et al. 2012), have stressed the importance of considering multiple interacting exposures in research, policy and practice. Initially, this discussion remained largely at the conceptual realm (Turner et al. 2003; Brklacich et al. 2009). A limited but increasing body of empirical work explores the nature of drivers and exposures, and the interactions between exposures as experienced by local groups and communities (O'Brien and Leichenko 2000; Bunce et al. 2010b; Bennett et al. 2014b). Yet, in many cases the bottom-up approaches taken in empirical studies have led to results that: (a) fail to explore the breadth of changes to which communities are exposed and (b) inadequately examine how these changes interact to produce variable outcomes for linked social and environmental assets that are important to local communities. Indeed, few case studies of coastal vulnerability are guided by conceptual frameworks, which have led to limited comparability among sites, countries and regions (Zou and Wei 2010). Typically, these conceptual and empirical approaches simplify the scope of changes to which communities are exposed, invariably leading to one-dimensional adaptation policies, programs and actions that fail to address the multifaceted and multi-scalar drivers of change, and the complexity and uncertainty of changes in local social-ecological systems.

No single conceptual framework synthesizes the broad range of theoretical advancements on multiple exposures. Deliberate progress toward the goal of long-term sustainability requires an understanding of the dynamics of multiple drivers of change, and resulting exposures, impacts and responses, in linked social-ecological systems. In this article, we review and synthesize the existing theoretical and empirical work on drivers of change in coastal social-ecological systems to: (a) present a conceptual framework for understanding vulnerability to multiple interacting exposures, (b) develop a comprehensive typology of drivers, exposures and impacts being experienced by coastal communities, (c) propose essential elements of a pragmatic approach for vulnerability analysis and adaptation planning and (d) explore methods for assessing the impacts of, and responses to, multiple exposures in coastal social-ecological systems. To limit the scope of the paper, this review focuses on coastal communities, which face both land- and sea-based exposures. However, we believe the framework, typology and approach can be applied to understand social-ecological change and to develop appropriate response strategies in various contexts.

Vulnerability to multiple exposures: key concepts and conceptual framework

The concept of vulnerability is rooted primarily in scholarship on development and livelihoods (Sen 1982; Chambers and Conway 1992; Scoones 1998), hazards (Burton et al. 1993; Watts and Bohle 1993; Mustafa 1998), global environmental change (Vogel 1998; Turner et al. 2003; Smit and Wandel 2006) and resilience (Holling 2001; Gunderson and Pritchard 2002; Folke et al. 2003). There have been several dominant ways of conceptualizing vulnerability (Adger 2006). The first is to view vulnerability as an outcome through focusing on the impacts of a hazard, such as climate change, and the ability of a system to respond. The purpose of "end point" vulnerability analysis is to estimate and reduce costs of hazards. A second perspective emphasizes vulnerability as the "starting point" and focuses on the historical factors or current characteristics of individuals, households, communities, sectors, nations, etc. that determine their differential susceptibility to harm. A more comprehensive view considers vulnerability to be the result of the interaction between exposure, sensitivity and adaptive capacity (Turner et al. 2003; Smit and Wandel 2006; Perry et al. 2010). Exposure refers to the degree to which trends and shocks, driven by changes at various scales, are experienced by a region, resource or group. Sensitivity is the susceptibility of an entity or system to the effects of an exposure. Historical, social, political, economic and environmental preconditions determine a system's sensitivity.

Watts and Bohle (1993) suggest resource distribution, political power and voice, rights, and access to institutions mediate sensitivity. Exposure and sensitivity combined define the potential impacts of a change. Impacts can be unevenly experienced by various similarly exposed groups (genders, ages, classes, racial groups, livelihoods, etc.) based on differential sensitivities (O'Brien and Leichenko 2000). Adaptive capacity refers to "the ability to respond to challenges through learning, managing risk and impacts, developing new knowledge and devising effective approaches" (Marshall et al. 2010). Adaptive capacity is latent potential until it is applied in response to a change. Adaptive capacity is determined by access to assets (human, social, physical, financial and natural), capacity to organize, leadership, learning and knowledge, imaginative resources and capacity to self-organize (Folke et al. 2003; Cinner et al. 2009; Bussey et al. 2012; Bennett et al. 2014a). In this view of vulnerability, the relationship between the three components of vulnerability might be simplified to an equation: $V = E + S - \mathrm{AC}$—whereby vulnerability (V) is determined by exposure (E) plus sensitivity (S) minus adaptive capacity (AC) (Adger 2006).

We next introduce seven key considerations that should shape analysis of vulnerability and responses to help maintain a resilient system. We integrate these elements into a conceptual framework for understanding community social-ecological vulnerability (Fig. 1). First, while many analyses of vulnerability focus on impacts and outcomes in either social or ecological subsystems, we argue that either focus is incomplete. Relevant systems for vulnerability analysis must address linked social and ecological components (Turner et al. 2003; Brklacich et al. 2009). Social-ecological systems can be defined as complex, integrative and adaptive systems, wherein humans are part of nature (Berkes and Folke 1998). Even in urban areas, ecosystems are important elements of resilience (Tyler and Moench 2012).

Second, large-scale exogenous conditions and trends that operate at different scales and speeds (defined as "drivers") drive local exposures (Armitage and Johnson 2006; Perry et al. 2010). More rigorous understandings of multi-scalar drivers will lead to insights into exposures and responses (Hall 2011; Kittinger et al. 2013). Drivers of change can be biophysical—i.e., climate change and other environmental changes—and socioeconomic—i.e., economic transformation, technological change, sociocultural evolution, demographic change and shifts in governance structures and institutions.

Third, exposures have often been framed as being affected by stressors, risks or hazards that lead to harms (Sen 1982; Burton et al. 1993; Watts and Bohle 1993; Berkes 2007). Yet, local exposure to trends and shocks does not necessarily lead to negative outcomes for all social or ecological components of systems. Exposures can also be experienced as opportunities for reorganization and renewal and may lead to either desirable or undesirable outcomes (Holling 2001; Gunderson and Pritchard 2002).

Fourth, better incorporation of multiple exposures into analysis of vulnerability will lead to more effective vulnerability research and adaptation policy (Leichenko and O'Brien 2008; Brklacich et al. 2009; Bunce et al. 2010a; Smith et al. 2013; Bennett et al. 2014b). Many vulnerability assessments rely on large-scale and top-down studies using predetermined indicators that make implicit assumptions about the nature of changes being experienced. More empirical studies are needed to ground theoretical work in the complexities of local experiences of multiple exposures (Turner et al. 2003; Silva et al. 2010; Zou and Wei 2010) and to better identify actions to improve institutions and policies (Hall 2011).

Fifth, many analyses of vulnerability, resilience and adaptive capacity are static snapshots of the present that do not account adequately for interactions and feedbacks. Systems are dynamic with constantly changing drivers, exposures, impacts, responses and outcomes. Impacts can be direct or interactive. Interactive impacts result from interactions between drivers at higher scales, cascading effects of direct impacts from exposures, autonomous feedbacks between and among social and ecological components, and the feedbacks of adaptive responses to direct impacts. For example, Friedman (2013) suggests that climate change can be a "scary hidden stressor" as distant communities might indirectly experience rises in the price of a staple food as a result of the impacts of climate change elsewhere, leading to political unrest. Cinner et al. (2011) argue that it is critical to understand whether adaptive responses lead to amplifying or dampening feedbacks. Amplifying feedbacks are those that increase vulnerability or erode social-ecological resilience over the longer term, whereas dampening feedbacks reduce the impact of negative trends. Outcomes slide back and forth on a continuum between vulnerability to sustainability for both social and ecological criteria and change over time.

Sixth, responses to exposures can be characterized as coping or adapting (Smit and Wandel 2006; Bennett et al. 2014a). Coping refers to short-term reactive or unplanned responses to moderate the impacts of, or reduce sensitivity to, exposures. Sometimes, coping strategies can be maladaptive and increase overall sensitivity and vulnerability in the longer term. For example, intensification of fishing effort is a short-term strategy often employed by fishers that will lead to longer-term reductions in fish productivity and abundance. Adapting refers to proactive planning of longer-term courses of action that lead to beneficial outcomes for social and ecological systems. Adaptations fall within three categories: (a) preventive actions to reduce exposure and sensitivity, (b) strengthening adaptive

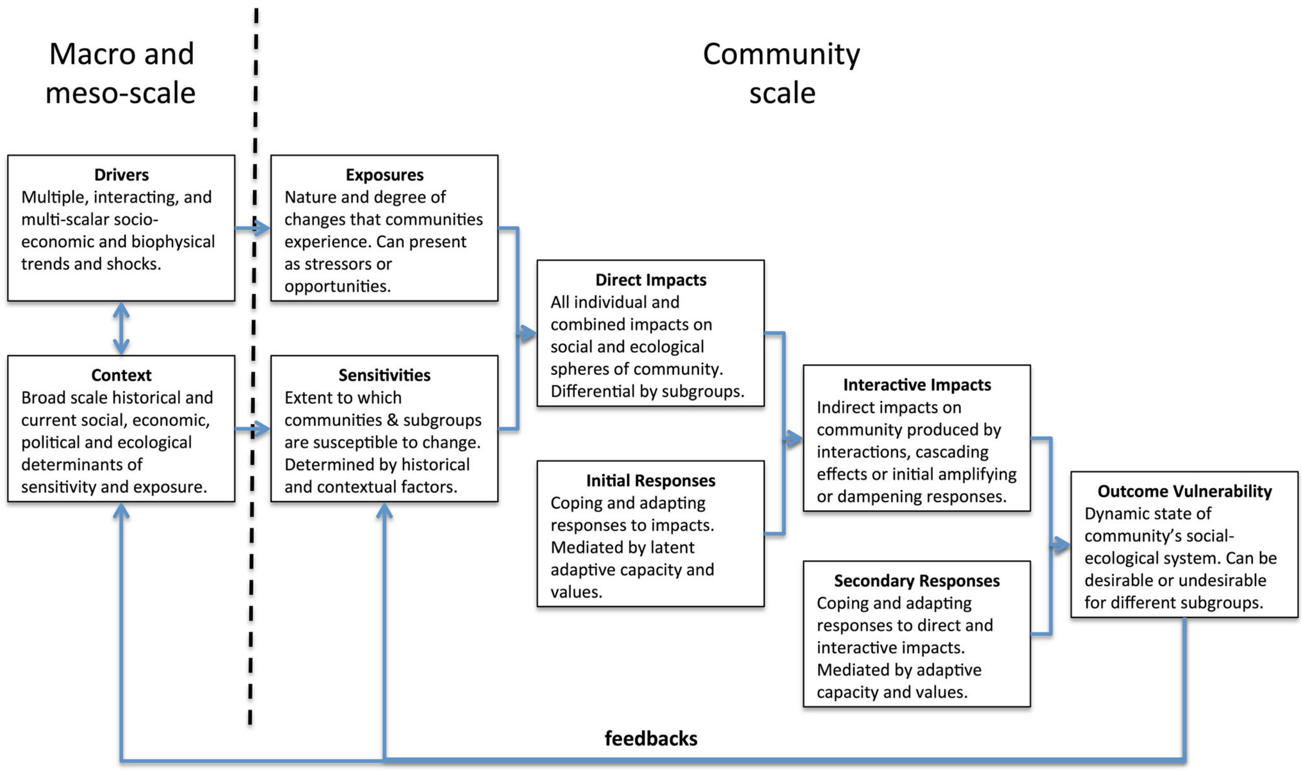

Fig. 1 Conceptual framework for understanding community social-ecological vulnerability to multiple interacting exposures

capacity and (c) measures that improve social and ecological outcomes (Smit and Wandel 2006). Adaptive strategies reduce exposure and sensitivity over the long term and thereby reduce system vulnerability.

Finally, adaptation options are limited by institutional and material constraints as well as social structures and governance processes, culture and values (Adger et al. 2009a; O'Brien 2009; Adger et al. 2009b, 2013; Elrick-Barr et al. 2014; IPCC 2014). Values mediate perceptions of risk, determine desired outcomes or goals and influence courses of action or adaptations (Hicks and Cinner 2014). O'Brien and Wolf (2010) argue "…what is considered as effective and legitimate adaptation depends on what people perceive to be worth preserving and achieving. How to adapt to climate change therefore hinges on the values underlying people's perspectives on what the goals of adaptation should be." Adaptation decision-making processes should make explicit and incorporate diverse values as well as feasibility and constraints.

The aforementioned considerations are incorporated into a conceptual framework for understanding and analyzing local community vulnerability to multiple exposures (Fig. 1)—which builds on work by others (Turner et al. 2003; Smit and Wandel 2006; Perry et al. 2010). The framework shows vulnerability as a dynamic process and outcome of social-ecological systems that results from exposure to multi-scalar and dynamic drivers, contextualized and differential sensitivities, direct and interactive impacts. Responses to perceived vulnerability include multiple coping and adapting measures mediated by adaptive capacity and values. Values define what are considered desirable or undesirable outcomes for social or ecological spheres of a community system.

Typology of drivers, exposures, impacts and interactions in coastal communities

This section reviews and categorizes drivers, exposures and impacts experienced by coastal communities (Table 1). The typology is separated into biophysical and socioeconomic drivers and exposures. Interactions within and between the two spheres are also discussed.

Bio-physical drivers, exposures and impacts

Climate change related

Between 1955 and 2010, the temperature of top 700 meters of the planet's oceans increased by an average of 0.18 °C, with direct impacts on marine life and the human communities that rely on marine resources (Bunce et al. 2010b; Levitus et al. 2012). One consequence of warming water is the reduction in sea ice. In Alaska, earlier spring ice break-up is limiting spring fishing (a critical source of protein following the winter), while unpredictable ice conditions hinder winter travel and access to marine resources (Moerlein and Carothers 2012). As a result of the decline of polar ice sheet mass, global mean sea level has risen by 0.19 meters during the last century and could potentially surpass a 1-m rise by 2100 (Pfeffer et al. 2008; Church and White 2011). Sea level rise will have profound impacts on coastal ecosystems, such as a projected loss of 10–20 % of global mangroves by 2100 (McGranahan et al. 2007). Moreover, sea level rise poses serious socioeconomic risk since 10 % of the world's population lives in low-elevation (<10 m) coastal zones (Nicholls et al. 2007). Climate change is increasing the frequency and magnitude of extreme weather events such as tropical storms, which threaten coastal infrastructure and exacerbate dangers fishers face at sea (Knutson et al. 2010; Blythe et al. 2013). The warming of the upper layers of the ocean is driving greater stratification of the water column, changes in ocean circulation and variable precipitation patterns, all of which will perpetuate significant change in coastal systems.

Climate change is also generating profound changes in chemical ocean properties. Since the industrial revolution, global oceans have absorbed 25 percent of anthropogenic carbon dioxide (Le Quéré et al. 2012). As a result of this uptake, the average pH of ocean surface waters has fallen from 8.2 to 8.1 in a process known as ocean acidification (Feely et al. 2009). While this decrease appears relatively small, a decrease of 0.3–0.4 pH units by the end of this century would represent the oceans' lowest pH value in 40 million years (Pelejero et al. 2010). Organisms that use carbonate ions dissolved in sea water to form shells or skeletal structures, such as plankton, benthic molluscs, echinoderms and corals, may be negatively impacted by lower ocean pH, although species' sensitivity will vary (Doney et al. 2009; Kroeker et al. 2010). Since many of these organisms form the foundation of marine trophic chains, ocean acidification may have large ecological and social consequences (Fabricius et al. 2011; Busch et al. 2013). Oceanic dissolved oxygen has also decreased since 1960, albeit with strong regional variations (Keeling et al. 2010). Decreased dissolved O_2 has widespread implications for ocean productivity, nutrient cycling, carbon cycling and marine habitats.

The changes in the physical and chemical conditions of the world's oceans have prompted a wide range of ecological responses. Increasing evidence suggests that many reef fish species are already living close to their thermal optima (Rummer et al. 2014), meaning that that higher ocean temperatures will lead to reduced fitness or mortality (Munday et al. 2008). Many marine species, ranging from turtles to phytoplankton, have altered their distributions in response to warming waters in order to maintain their optimal thermal range (Polovina et al. 2008; Pike 2014). These relocations

Table 1 Typology of biophysical and socioeconomic drivers and exposures

Drivers of change		Exposures	
Classification	Subclassification	Categories of exposure	Types of exposure
Biophysical	Climate change	Physical properties	Changing oceanic temperature
			Reduced sea ice
			Sea level rise
			Extreme weather events and storm surges
			Variable precipitation patterns
			Changing atmospheric temperature
		Chemical properties	Ocean acidification
			Reduced dissolved oxygen
		Ecological responses	Species range shifts
			Reduced thermal optima
			Coral bleaching
			Ecosystem changes, invasive species, diseases and biodiversity loss
	Other Environmental	Ocean-based	Overfishing
			Habitat degradation
		Hazards	Earthquakes, tsunamis, fires, floods
		Land-based	Nutrient loading
			Fresh water use
			Pollution and garbage

Table 1 continued

Drivers of change		Exposures	
Classification	Subclassification	Categories of exposure	Types of exposure
Socioeconomic	Demographic	Population	Urbanization/gentrification
			Changing age/sex distribution
		Migration	In-migration from other regions or countries
			Permanent or temporary out-migration
		Health	Chronic illness or acute diseases
			Injuries and disabilities
			Mental, emotional and spiritual health
	Economic	Macroscale economic institutions and processes	Economic globalization
			National economic policies (e.g., market liberalization, privatization, trade tariffs, subsidies)
			Changing patterns of consumption
			Changing livelihood opportunities and dependencies
			Private sector investments and partnerships
		Costs and credit	Increasing food costs
			Rising livelihood costs (e.g., gear, fuel)
			Access to credit
		Market demand and prices	Changing demands for natural resource products
			Changing market prices
	Infrastructure and technology	Increasing physical and technological capacity	Bigger boats, larger engines, improved gear
			Navigation and fish-finding technology (e.g., sonar, GPS)
		Coastal development	Urbanization and restructuring of coasts
			Tourism infrastructure
			Extractive industries (Sand, mining, gas projects)
			Aquaculture and mariculture
		Basic services and social infrastructure	Roads and public transportation
			Schools, hospitals, electricity, water, waste treatment
			Communication infrastructure and media
		Engineered structures	Dams, levees
		Household	Household infrastructure
			Household assets
	Governance and policy	Changing governance institutions and structures	Organizational jurisdictions and mandates
			Decision-making structures, processes (centralization, inclusion, scale) and legitimacy
			Societal norms and values
			Networks of organizations and actors
			Capacity and resourcing
		Changing regulations	Changes in tenure and rights (property, harvest, access, management)
			Natural resource management, fisheries and conservation policies
			Market-driven changes in allocations and harvesting
		Conflict and security	Conflicts between groups and resolution mechanisms
			Politics and violence
	Sociocultural	Shifting traditions, knowledge and values	Changing value systems
			Loss or re-invigoration of traditional practices
			Changing knowledge systems
		Networks and relationships	Shifting family relationships and gender roles
			Organizational networks and bridging social capital

may lead to local extinctions of fish populations, new species interactions and profound changes in marine food webs (Mueter and Litzow 2008). The southeastern Australian sea urchin, for example, has recently expanded its range into Tasmanian waters, where it has catalyzed a regime shift from macro-algal communities into urchin barrens (Ling 2008). In Norway, increases in ocean temperatures have driven collapses in the Barents Sea capelin stocks, with negative impacts on both Arcto-Norwegian cod stocks and the fishing communities in the region (Perry et al. 2011). Among the most significant influences of climate change on the world's oceans are its impacts on habitat-forming species such as corals. Mass coral bleaching and mortality, the result of increasing temperatures, is already reducing the richness and density of coral reef fishes with significant impact on reef fish and fisheries (Bellwood et al. 2006; Cinner et al. 2012b). Climate change is projected to change metabolic rates of marine species, reduce primary productivity and increase incidence of disease (O'Connor et al. 2009; McLeod et al. 2013). Climate change is also expected to challenge the ocean's capacity to meet the fish consumption demands of a growing human population (Merino et al. 2012).

Other environmental

Overfishing may outweigh all other pervasive human disturbances to coastal ecosystems, including anthropogenic climate change, pollution and degradation of water quality. Overfishing alters marine population demographics (removal of older individuals), spatial dynamics (changes in spawning grounds) and species abundance and thus reduces the ocean's ability to provide food, maintain water quality and recover from perturbations (Worm et al. 2006; Rockström et al. 2009a; Watson et al. 2014). Historic exploitation of sea otters in the Aleutian Islands removed the primary predator of sea urchins, resulting in massive deforestation of kelp forests via an unregulated sea urchin population (Steneck et al. 2002). The ability of Atlantic cod stocks to tolerate environmental variability has been eroded by fishing, which removes older fish and thus the buffering capacity provided by older individuals (Ottersen et al. 2006). Perhaps the most detrimental impact of overfishing on coastal systems is the negative effects on food and livelihood security for millions of small-scale fishers and their families particularly in the developing world. In Mozambique, for example, over 80 % of small-scale fishers surveyed reported food insecurity, which they attributed to declining catch resulting from overfishing (Blythe et al. 2014). Within a few years, aquaculture's contribution to fish supply for human consumption will exceed that of wild capture fisheries and the industry stands to make important contributions to food security. However, the explosive development of coastal aquaculture has been criticized for the destruction of mangroves, saline intrusion, damaging runoff and collection of wild broodstock, as well as for forcing local stakeholders off their land and for converting multiple-use coastlines into single-use monocultures, and may pose a serious threat to the well-being of coastal communities (Duke et al. 2007; Paul and Vogl 2011; Zou et al. 2011). Many other forms of coastal development and land-use changes impact previous livelihoods.

Land-based activities produce profound impacts on coastal systems. Over the last five decades, conversion of forests and other ecosystems into agricultural land has occurred at an average global rate of 0.8 % per year (Millenium Ecosystem Assessment 2005). The manufacture of fertilizer for food production and the cultivation of leguminous crops convert more nitrogen from the atmosphere into reactive forms than all of the Earth's terrestrial processes combined (Rockström et al. 2009b). Much of this new nitrogen ends up in the environment, polluting coastal zones and increasing incidence of hypoxia (Diaz and Rosenberg 2008). The extent and intensity of hypoxic zones in the Baltic Sea, for example, have increased dramatically during the last half-century with considerable impacts on biogeochemical processes, ecosystem services and coastal habitats (Conley et al. 2011). Annually over 8.5 million tonnes of phosphorous flow into the world's oceans, which is 8–9 times higher than the natural background rate (Rockström et al. 2009a). Phosphorus-induced anoxic events have been linked to mass extinctions of marine life (Handoh and Lenton 2003). Humans are currently the dominant driver of change in global river flow (Shiklomanov and Rodda 2004). An estimated 25 % of the world's river basins run dry before reaching the oceans due to human use (Molden et al. 2007). Global manipulations of the freshwater cycle affect biodiversity, food and health security, and ecological functioning, such as provision of habitats for fish recruitment, carbon sequestration and climate regulation (Rockström et al. 2009b). In central Mozambique, poor dam management has contributed to severe flooding and villagers report saltwater spreading up the estuary when the dam is closed, which harms agricultural crops and contaminates drinking water (Bunce et al. 2010b). Furthermore, humans are increasing the river transport of sediment through soil erosion activities and decreasing transport to the coastal zone through sediment retention in reservoirs (Syvitski and Kettner 2011). Changes in sediment supply can create significant changes in the benthic environment of coastal estuaries, coral reefs, sea grass communities and coastal fisheries.

Socioeconomic drivers, exposures and impacts

Demographic

Earth's population is expected to grow by one billion between 2013 and 2025, reaching over 8 billion people

(UNDP 2013). Rapid increase in population density has been prevalent in coastal zones, exposing coastal systems to new risks (Nelson et al. 2005; Mee 2012). For example, migration is one of the central drivers of increased exposure to flooding as low-lying coastal areas are becoming urbanized (Adelekan 2010; Hanson et al. 2011). In Kenya and Mozambique, increasing population along the coast, resulting from both local population growth and migration of people in search of economic opportunity, represents the main force exerting pressure on the coastal fishery (Mangi et al. 2007; Blythe et al. 2013). Brewer et al. (2012) demonstrate a negative relationship between coastal population density and the diversity and function of coral reef fishes.

Migration is another demographic change exerting pressures on coastal systems. For example, in Mozambique, fighting inland during the civil war drove millions of people to the coast, many of whom turned to fishing (Blythe et al. 2013). Migrant fishers can be marginalized in their new communities and exposed to poor living conditions, such as lack of safe drinking water or adequate living quarters (Njock and Westlund 2010). Gentrification in fishing communities in the USA, driven by increasing coastal populations, changing demographics, and a desire for access to natural amenities, is accelerating a move toward non-marine-based economies that displace local residents and their dependence on fishing (Colburn and Jepson 2012). Another dimension of coastal migration is the movement of young people out of fishing communities to larger urban centers, resulting in the aging of traditional fishing communities (Ommer and Team 2007).

Economic

The increasingly interconnected nature of our globalized economy can create opportunities and challenges for coastal communities. Increasing international trade has exposed local producers to boom and bust cycles associated with expanding luxury markets for marine products such as shrimp (Blythe et al. 2014), shark fins and sea cucumbers (Eriksson and Clarke 2015) and live reef fish (Fabinyi and Dalabajan 2011). In India, Chinese interest in a range of species that had previously been ignored by local fishers produced an export-induced economic surge in the coastal fishery in the late 1980s (Armitage and Johnson 2006). However, the boom proved unsustainable and collapsed following the Asian financial crisis in 1997. Trade-induced increases in demand for marine resources have also resulted in sequential depletions of internationally targeted species (Berkes et al. 2006). Unregulated harvest of green sea urchin, driven by demand from Japanese sushi markets, led to rapid stock depletion in Maine (Steneck et al. 2002). However, increasing international demand for sea cucumber has driven overexploitation of stocks in the Western Indian Ocean (Eriksson et al. 2010). Changes in the compositions of people's diets, driven by rising per capita income and globalization of our food systems, have been characterized by less consumption of starchy staples (rice, wheat and potatoes) and more of fat, meat, fish, fruits and vegetables (Nelson et al. 2005). In some cases, this has led to better nutrition. However, in other cases, such as the Solomon Islands, traditional diets have been replaced by consumption of processed foods and associated with rising health concerns such as diabetes (Schwarz et al. 2011).

Coastal communities are vulnerable to drastic price changes driven by global market dynamics. In Mozambique, rising food prices have eroded traditional reciprocal sharing networks and worsened food insecurity (Bunce et al. 2010b; Blythe et al. 2014). Moreover, increasing prices for fuel have led to reduced fishing days (Tuler et al. 2008; Bunce et al. 2010b). These impacts are exacerbated for marginalized coastal people, including migrant and subsistence fishers, who typically do not have access to credit (Mills et al. 2011; Blythe et al. 2014). In some areas, declining prices for marine products are reducing fishers' income and driving increasing fishing pressure (Bennett et al. 2014b). Constantly shifting prices and seasonal demand for marine resources and tourism affect income and household stability (Tuler et al. 2008; Bennett et al. 2014b). In some cases, lower incomes have caused fishers to fish longer hours, in increasingly dangerous conditions (Tuler et al. 2013). Globalization has also driven a dramatic increase in international tourism, with varying results for coastal communities. On the Andaman coast of Thailand, for example, some people have profited from tourism through sales, restaurants and ocean tours, while others are experiencing loss of livelihood options due to exclusions from national marine parks (Bennett et al. 2014a). This example demonstrates how rapid and drastic changes in market characteristics and prices can benefit some and not others, which can reinforce inequities for vulnerable groups.

Technology and infrastructure

Coastal landscapes are being transformed as a consequence of new technology. Larger engines, more efficient gear and improved fish-finding capabilities have significantly changed our relationship with marine resources. In many countries, increasing fishing capacity has led to initial increases in marine landings, followed by a marked decline (Tuler et al. 2008; Perry et al. 2011; Blythe et al. 2013; Kittinger et al. 2013). In India, the rise of trawling combined with motorization of the small-scale fleet has led to conflicts between trawlers and small-scale fishers (Armitage and Johnson 2006). In Nunavut territory of Canada, new technologies, such as citizen band (CB) radios, global positioning systems (GPS), personal location beacons and consultation of satellite images of sea ice prior to travel, have both increased safety for Arctic hunters by allowing them to avoid dangerous areas and situations while increasing risks for less experienced hunters in the case of gear malfunction (Ford et al. 2006).

Rapid coastal development has many consequences. Close to one quarter of the world's population lives within 100 km of the coast, meaning that coastal systems have experienced disproportionately rapid expansion of economic activity and infrastructure development (Small and Nicholls 2003). Coastal dredging for land reclamation and port construction increases sedimentation and turbidity and has been linked with significantly higher incidence of coral disease in Western Australia (Pollock et al. 2014). Extractive industries, including mining and fossil fuel exploitation, can create exposure to new stressors in coastal communities. During the development of a gas project in Tanzania, promises of equipment that would allow fishers to fish offshore went unmet, villagers were forced to relocate, and protests escalated into violent conflicts (Bunce et al. 2010b).

In many areas, improvements in basic services have led to better access to markets, schools, hospitals and communication technologies, such as cell phones, with primarily positive impacts on coastal communities. Within weeks of installation of a cell tower in south India, the local price of fish converged where previously it varied highly from market to market (Jensen 2007). By calling ahead from sea, fishermen travelled to markets where fish were in low supply leading to an average 5 % reduction in the price of fish for consumers and a 9 % gain in income for fishers. Infrastructure developments such as increasing road access can reduce vulnerability in remote rural areas, which have been geographically isolated and characterized by high transaction costs, limited access to markets and low provision of government services or infrastructure (Béné 2009).

Governance and policy

Governance refers to the prevailing set of processes, institutions and policies through which the rules shaping the use of coastal resources are set and revised (Bennett 2015). Governance systems produce profound consequences for coastal communities and linked ecosystems. Organizational mandates, agency jurisdictions, formal decision-making structures and processes are often realigned by governments or through the interactions of influential stakeholders with the governance system (Ommer and Team 2007; Chuenpagdee 2011). Changing societal norms and values can also manifest in governance systems by stimulating new policy directions (e.g., in fisheries or conservation) and determining what constitutes appropriate governance processes (e.g., levels of participation, transparency, accountability). In general, institutions can serve as enablers or inhibitors of adaptive capacity and corrective adaptations (Tyler and Moench 2012)—for example, in the adoption of an ecosystem-based approach to climate change (Elrick-Barr et al. 2014; Lukasiewicz et al. 2015). Levels of resourcing and organizational capacity determine whether agencies are able to learn through research, engage with the knowledge produced and implement management actions (Jantarasami et al. 2010; Cvitanovic et al. 2014). Shifting relationships and levels of collaboration between networks of organizations and individuals involved in governance can also determine the level of participation of local communities and the effectiveness of coastal management initiatives (Bodin and Crona 2009; Alexander and Armitage 2015).

Governance structures and decision-making processes strongly affect whose voices are heard in decision-making and how local knowledge and needs are incorporated. This means that in order to engage local knowledge in evidence-based decision-making, governance processes themselves may need to be revised. There is a growing literature on the potential for combining local knowledge systems with scientific knowledge to cope with change in resource and ecosystem management (Haggan et al. 2007; Armitage et al. 2007). For example, in the Solomon Islands, indigenous knowledge and sea tenure systems were used in combination with scientific knowledge to establish marine protected areas for bumphead parrotfish conservation (Aswani and Hamilton 2004). Community-based and collaborative (e.g., co-management) initiatives have reduced exposure to threats such a stock declines (Pinto da Silva and Kitts 2006) and have created a greater degree of democracy in regard to resource governance (Cinner et al. 2012a) in many coastal communities, although the impacts of collaborative initiatives vary widely within the social-ecological complexity of coastal systems (Cohen and Alexander 2013).

In other cases, regulatory changes can create negative consequences for coastal communities when marine resources or spaces are reallocated or when "ocean grabbing" occurs (Bennett et al. 2015). The establishment of marine protected areas (MPAs) alters resource-use rights and has been associated with increasing incidence of elite control of resources, the exclusion of resource users and the criminalization of local people (West et al. 2006; Bennett and Dearden 2014). In Tanzania, conflict over resource access in a MPA escalated to the use of tear gas by police on local fishers (Bunce et al. 2010b). Even when reserves are specifically designated for the benefit of local users, such as the 3000-m limit in Thailand, conflict can arise between illegally fishing commercial vessels and small-scale fishers (Bennett et al. 2014b). Quota systems in the USA can increase unsafe decision-making and risk-taking by fishers (Tuler et al. 2008). For example, when a fishery is approaching its quota, fishers may race to finish their fishing before the quota is reached, even if it means venturing out in bad weather. Furthermore, consequences of regulatory change extend beyond those directly involved in marine resource harvesting. Tuler et al. (2013) documented how a regulatory change, introduced by the New England fishery Management Council in 2010, led to fewer fishing trips meaning that onshore workers lost hours and that the availability of dockage shrunk, since more vessels remained in port longer.

Sociocultural

In many coastal communities, concern about shifting values and norms is rising. Along numerous coasts, the use of marine resources has been regulated through taboos and beliefs controlled by community elders. These informal restrictions on fishing practices acted to maintain social control and access to common pool resources (Foale et al. 2011). Recently, many of these traditions have been eroded due to changing religious and cultural norms and declining interest of younger generations (Mangi et al. 2007; Blythe et al. 2013). A second, quite different impact of shifting values and norms can be seen in the Canadian Arctic. As Inuit hunters become more integrated into a "Western culture," traditional knowledge is being lost and risk-taking behavior has risen. Time off from formal employment must be booked months in advance, so hunters feel committed to a particular time regardless of weather or safety concerns (Aporta 2004). Younger hunters rely less on traditional knowledge and practice less caution due to perceived safety nets provided by technological developments (Ford et al. 2006). Changing family dynamics are creating exposure to new stressors. Following the cod moratorium in Newfoundland, Canada, some families replaced male fishing crew with wives in order to concentrate diminished earnings within the household (Grzetic 2004). In Kenya, the capacity to participate in traditional family reciprocity is being challenged by growing food insecurity (Casale et al. 2010). These examples reflect how shifting values and norms can create exposure to new stressors in coastal systems.

Interactions between exposures and adaptations

A key challenge for those living and working in coastal social-ecological systems is that multiple exposures do not simply converge—they interact. Moreover, most coastal systems are characterized not by single interactions between exposures but by multiple overlapping interactions. Furthermore, multiple exposures interact through autonomous, cascading, cross-scale and adaptive feedbacks leading to differential impacts and community social and ecological vulnerability outcomes depending on the context. Interactions and feedbacks can amplify, dampen or mitigate the impact of individual exposures. Due to the unlimited number of different contexts and factors involved, it is neither possible nor desirable to attempt to describe the multitude of expected and unexpected interactions between different exposures. Additionally, many impacts and interactions are unanticipated or novel, making vulnerability outcomes unpredictable. Below we provide two illustrative examples of interactions among exposures and adaptations.

In the coastal city of Quy Nhon, Vietnam, an analysis of sources of flood risk in peri-urban areas found that existing residents were placed at increased risk of catastrophic flooding due primarily to urban development patterns and livelihood threats, rather than climate and hydrological changes per se (DiGregorio and Huynh 2012). The lack of integration between construction of new transportation infrastructure, dikes, urban development zones with land fill to raise surface elevation and drainage in low-lying coastal floodplains combined with displacement due to urban land acquisition created a flood risk profile for community members that had increased in unexpected ways. While climate change was not yet a central factor in this case, increased likelihood of extreme climate events will contribute both to uncertainty and magnitude of adverse outcomes. This pattern of multiple exposure and unintended consequences creates dynamic and unanticipated risks for those community members who have limited choices.

The vast majority of the literature on interactions focuses only on the negative impacts of interacting stressors, neglecting to take into account the opportunities that can arise from macro- and mesoscale changes or the ways that responses (or adaptations) can amplify, dampen or mitigate single or multiple exposures. Our second example illustrates how drivers of change at various scales can interact to create both opportunities and constraints at the community scale. In the early 1990s in Mozambique, macroeconomic policy shifts (market liberalization) opened the economy to foreign investment for the first time, which led to the establishment of a French-owned, export-oriented shrimp farm on the central coast. The shrimp farm created local employment opportunities, benefitting several hundred people in a context where wage work is extremely limited. Yet, it also exposed shrimp farm employees to a new stressor (termination of their jobs due to shrimp disease outbreak) and it blocked access to previously communal land used by the greater community for making salt. As a result, people are moving into coastal fisheries, where climate changes are causing more frequent and severe storm events and increasing the risks fishers face at sea. Thus, macroscale drivers of changes created exposure to new stressors that created positive and negative impacts on community vulnerability (Blythe et al. 2015).

Assessing vulnerability and identifying adaptations: a pragmatic approach

In this section, we propose a pragmatic yet comprehensive approach for assessing coastal community vulnerability based on the framework and typology introduced in the previous sections. The intent of this approach is to shift the analytical focus from a particular hazard or exposure to the community itself, which will inevitably be dealing with multiple exposures. The aim is to provide practical guidance to researchers, practitioners, managers and policy makers for identifying key drivers of change, exposures and impacts and for developing contextually appropriate response strategies without being overly prescriptive. In brief, the following elements are essential for analyzing social-ecological vulnerability and identifying adaptive responses.

1. Identify important social and ecological components of the system of interest and establish criteria for evaluating each component;
2. Characterize the nature and severity of socioeconomic and biophysical drivers and resulting exposures and potential impacts;
3. Describe the autonomous interactions and feedbacks between drivers, exposures and impacts within and between social and ecological systems;
4. Analyze components of latent adaptive capacity and potential barriers to adaptation;
5. Identify potential adaptations that reduce sensitivity or exposure, improve adaptive capacity and enhance social-ecological outcomes to individual stressors;
6. Characterize interactions resulting from adaptations (i.e., amplifying, dampening, and mitigating) and analyze trade-offs among social and ecological outcomes of potential adaptations;
7. Identify adaptations that lead to win–win and most-benefit social-ecological outcomes;
8. Prioritize actions to reduce sensitivity, improve adaptive capacity and enhance social-ecological outcomes based on feasibility (adaptive capacity) and desirability (values) of outcomes;
9. Identify who is responsible for implementation and what resources will be provided; and
10. Implement, monitor and adapt.

These elements build on and extend rich literature in various fields. For example, there is extensive literature exploring characterization of social-ecological systems (Folke et al. 2003; Turner et al. 2003; Walker et al. 2004) and analysis of adaptive capacity (Marshall et al. 2010; Engle 2011; Bennett et al. 2014a). Climate change vulnerability and adaptation planning literature have emphasized important best practices—e.g., facilitating inclusive and place-based analyses, focusing on building adaptive capacity, strengthening institutions, integrating diverse knowledges, identifying no-regrets adaptations, prioritizing actions, clarifying resourcing and responsibility, understanding differential impacts, implementing cooperative and adaptive management (Smith et al. 2003; Leary et al. 2008; Burton 2009; Leary et al. 2009; Ensor and Berger 2009; Hall 2011; Bundy et al. 2015; Nalau et al. 2015). Yet, the majority of the previous literature has focused on single stressors and, in particular, climate change.

Lacking are simple methods for understanding vulnerability to multiple interacting exposures and clear and effective processes for identifying adaptations that take into account multiple exposures. Below we discuss methods for: (a) characterizing exposures and impacts, (b) interrogating the interactions between exposures and (c) identifying effective adaptations to multiple exposures that reduce sensitivity, increase adaptive capacity and enhance outcomes. Descriptions, uses and examples of applications of these methods are provided in Table 2.

Characterizing exposures and impacts

The majority of studies that have sought to characterize the nature and severity of exposures in a given locale have been externally driven efforts that focus on single hazards. We suggest that the typology presented here could provide a comprehensive frame of reference for future community-centered vulnerability assessments using qualitative, quantitative or mixed methods with a focus on local perspectives and experiences. For example, each category of driver or type of exposure in the framework could be explored through qualitative interviews, or results emerging from interviews could be compared with or coded against the framework. Interviewing could be used to examine local perceptions of the presence or absence of specific exposures that are occurring in each locale, the severity of exposures and the drivers of local exposures (Blythe et al. 2015). Different exposures could be ranked by importance or rated (e.g., on a Likert scale of 1–5) to determine the relative severity of the exposure or the sensitivity of communities, households or groups (Tschakert 2007; Bennett et al. 2014b). As Eakin and Leurs (2006) argue, it is essential to distinguish the most relevant and impactful drivers. In particular, it is crucial to identify extreme events—e.g., irregular or unpredictable exposures to which communities are highly sensitive—and "Achilles heel" vulnerabilities—i.e., those slow variables that significantly outweigh other stressors and that might undermine adaptations if sensitivity is not reduced through mitigative actions. Two examples of acute exposures are the 2004 tsunami in Southeast Asia or rapid hypoxic events that undermine localized conservation measures. Examples of chronic stressors include the steadily increasing impacts of ocean acidification for the shellfish industry or of sea level rise for communities that are situated in low-lying coastal areas. Quantitative analysis of exposures would also allow for scaling up research for broader-scale comparisons of exposures, sensitivities and differential impacts—for example, among communities and across regions or countries (e.g., Cinner et al. 2011). Our typology could be used as the basis of participatory focus groups or discussions on historical, present or future changes (e.g., Bennett et al. 2014c). Yet, future work in this area needs to move beyond just describing the drivers and exposures to understanding their impact, importance, causal mechanisms and interactions between exposures (Bunce et al. 2010b).

Exploring interactions

The dynamic interactions between multiple exposures have been examined using numerous participatory, qualitative and/or quantitative methods. Qualitative, ethnographic and visual methods will lead to rich narratives and historical accounts of local experiences of the interactions between stressors (Moerlein and Carothers 2012; Bennett and Dearden 2013). For participatory methods, previous studies have used mental models (Bunce et al. 2010a, b), the Driver-Pressure-State-Impact-Response (DPSIR) framework (Mangi et al. 2007; Suckall et al. 2014) and community-based scenario planning processes (Bennett et al. 2014c) to explore interactions between stressors. The following qualitative or semiquantitative methods also show some promise for exploring interactions—Bayesian networks, inference trees, expert judgments, influence diagrams, participatory mapping, historical timelines, trend lines, importance–incidence charts and causal dynamics (Bunce et al. 2000; Tomei et al. 2006; Chevalier and Buckles 2008; Gregory et al. 2012; Chevalier and Buckles 2013; Ban et al. 2014). Quantitative methods and multivariate statistical approaches—including factorial multiple ANOVA, ANCOVA, regression, canonical correlation, multi-way frequency, logistic regression, discriminate function, non-metric, cluster and principle component analyses—can also be useful for exploring the relationships between interacting exposures (see Menzie et al. 2007). Spatial approaches (O'Brien et al. 2004) are also useful but may be more applicable at broader scales.

Researchers are applying a miscellany of methods in diverse contexts to understand the interactions between multiple exposures—usually with a greater focus on either the social or the ecological components of the system. We suggest that a more systematic approach is required. Mixed methods approaches and triangulation of data from perceptual studies, biophysical studies, historical methods and policy studies will create a cohesive picture of how different trends, shocks and adaptations are interacting. Multi-sited, spatial and historical accounts should be incorporated to help to reconcile different scales and speeds of change and to tease out the impact of contextual factors (e.g., geography, ecology, demographics, economics) and specific events. Whichever methods are employed, there is a need to better understand and typify whether the interactions are mitigative (o), amplifying (+) or dampening (−) across different categories and indicators of social and ecological change and to demonstrate effect size—which will require meta-analyses drawing on the results of multiple local studies.

Identifying and prioritizing adaptations

The cataloging and ranking of exposures and their interactions may seem like an academic exercise. However, as Hall (2011) argues "…the relative importance of the various drivers and the pathways through which they might act must be weighed to help prioritize actions." This signals an important shift from research about change to research for change (Fazey et al. 2015). The identification and prioritization of effective adaptations, in the context of multiple interacting exposures, is a significant challenge requiring foresight and long-term thinking to avoid coping strategies or "manipulations" (Thomsen et al. 2012) that lead to maladaptations and increased sensitivity. Whenever possible, it behooves decision makers to identify first "no-regrets" adaptations that reduce sensitivity and lead to win–win outcomes. Addressing shortcomings in some facets of adaptive capacity may always be a "no-regrets" solution (Adger et al. 2003). Resilience scholars suggest that organizational and institutional learning, diversity of livelihoods and knowledge, access to assets and adaptive co-management processes decrease vulnerability (Folke et al. 2003; Cinner et al. 2009; Bennett et al. 2014a). Mills et al. (2011) propose that non-sectoral interventions, such as improved community sanitation, might have the greatest effect on reducing vulnerability for the most people. However, it will often be necessary to recognize and make trade-offs in order to identify "least-harm" adaptations that will lead to the most beneficial outcomes.

In a similar manner to how interactions are classified, the mitigative (o), amplifying (+) or dampening (−) effects of potential adaptations on social and ecological outcome criteria might be explored. There are numerous trade-off approaches, deliberative decision-making methods and participatory research methods that can facilitate choice of adaptation in the face of multiple exposures such

Table 2 Examples of methods for characterizing exposures and impacts, exploring interactions and identifying adaptations

Topic	Methods	Description	Examples and references
Characterizing Exposures and Impacts (Nature and Severity)	Qualitative interviews	Open-ended interviews with community members, knowledge holders or experts allows for rich and contextualized narratives and historical descriptions of perceived exposures, potential drivers and associated risks or impacts. Perceptions are understood as relational and subject to multiple meanings based on interpretations	Bunce et al. (2010b), Fabinyi (2010), Moerlein and Carothers (2012), MacDonald et al. (2013), Bennett et al. (2014b), McCubbin et al. (2015)
	Participatory methods	Workshops or focus groups with stakeholders, decision makers and/or experts can employ a variety of participatory methods to elicit lists, narratives, matrices, historical timelines or artistic expressions of the changes that are occurring and how these are impacting communities. Severity can be documented numerically, through participatory ranking or rating exercises, or qualitatively. Skilled facilitation is required to ensure all voices are heard	Kindon et al. (2007), Tschakert (2007), CARE 2009, Mills et al. (2011a), Chevalier and Buckles (2013)
	Quantitative rating or ranking	Household surveys in single or multiple sites can be used to quantitatively rate or rank the impact of stressors or exposures on different social, economic and ecological outcomes. Surveys allow for incorporation of larger samples and comparison among groups (livelihoods, genders, socioeconomic status, ethnicity), communities, regions or countries. All exposures need to be included	Bunce et al. (2010b), Mills et al. (2011a), Cinner et al. (2012b); Bennett et al. (2014b), Blythe et al. (2015)
	Spatial approaches	People's spatial knowledge of exposures and their impacts can be elicited using participatory methods—e.g., collaborative mapping, transect walks, hazard mapping, participatory geographic information systems—and spatial information management tools. Maps can also be useful tools for sharing and discussing interactions and potential adaptations	Ban et al. (2009), Raymond et al. (2009)
	Expert elicitation techniques	Opinions regarding exposures and their relative impacts can be elicited from experts, who are knowledgeable about social or ecological aspects of the system, through such methods as Bayesian methods, Delphi processes or nominal groups. This can be done individually or in a focus group setting	Richards et al. (2013), Ban et al. (2014)
	Arts-based methods	Various arts-based methods (e.g., participatory drawing, photovoice, participatory video, photohistory, documentary film making, digital storytelling) can provide in-depth empirical insights into exposures and impacts to community well-being and environmental health. These can serve as basis for conversations and deliberations around adaptations	Kunuk and Mauro (2010), Walker (2012), Bennett and Dearden (2013), Lemelin et al. (2013), Willox et al. (2013)
Exploring Interactions (Additive or Dampening)	Mental models	Mental models are people's cognitive frameworks of the world. They can provide insights into perceived relationships and feedbacks between different exposures. Data are collected through individual or group interviews and analyzed using content analysis, procedural mapping, task analysis, cognitive mapping and consensus analysis	Bunce et al. (2010b), Jones et al. (2011), Lynam et al. (2012)
	Drivers-Pressures-States-Impacts-Responses	The DPSIR framework provides a tool to organize information on drivers, exposures (*pressures*) and impacts (*states and impacts*) on social and ecological outcomes (*states*). The DPSIR framework can help to identify trade-offs between adaptation, mitigation and development *response* options and to avoid maladaptations. Does not help to understand bridges, barriers or steps to achieve actions	Tscherning et al. (2012); Suckall et al. (2014), Maccarrone et al. (2014), Breslow (2015)
	Participatory methods	Participatory methods, such as force field, causal dynamics, vulnerability matrix, influence diagrams, can be used to assess the perceived level of positive or negative impact of key factors (drivers and exposures) on social and/or ecological problems and to identify how these factors interact to produce net positive, negative or neutral outcomes	Chevalier and Buckles (2008), CARE (2009), Mills et al. (2011b), Gregory et al. (2012), Chevalier and Buckles (2013)
	Quantitative and multivariate analyses	Multiple case studies, meta-analyses or a systematic reviews would allow for quantitative comparisons and multivariate analyses (e.g., factorial multiple ANOVA, ANCOVA, regression, canonical correlation, multi-way frequency, logistic regression, discriminate function, non-metric, cluster and principle component analyses) to explore relationships between interacting exposures	Menzie et al. (2007)

Table 2 continued

Topic	Methods	Description	Examples and references
	Spatial approaches	See above description. Interactions between the different exposures might also be explored using spatial overlays and qualitative discussions of maps	(O'Brien et al. 2004)
Identifying and Prioritizing Responses (Amplifying, Mitigative and Adaptive)	Structured decision-making	Structured decision-making (SDM) is an approach that seeks to identify options, evaluate the outcomes of alternate courses of action, find "win–win" solutions, clarify trade-offs and provide a space for communicating views regarding options and trade-offs. It does not provide solutions but can inform deliberations on difficult decisions while making processes transparent and efficient. SDM employs rigorous decision-making methods, such as strategy tables, consequence tables, participatory cost–benefit analysis, to identify trade-offs and prioritize responses	(Espinosa-Romero et al. 2011; Gregory et al. 2012)
	Multi-criteria decision analysis	Stakeholder judgments are used to evaluate different alternatives or options using ranking or weighting algorithms. The results can be communicated to facilitate decision-making. Primary data (from document reviews, interviews or focus groups) are required to identify the range of options. MCDA is useful when decisions involve uncertainty but need to be made quickly	(Kiker et al. 2005; Scheuer et al. 2011; Porthin et al. 2013; Sahin et al. 2013; Munaretto et al. 2014)
	Cost–benefit and cost-effectiveness analysis	Cost–benefit and cost-effectiveness analysis provides tools for comparing net economic efficiencies of adaptation options across multiple climatic and other exposures. It is useful for examining public policies or actions when key effects can be easily monetized	(Leary 1999; Wegner and Pascual 2011; Kull et al. 2013; Mechler and Nabiul Islam 2013; Watkiss et al. 2014; Nay et al. 2014)
	Futures, planning and deliberation methods	Futures planning methods—e.g., scenario planning, visioning, backcasting, participatory integrated assessments, adaptation pathways approaches, transformation planning—can provide a forum for exploring possible and/or desirable futures given current and unknown trends or shocks and deliberating on response strategies. Analysis of drivers, exposures, impacts, responses and outcomes can be done using participatory, technological or combined approaches	(Swart et al. 2004; Evans et al. 2006; Salter et al. 2010; Sheppard et al. 2011; Cinner et al. 2011; Smith et al. 2013; Hamilton et al. 2013; Moore et al. 2014; Butler et al. 2014; Wise et al. 2014; Reid et al. 2014)
	Multiple case study comparisons, synthesis and historical methods	Methods that draw on multiple case studies and historical cases for syntheses or comparisons provide a tool for identifying similar cases and insights into past adaptations that have worked. These understandings can provide general lessons that can be applied to current contexts	(Bussey et al. 2012; Bundy et al. 2015; Fazey et al. 2015)

as: structured decision-making processes (Espinosa-Romero et al. 2011; Gregory et al. 2012), participatory and weighted multi-criteria analysis (Scheuer et al. 2011; Heck et al. 2011; Bhave et al. 2014), quantitative or qualitative cost–benefit analysis (van den Bergh 2004) or the (DPSIR) framework (Mangi et al. 2007; Suckall et al. 2014). Efforts to identify adaptations could also draw on future methodologies such as scenario planning, visioning or backcasting (Berkhout et al. 2002; Kloprogge and Sluijs 2006; Sheppard et al. 2011; Hamilton et al. 2013; Evans et al. 2013).

Whichever approach is used to select adaptation actions, a number of important decision criteria should be incorporated from earlier steps in the analysis including: key social and ecological system components to maintain system stability; normative criteria and values for social and ecological outcomes; nature and severity of drivers and exposures; contextual factors that influence sensitivity; potential impacts on social-ecological systems; interactions among stressors and resulting from adaptations; and the feasibility of and barriers to adaptations based on adaptive capacity and institutional context. Exploring these criteria may require using several different decision-making approaches in combination. Qualitative or quantitative analysis of trade-offs will not lead to decisions but can contribute to evidence-based deliberative decision-making processes that incorporate various perspectives and values. Further work is needed that compares the processes, outputs and outcomes of the different decision-making tools and trade-off approaches, particularly in the context of adaptation planning. A review and comparison of the strengths, weaknesses, insights and implications of different approaches for assessing adaptive capacity is also warranted.

Concluding thoughts

In this paper, we provided a framework and typology of drivers and exposures to analyze community social-ecological vulnerability and suggested processes and methods for better understanding how multiple interacting exposures act on coastal communities. We hope that this article will provide stimulus for future empirical work on vulnerability and adaptation to multiple interacting exposures, including facilitating further exploration of interactions, broader-scale analyses and comparisons between sites. However, we want to emphasize that this is not just an academic exercise. Change is a ubiquitous force that has very real impacts for communities and the ecosystems on which they rely. Management interventions tend to be driven by the policy du jour—whether it is biodiversity conservation, marine protected areas, climate change adaptation or disaster management—resulting in a narrow analytical focus that ignores or downplays the complications of multiple interacting exposures. This can result in the identification and implementation of well-intended policy and expensive programmatic responses that do not adequately address the issues or, worse yet, that further exacerbate sustainability challenges for local communities. We contend that our framework, typology and pragmatic approach will improve understanding of the types of socioeconomic and biophysical changes occurring and how these are interacting and impacting communities in order to identify more effective leverage points (whether via local actions or broader policies and programs) within the system for decreasing the vulnerability of communities to change.

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