



Synthesis

## Human Dimensions of Coral Reef Social-Ecological Systems

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**ABSTRACT.** Coral reefs are among the most diverse ecosystems on the planet but are declining because of human activities. Despite general recognition of the human role in the plight of coral reefs, the vast majority of research focuses on the ecological rather than the human dimensions of reef ecosystems, limiting our understanding of social relationships with these environments as well as potential solutions for reef recovery. General frameworks for social-ecological systems (SESs) have been advanced, but system-specific approaches are needed to develop a more nuanced view of human-environmental interactions for specific contexts and resource systems, and at specific scales. We synthesize existing concepts related to SESs and present a human dimensions framework that explores the linkages between social system structural traits, human activities, ecosystem services, and human well-being in coral reef SESs. Key features of the framework include social-ecological reciprocity, proximate and underlying dimensions, and the directionality of key relationships and feedback loops. Such frameworks are needed if human dimensions research is to be more fully integrated into studies of ecosystem change and the sustainability of linked SESs.

**Key Words:** coral reefs; human dimensions; reciprocity; social science; social-ecological systems; sustainability science

### INTRODUCTION

Coral reefs are among the richest and most diverse ecosystem types found in the global ocean, but are also among the most threatened (Hoegh-Guldberg 1999, Hughes et al. 2003, Pandolfi et al. 2003). Found worldwide in the tropical oceans, coral reefs are complex, highly diverse, and have evolved to occupy a narrow range of oceanographic conditions and natural disturbance regimes, making them vulnerable to perturbations that may exceed their adaptive capacity (Nyström et al. 2000, Nyström and Folke 2001, Hughes et al. 2003). Human societies in tropical regions worldwide depend heavily on the critical ecosystem goods and services provided by these environments, and the degradation of resource pools places these populations at considerable risk (Moberg and Folke 1999, Whittingham et al. 2003, Bell et al. 2009).

Coral reefs and their associated human systems are complex, peopled seascapes that are sometimes characterized as social-ecological systems (SESs) or human-dominated anthroposystems (Shackeroff et al. 2009, Cinner and David 2011). Global patterns of decline in coral reef SESs have been documented (Jackson et al. 2001, Pandolfi et al. 2003), but evidence of recovery and sustainable SES interactions are also emerging (Cinner et al. 2009b, Kittinger et al. 2011, Lotze et al. 2011). The differences in trajectories of SESs highlight the need to understand the human dimensions associated with sustainability or decline. Here, we define human dimensions as the ways in which individuals, communities, and societies interact with, affect, and are affected by natural ecosystems and environmental change through time. This characterization recognizes three key elements, including: reciprocity in relationships between societies and ecosystems; the scale of the systems being considered (both social and biophysical),

and; the role of dynamism, feedbacks, and complex interactions as critical in determining the past and future trajectories of social-ecological relationships.

The need to understand more fully the complexity of human relationships with oceans, including their cultural, social, and economic dimensions (Samonte et al. 2010), however, is complicated by the lack of comprehensive frameworks or approaches. Comprehensive approaches to understanding SESs are being increasingly recognized as a problem requiring interdisciplinary collaboration among social, biophysical, and institutional research domains. To support this integration, there is a need to develop conceptual frameworks that link different research fields and their knowledge systems, methodologies, and approaches (Turner et al. 2003, Ostrom 2009). Generalizable frameworks have been advanced for characterizing social-ecological relationships (Turner et al. 2003, Redman et al. 2004, Millennium Ecosystem Assessment 2005, Ostrom 2007, 2009), but system-specific approaches can yield more nuanced understanding about linked SES sustainability for specific contexts and resource systems, and at specific scales.

In coral reefs and related tropical marine environments, there has been significant work in developing variables and associated indicators for socioeconomic monitoring programs (e.g., Bunce et al. 2000, McField and Kramer 2007, Wongbusarakum and Pomeroy 2008) as well as comprehensive assessments of social conditions (e.g., Crossett et al. 2008, Loper et al. 2008). Although existing social indicator and assessment protocols can guide the collection and analysis of social data, there still exists no substantive approach or framework for linking social information to ecological conditions or outcomes.

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Transforming social-ecological relationships into more sustainable pathways requires going beyond social assessments and toward an operational approach to linking social and ecological data sets to better understand SES dynamics (Chapin et al. 2010, Westley et al. 2011). Direct linkages between social factors (e.g., human activities and their underlying drivers) and ecosystem conditions have been identified in some studies of coral reefs, but most studies focus on either a single factor (e.g., population, economic markets) or a small subset of factors, rather than a broad array of inter-related human dimensions that are necessary to characterize SESs. From a more applied perspective, operational approaches to understanding relationships and connections between human activities and their underlying (or distal) causes and ecosystem conditions can help inform more effective strategies to transform SESs to trajectories of sustainability.

Here, we propose a conceptual framework that characterizes the broad range of human dimensions of coral reef ecosystems and explores the integration of these social dimensions into analysis of linked SESs at the community scale. Whereas significant research has been invested in understanding the biophysical dynamics of coral reefs, relatively few studies have attempted to assess holistically the human dimensions of reefs and their complex relationships to ecosystem structure and function. This is due in part to the disciplinary backgrounds from which coral reef researchers primarily draw, but is also attributed to the lack of frameworks that adequately define the social variables and dimensions relevant to these tropical marine ecosystems. This has led to an incomplete understanding of how social change and the structure of social systems mediates ecological outcomes. From an applied perspective, this knowledge is critical in formulating the basis for effective conservation and transitioning to effective ecosystem stewardship (Chapin et al. 2009, Olsson et al. 2010).

### **DEVELOPING THE FRAMEWORK**

Systematic approaches to characterizing the social dimensions of ecosystems require conceptual frameworks that help define the structure and dynamics of SESs. Conceptual frameworks can help establish a general, nested set of variables and their potential relationships, which can provide an operational approach for integrating social and ecological data in analysis of SESs (Heemskerk et al. 2003, Ostrom 2007). At the macro level, this involves developing a conceptual map or model of the basic system components and their linkages. From this conceptualization, lower-tier attributes can be identified, and more complex linkages and relationships teased apart. This type of nested, hierarchical design provides advantages in allowing researchers to determine which hierarchical level of detail is necessary for gathering data to test specific research questions and, because it allows empirical investigations to feed information back, to further refine the conceptual model

and its structural attributes (Ostrom 2007, 2009). Further, many existing frameworks are highly generalizable to a broad array of resource systems, but system-specific frameworks and approaches can provide a more nuanced view of SES interactions for specific contexts and resource systems and for specific scales (Brock and Carpenter 2007). The framework presented herein synthesizes concepts from a set of related literature to develop a conceptual model for characterizing the human dimensions relevant to coral reef SESs at the community-level scale.

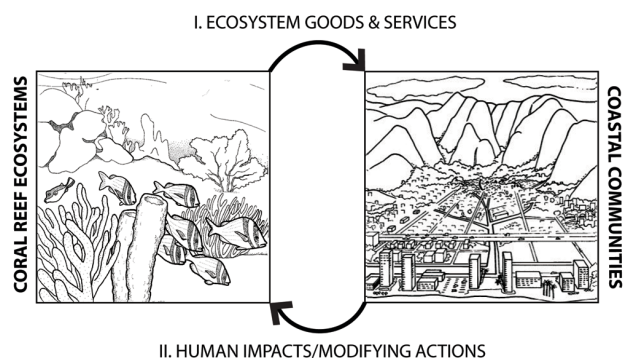
We engaged in two primary tasks to develop a human dimensions framework for integration in SES analysis for coral reefs. We note at the outset that, although our focus is primarily on coral reefs, this framework may also be applicable to other closely related tropical marine systems (e.g., tropical estuaries, mangroves, and seagrass beds), which are often functionally linked to or considered part of coral reef ecosystems, as well as potentially to other marine SESs. First, we conducted a comprehensive review and synthesis of human dimensions monitoring, assessment, and research literature. Our review focused primarily on coral reefs and closely associated tropical marine environments, but relevant literature and case studies from marine, coastal, and terrestrial systems were also included. Based on this review, we developed a preliminary framework and held an expert workshop to solicit review and revisions to this preliminary framework. Workshop participants included 20 experts comprising 13 trained social scientists from academia, research institutions, or consultancies; four natural resource managers with expertise and experience in coral reefs; and three researchers with expertise in biophysical aspects of coral reefs. The one-day workshop consisted of a facilitated discussion among these experts to revise and improve the preliminary framework. Together, these activities led to a framework for integrating human dimensions more substantively within coral reef SES analyses. We present the framework first in terms of a basic conceptual model that defines system attributes and their relationships. Subsequently, we explore in more detail lower-tier attributes, their complex interrelationships, and the feedback mechanisms that exist between framework components.

### **RECIPROCITY IN SOCIAL-ECOLOGICAL LINKAGES**

Relationships between people and oceans are complex and multidimensional (Shackeroff et al. 2009, Samonte et al. 2010), but these social-ecological relationships can be characterized at the macro level as comprising two primary reciprocal interactions. These interactions include: anthropogenic impacts and modifying actions; and ecosystem goods and services provided to individuals, communities, and coastal societies (Fig. 1). These linkages between ocean ecosystems and human systems act in tandem: Anthropogenic actions alter the structure and function of ecosystems, just as resource pools

and ecosystem services can help define the structure and function of coastal societies. Together these interactions compose social-ecological reciprocity (Fig. 1).

**Fig. 1.** A conceptual model illustrating the reciprocal nature of social-ecological relationships between coral reef ecosystems and coastal communities. Coastal communities derive ecosystem services and benefits from coral reefs (I), but also alter these ecosystems through anthropogenic impacts and modifying actions (II).



Reciprocal social-ecological interactions together influence the range and complexity of human behaviors in coastal marine ecosystems and the trajectory of these linked systems in terms of their sustainability. The nature of reciprocal interactions in SESs are often rooted in historical context, coastal heritage, and place-based socio-cultural traditions (Kirch 2007, Liu et al. 2007, Kittinger et al. 2011, Shackeroff et al. 2011). Understanding how these linkages have evolved and the factors that have influenced changes in social-ecological reciprocity can provide an important context for current efforts to manage systems toward more sustainable pathways.

To date there has been far more focus among coral reef researchers on the historical development, intensification, and ecosystem responses to anthropogenic drivers of coral reef ecosystem decline (McClanahan 2011), and far less focus on the ecosystem goods and services that human societies gain from reefs. This has contributed to a dominant narrative of people as problems for reefs, and ignores evidence that human societies have also modified ecosystems in a positive way to sustain key processes that maintain the flow of desirable goods and services or to generate specific conditions beneficial to human use (e.g., Fairhead and Leach 1995, Rocheleau et al. 2001, Shackeroff et al. 2009). A disproportionate focus on human impacts instead of benefits associated with reefs can also limit the portfolio of prescriptions available for management interventions and conservation strategies. An equivalent and more balanced focus on both of these reciprocal interactions is needed to understand how best to promote

sustainable human behaviors and successfully manage linked SESs. This can be achieved in part through increased recognition of social-ecological reciprocity and the structuring influences of these relationships between society and ocean ecosystems.

### PROXIMATE AND UNDERLYING DIMENSIONS

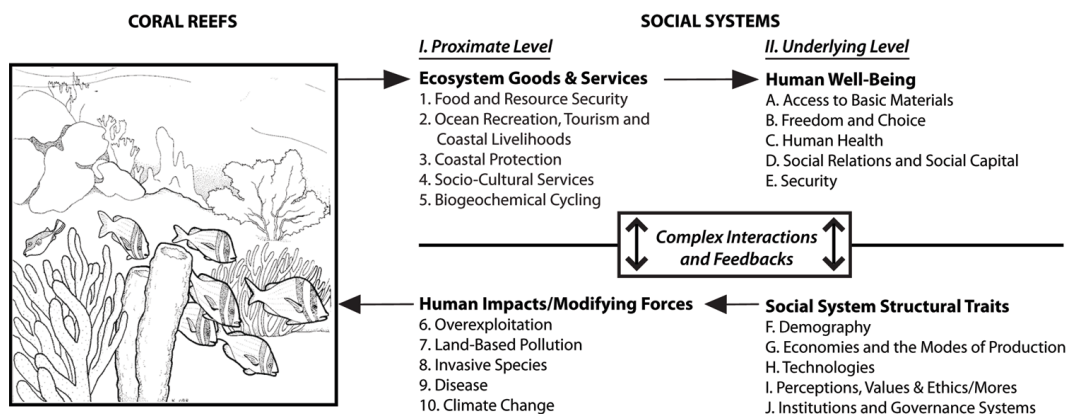
Social systems, like ecosystems, can exhibit hierarchical patterns of organization, which bear on social relationships to biophysical systems. Social relationships with ecosystems can be characterized in a generalizable form by differentiating between proximate and underlying levels of SES relationships (Fig. 2). At the proximate level, social systems interact directly with resources and biophysical systems in a reciprocal nature. These proximate, or direct, relationships comprise the ecosystem services and benefits that coastal societies accrue as well as the impacts and modifying actions that alter ecosystems (Fig. 2: 1–10). These direct relationships also exhibit underlying dimensions that serve to explain the indirect relationships between ecosystems and fundamental social system structuring traits and human well-being (Fig. 2: A–J). These underlying dimensions are also sometimes referred to as distal or ultimate drivers.

The differentiation between proximate and underlying dimensions of environmental change has been applied primarily to studies of terrestrial systems, including studies of agrosystems and land-use change (Turner et al. 1990, Stern et al. 1992, Gibson et al. 2000, Lambin et al. 2001, Geist and Lambin 2002). However, it has not been widely adopted for analysis of SESs in marine systems (Birkeland 2004). We next describe the proximate and underlying human dimensions of this SES framework, including the directionality of relationships posited in this conceptual model. Subsequently, we discuss the complex feedbacks, relationships, and interactions that characterize these direct and indirect interactions.

### ECOSYSTEM SERVICES AND SOCIAL WELL-BEING IN COASTAL SOCIETIES

Coral reefs and associated tropical marine ecosystems support millions of people whose lives depend on coral reef resources for a source of food and income. Economic estimates of the value of goods, services, and livelihoods associated with coral reefs exceed USD\$30 billion (Cesar et al. 2003). Coastal fisheries in the tropics feed millions of people, many of whom live in developing countries and depend on living aquatic resources as their primary source of protein (Moberg and Folke 1999, Whittingham et al. 2003). Reefs also provide protection from storms and other disturbances (Hoegh-Guldberg et al. 2007, Koch et al. 2009). Ecosystem services associated with coral reefs extend beyond food production, however, and encompass a broad array of goods and services that benefit coastal societies and define coastal cultures. Many coastal communities in the tropics, for example, exhibit livelihood

**Fig. 2.** A heuristic framework describing the human dimensions of coral reef ecosystems, their proximate and underlying hierarchical structure, and the directionality of primary linkages. Coral reefs provide ecosystem services and benefits to coastal communities (1–5), which in turn mediate dimensions of human well-being (A–E). Social system structural traits (F–D) modulate human interactions with coral reef ecosystems and their associated impacts and modifying actions (6–10). A complex and poorly understood portfolio of interactions and feedbacks characterize the social-ecological interactions between ecosystem services, human stressors of reefs, community well-being, and underlying social system structural traits.



strategies that are tied closely to coral reefs (Whittingham et al. 2003, Hicks 2011, Cinner et al. 2012). Additionally, the traditions, values, and identities of coastal peoples are defined by socio-cultural practices that perpetuate connections to coastal environments and resources (Johannes 1981, Kikiloi 2010).

The general categories of ecosystem services for marine systems include supporting, provisioning, regulating, and cultural services that are common in valuation studies and related literature (e.g., Costanza et al. 1997, Daily 1997, de Groot et al. 2002, Millennium Ecosystem Assessment 2005, Beaumont et al. 2007). This ecologically focused typology, however, does not differentiate between direct and indirect benefits or the scale at which services accrue to coastal societies, making it difficult to determine which specific goods, services, and benefits accrue to which people (Wallace 2007, Daw et al. 2011, Tallis et al. 2012). To address this within the context of coral reef systems, we developed a human-centered categorization for ecosystem services that gives primary focus to the direct goods and services that coastal communities use or benefit from directly, rather than the ecosystem functions that indirectly benefit societies or accrue to global scales (Table 1). From an applied perspective, this human-centered typology can guide field research efforts to gather empirical information on coral reef ecosystem goods and services and may potentially make it easier to link ecosystem services to human well-being at the community level.

Ecosystem goods and services from coral reefs and associated tropical marine ecosystems support the health and well-being

of coastal societies worldwide. Human well-being, as defined in the Millennium Ecosystem Assessment (2005), has five inter-related dimensions: access to basic materials, freedom and choice, human health, social relations and social capital, and security. The Millennium Ecosystem Assessment (MEA) framework also articulates the complex ways that ecosystem services support human well-being. In the MEA, these linkages are described in terms of their intensity (weak, medium, strong) and the potential for mediation by socioeconomic factors (Millennium Ecosystem Assessment 2005:15, Fig. 1.3). While potentially illustrative for assessing global-scale relationships between ecosystems and human well-being, these linkages need to be articulated in greater detail to understand social-ecological dynamics at lower-level scales (e.g., for coastal communities) and for specific contexts and resource systems.

This framework recognizes the importance of ecosystem services as directly and indirectly supporting human well-being, without explicitly describing these linkages, which are likely to vary across scales and cases due to a variety of contextual factors (Daw et al. 2011). Contextual factors include access and property rights regimes, knowledge and power dynamics, resource and ecosystem conditions, livelihood strategies and diversification, and other socioeconomic factors that might be either endogenous or exogenous to a given system (e.g., a community; Adger et al. 2006, Young 2006, Cinner et al. 2007, 2009a,b, Basurto and Coleman 2010, Wamukota et al. 2012). Thus, there is a need to explore more fully the complexity of factors that mediate the linkages between ecosystem services and human well-



**Table 1.** Human-centered typology of ecosystem goods and services from coral reefs and associated tropical marine ecosystems.

Ecosystem service or benefit	Description	Supporting references†
Food and resource security	Physical, social, and economic access to food sources and other resources from tropical marine ecosystems	1–3
Ocean recreation, tourism, and coastal livelihoods	Employment and income from fisheries, tourism, and recreational industry-based livelihoods; recreational use	1–4
Coastal protection	Flooding protection and wave attenuation from storms, extreme tides, tsunamis, and other disturbances	1–2
Socio-cultural services	Aesthetic, cultural, religious, and spiritual values, services, practices, and traditions	1–4
Biogeochemical cycling	Transformation, detoxification, and sequestration of wastes; cycling of key life-sustaining nutrients, elements, and compounds	1–4

†(1) Moberg and Folke (1999); (2) Beaumont et al. (2007); (3) Holmlund and Hammer (1999); (4) Peterson and Lubchenco (1997).

being in a variety of case studies from different socioeconomic contexts. Understanding how these linkages vary at different scales (local, regional, global) and developing a stronger base of case studies will allow for the derivation of empirically supported higher-order linkages such as those posited in the MEA. For marine systems, this is particularly germane given the increased interest in human well-being as an integrative concept for understanding and assessing the social dimensions of marine environmental change (Pollnac et al. 2006, Coulthard et al. 2011, Daw et al. 2011).

#### **SOCIAL SYSTEM STRUCTURAL TRAITS AND HUMAN IMPACTS AND MODIFYING FORCES**

Human modifications to coral reef ecosystems have been described in great detail in a variety of contexts. Impacts and modifying actions are specific to the context of a given system, but many human activities and their effects on coral reefs are common worldwide. These include: exploitation and resource use; land use and related land-sea interactions such as pollution and sedimentation; species introductions and invasions; recreational use; and climate change (e.g., thermal stress, ocean acidification; Fig. 2). Each of these activities is the focus of intensive research efforts, and indicators for determining their level of intensity and impacts to coral reef ecosystems have been identified in a number of publications and initiatives (e.g., Burke et al. 2001, 2011, Waddell et al. 2005, Wilkinson 2008; U.S. Coral Reef Task Force, local action strategies: <http://coralreef.gov/las/welcome.html>).

Anthropogenic activities vary in terms of their impacts on the structure and function of coral reef ecosystems. For example, reef fish populations are affected differently by fishing exploitation than by coral bleaching from thermal stress. In heavily exploited coral reefs, large herbivorous fishes

typically become less abundant; the loss of herbivory can make reefs more vulnerable to undesirable regimes shifts from coral-dominated to algal-dominated states (Hughes et al. 2003, 2007). In contrast, coral bleaching can result in a loss of structural complexity, which reduces critical juvenile habitat and can result in lower recruitment to bigger size classes (Graham et al. 2007). The effects of human activities will also vary based on the fine-scale spatial attributes of a given system and the broader-scale spatial mosaic of coral reef and associated habitats. Fringing reefs, for example, may be less resilient to specific human activities than barrier reef systems with extensive lagoon systems. Coral reef systems that exhibit a diversity of habitats with strong connectivity between habitat patches may also be more resilient than isolated or poorly connected systems characterized by less dynamic capacity for recovery from disturbance (Nyström and Folke 2001, Bengtsson et al. 2003, Bodin and Saura 2010).

In our framework, the impacts and modifying actions that coastal societies impart on marine ecosystems are mediated by underlying dimensions, which we characterize as fundamental social system structural traits. These structural traits of social systems include: demography; economic systems and modes of production; technological factors; perceptions, values, and ethics or mores; and institutions and governance systems (Fig. 2). These structural characteristics of social systems determine the basic modes of interaction with ecosystems and resources and play a structural role in determining proximate-level interactions (Stern et al. 1992, Redman 1999, Geist and Lambin 2002, Berkes et al. 2003, Ostrom 2009). Indicators for these structural traits are commonly used to characterize social conditions or to assess social change, which we define here as an alteration in these

inter-related social structural traits and resultant changes in social relations and human behaviors related to ecosystems and resources.

For coral reefs, considerably less attention has focused on how these fundamental social system structural traits indirectly shape social-ecological interactions in coral reefs (Kittinger et al. 2011). Exploitation pressure, for example, can be driven by changes in demography (e.g., increase or decrease in the number or age structure of fishers), technology (e.g., introduction of new gear or technology that changes the catch per unit effort or dynamics of the fishery), economic factors (e.g., establishment of new markets for coral reef products), or institutional factors (e.g., deterioration of local-level rules and practices). There is thus an increasing need to move beyond flawed, simplistic cause-consequence relationships between environmental conditions and social parameters, which are increasingly found to be inadequate to explain the complexity of SESs (Lambin et al. 2001). Neo-Malthusian assumptions about the link between population growth or size and environmental decline, for example, can obfuscate the importance of understanding other direct and indirect drivers of resource use patterns and the institutions that organize human behavior and consumption (Aswani 2002, Curran et al. 2002, Steneck 2009).

Further, the prevailing view in extant literature primarily characterizes humans and their activities as stressors of coral reefs (e.g., Knowlton 2001, Sandin et al. 2008). This normative view of humans primarily as stressors ignores socio-cultural traditions of resource stewardship, cultivation activities, and ecosystem engineering efforts designed to ensure the flow of beneficial goods and services to coastal communities and cultures. As integral components of coral reef ecosystems, humans and their activities can be better described as impacts or modifying forces (Fig. 1), which encompass a portfolio of actions that alter coral reef structure and function, but are inherently non-normative in their classification. A non-normative typology for human use moves away from classifying humans and their activities primarily as problems for coral reefs and instead puts the focus on understanding what patterns, behaviors, use intensities, and their determinants constitute sustainable interactions with coral reef ecosystems and resources.

This aspect of the framework may aid researchers in assessing the full portfolio of indirect drivers, which need to be unraveled and understood in more detail to develop more successful management strategies for coral reefs (Birkeland 2004, Brewer et al. 2012). As with the relationships between ecosystem services and human well-being, the complex interaction of these fundamental traits of social systems and their effects on anthropogenic activities and use patterns are likely to vary based on place-specific contextual factors. Common property institutions, for example, are often

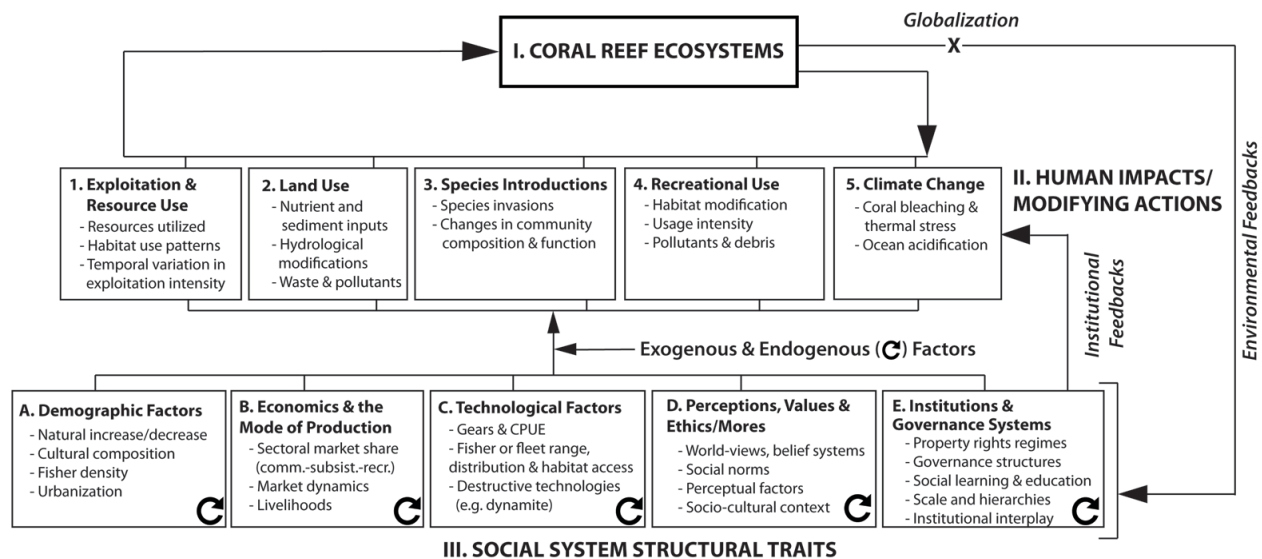
historically situated and unique to place, and the interaction between these rights regimes and the social changes that are associated with a given locale can produce variable outcomes in both resource condition and the robustness of social institutions to withstand demographic, economic, and political changes (Aswani 2002, Cinner et al. 2007). For example, Aswani (2002) examined several adjacent communities that occupy similar environments, experience similar demographic processes, and depend on similar marine products for the generation of household income. Despite these similarities, the customary sea tenure regimes for reef resources in these villages exhibit variable outcomes in terms of both environmental outcomes and their robustness to demographic, economic, and political change, which was attributed to historical changes in settlement, kinship patterns, and cultural attitudes. This example and others (e.g., Basurto 2008, Cinner et al. 2009b) demonstrate the advantages of comparative approaches in understanding the social dimensions associated with sustainability.

#### **COMPLEX FEEDBACKS AND SOCIAL-ECOLOGICAL INTERACTIONS**

SESs are characterized by complexity, multiscale relationships, feedback loops, reciprocal and dynamic interactions, and historical legacies (Berkes et al. 1998, Lambin et al. 2003, Adger et al. 2006, Walker et al. 2006, Liu et al. 2007). Generally, the portfolio of complex interactions and feedback loops among human system components and between social and ecological system components are not well understood (Fig. 2), but it is generally agreed upon that these interactions are critical to understanding the trajectory and sustainability of SESs. Feedback loops, for example, are believed to play important roles in SESs in determining system stability and resilience (Olsson et al. 2004, 2006, Cumming et al. 2006, Cinner et al. 2011). Feedback loops have been described in many ways, but are defined here as causal pathways that describe the initial generation of a feedback signal to the subsequent modification of an event, pathway, or outcome. The fundamental characteristic of a feedback process or loop is thus the generation of a response from an initial signal; these two-way interactions can take the form of either reinforcing (positive) or dampening (negative) effects on the trajectory of a system (Chapin et al. 2009, Cinner et al. 2011).

For coral reef SESs, feedbacks between social and ecological systems (as opposed to those solely within social systems, for example) can be characterized as encompassing two primary types: (1) environmental feedbacks, which include information, responses, or stimuli from ecosystems to social system structural traits (primarily to social perceptions, values, ethics or mores, and to human institutions and governance systems) in response to human activities or actions; and, (2) institutional feedbacks, which include actions, responses, or policies from human institutions and governance systems,

**Fig. 3.** A conceptual model showing how human impacts and modifying actions (1–5) and underlying social system structural traits (A–E) mediate ecosystem conditions in coral reefs. Social system structural traits and their attributes (III) are fundamental to the duration, timing, and intensity of proximate human impacts and modifying actions (II) on coral reef ecosystem structure and function (I). Exogenous and endogenous factors influence the internal dynamics of underlying social systems (A–E) and the relationship between underlying and proximate factors. The globalization of socioeconomic systems can decouple environmental feedbacks that provide a structuring influence on human relationships with coral reefs. Management interventions that are primarily developed through governance systems, but which are affected by a suite of social system structural attributes, can also modify the portfolio of human interactions with reef systems.



taken in response to social or environmental stimuli, which may alter the ways in which people interact with reef environments (Fig. 3).

Empirical data on institutional feedback loops are limited, but some existing studies have characterized these linkages in research on coral reef SESs. Cinner and colleagues, for example, have characterized how the absence of strong institutions and a confluence of social and ecological factors can result in poverty traps and negative feedback loops that can make escaping this destructive cycle difficult (Cinner et al. 2009a, Cinner 2011). Cinner et al. (2011) have also described socioeconomic factors associated with amplifying (such as fishing harder) versus dampening (such as reducing effort) strategies among fishers in response to hypothetical changes in average catch. Birkeland (2004) has used the concept of ratchets to describe how changes in social system structural traits can create amplifying effects that further intensify reef degradation. For example, the adoption of new technologies such as SCUBA, night lights, and GPS can rapidly diminish the presence of natural refugia and create amplifying effects that reinforce destructive methods of

resource harvest (Birkeland 2004). The introduction of new technologies may result in threshold effects by rapidly changing modes of human interactions with coral reefs, and attendant impacts on resource conditions.

Research on environmental feedbacks suggests these may become eroded or diffuse if the spatial domain of management efforts does not match the spatial scale at which resource users operate or the scale of resource recruitment or distribution (Wilson 2006, Steneck and Wilson 2010). Socioeconomic globalization can also weaken or sever feedbacks to human institutions (Belsky 2004, Young et al. 2006) by removing environmental stimuli that may have served as dampening feedbacks (Fig. 3). For example, in historic times, Pacific island cultures were highly reliant on reef-derived protein sources, and the development of socio-cultural institutions for reef resource management may have been driven in part by awareness of the limits of resource availability under exploitation pressure (Johannes 2002, Cinner and Aswani 2007, Kittinger et al. 2011). As these island societies became integrated into globalized economies and markets, however, dependence on reef resources became less prominent,

**Table 2.** Summary of human dimensions variables and indicators for coral reefs and associated tropical marine ecosystems in key literature and reports. Indicators and variables in supporting references include quantitative and qualitative metrics for gathering empirical data for proximate (1–10) and underlying (A–J) human dimensions data.

Proximate level	Supporting references†	Underlying level	Supporting references†
<b>Ecosystem services and benefits</b>		<b>Human well-being</b>	
1. Food and resource security	see Table 1	A. Access to basic materials	1, 2
2. Ocean recreation, tourism, and coastal livelihoods	see Table 1	B. Freedom and choice	1, 2
3. Coastal protection	see Table 1	C. Human health	1, 2, 10, 11
4. Socio-cultural services	see Table 1	D. Social relations and social capital	1, 2
5. Biogeochemical cycling	see Table 1	E. Security	1, 2
<b>Human impacts and modifying actions</b>		<b>Social system structural traits</b>	
6. Exploitation	6–8, 10	F. Demography	3–5, 7, 9–10
7. Land-based pollution	6, 7, 10	G. Economies and modes of production	4, 5, 8–12
8. Invasive species	6, 7	H. Technologies	4, 5
9. Recreational impacts	6, 7, 9, 10	I. Perceptions, values, ethics, or mores	4, 5, 9, 11
10. Climate change	6, 7, 10	J. Institutions and governance systems	4, 5, 10, 11, 13, 14

† (1) Millennium Ecosystem Assessment and World Resources Institute (2005); (2) World Resources Institute (2007); (3) Crosssett et al. (2008); (4) Bunce et al. (2000); (5) Wongbusarakum and Pomeroy (2008); (6) Burke et al. (2011); (7) Burke et al. (2001); (8) Garcia and Staples (2000); (9) Loper et al. (2008); (10) McField and Kramer (2007); (11) Pomeroy et al. (2004); (12) Allison and Ellis (2001); (13) Ostrom (1990); (14) Ostrom (2005).

particularly as cheaper, and often unhealthier, alternatives became available (Turner et al. 2007). Thus, the environmental feedback of resource limitation, and the reciprocal institutional response, may become decoupled because of the availability of alternative products or goods through globalized market systems, shifts in livelihoods, and the erosion of socio-cultural institutions (Fig. 3).

Globalized markets for marine resources can have major impacts on locally managed resource pools and can result in heightened uncertainty and higher probability of surprise events (e.g., sudden resource collapse; Berkes et al. 2006, Young et al. 2006). For reefs, globalized markets for live reef food fish, aquarium species and live coral rock, edible holothurians, *Trochus* spp., and other coral reef products can produce intensive, widespread exploitation pressure (Jaquemet and Conand 1999, Bruckner 2001, McGilvray and Chan 2003, Clarke 2004, Berkes et al. 2006). The emergence of export markets and the economic modernization and integration of coastal communities can also challenge the viability and resilience of traditional resource management institutions, with variable outcomes observed (Gelcich et al. 2006, Cinner et al. 2007). The above described examples and others in the literature continue to highlight the importance of feedback loops and their role in determining the trajectory, stability, and resilience of SESs, but clearly, more conceptual and empirical research needs to be done on these aspects of complex systems.

#### SCALE, CONTEXT, AND EXOGENOUS VS. ENDOGENOUS DRIVERS

The drivers of linked SES change operate at different hierarchical levels (proximate vs. underlying) and at different scales (local, regional, national, global). As discussed previously, the specific linkages between proximate and underlying levels of human systems and their relationships to biophysical systems are specific to both scale and context (Fig. 2). Whereas issues of scale have been more explicitly and consistently addressed in the natural sciences, scaling issues are less prominent and more disparate in social science research (Gibson et al. 2000, Silver 2008). The different scaling issues that confront interactions between social and ecological systems require a common understanding to characterize adequately cross-scale interactions, feedback loops, and reciprocal linkages in SESs (Gibson et al. 2000, Cumming et al. 2006, Silver 2008).

Scaling issues can be partially resolved by properly bounding SESs (Carpenter et al. 2001). The conceptual framework presented herein focuses at the community scale. Bounding a community-level SES requires defining the relevant social and ecological attributes and characteristics that can be used to define the limits of a given SES. These need not be arbitrary, but instead can be based on contextual factors specific to a given setting. For example, in tropical Pacific islands, customary resource management systems often encompass a well-defined social unit and associated resource system, which



together form a bounded SES (Kaneshiro et al. 2005). Similar systems exist elsewhere in indigenous societies in tropical settings and demonstrate the feasibility of using traditional or established boundaries or other relevant contextual factors to bound SESs properly (e.g., see list of contextual factors in Wamukota et al. 2012).

Once an SES has been bounded, researchers can empirically determine which linkages and feedbacks are endogenous or exogenous to a given SES. For example, at the community scale, coral reef conditions can be determined by local activities that may be endogenous to a given SES (e.g., fishing, land-based pollution). The same reefs, however, may also be affected by regional or global processes (e.g., episodic ENSO events, climate change) that are exogenous to a local SES. For example, the introduction of a new export market for coral reef species has been shown to shift radically exploitation patterns and the customary institutions for coral reef fisheries management (Cinner et al. 2007). Similarly, the adoption of new technologies such as SCUBA, night lights, and GPS can rapidly diminish the presence of natural refugia and amplify destructive methods of resource harvest (Birkeland 2004). Bounding an SES not only can allow researchers to understand which drivers operate within or outside of a given SES, but may also have implications for the scale of management necessary to address the direct and indirect drivers of change. Understanding the interactions and feedbacks that transcend scales (cross-scale interactions) and the factors associated with threshold effects that drive regime shifts to undesirable states remain critical, yet understudied, aspects of SESs (McClanahan et al. 2011).

#### **OPERATIONALIZING THE FRAMEWORK USING EXTANT INDICATORS**

Understanding to what extent and at what scales ecological systems mediate specific components of social system conditions (e.g., aspects of human well-being) remains a central challenge. Human well-being can be affected by multiple overlapping factors, including economic, social, technological, and cultural factors (Millennium Ecosystem Assessment 2005), of which coral reefs may only compose a part. The heuristic model presented herein articulates the human dimensions of coral reefs and links human well-being to anthropogenic activities, ecosystem services, and the fundamental social system structuring traits for a given SES. This framework can potentially be used to help address the paradoxical issues associated with declining marine resources and increasing human well-being (Raudsepp-Hearne et al. 2010; and see Duraiappah 2011, Nelson 2011, Raudsepp-Hearne et al. 2011). Untangling this paradox requires understanding human well-being from a holistic viewpoint, empirically determining to what extent well-being is tied specifically to ecosystem goods and services, and determining the social and ecological scales at which those goods and services are actualized.

This framework can also be used in field research to guide the gathering and analysis of empirical data on human dimensions of coral reef SESs. The framework can be operationalized for field research by systematically gathering or synthesizing human dimensions data using the components in the proposed framework (Fig. 2). It is beyond the scope of this article to develop specific variables for this conceptual model, but existing publications and reports have identified many of the key indicators and variables (e.g., for socioeconomic monitoring programs) that can be used with this framework (Table 2).

Using existing indicators within this framework can allow researchers to go beyond integrating or analyzing existing social data sets to linking social and ecological data sets to understand social-ecological interactions. For example, Cinner and colleagues combined several socioeconomic variables into an index of social adaptive capacity, using secondary data derived from government agencies as well as household survey data gathered within target communities, to determine the likelihood of success of different coral reef conservation strategies under climate change (McClanahan et al. 2008, Cinner et al. 2009b). Similarly, Pollnac et al. (2010) drew upon a large social data set to determine which socioeconomic variables were correlated with performance of marine reserves. Integrative approaches such as these illustrate the flexibility and research applications of linking social and ecological data sets and advantages of systematically assessing human dimensions. Such approaches also hold promise in teasing apart the complexity of drivers, their hierarchical dimensions and scales, and the multiple outcomes and trajectories associated with complex SESs (Agrawal and Chhatre 2011).

#### **CONCLUSIONS**

The explicit consideration of human dimensions has the potential to enrich significantly our understanding of complex interactions between society and ecosystems and the sustainability of linked SESs. Generalizable frameworks for SESs need to be supplemented with system-specific approaches that can yield more nuanced understandings about the complex linkages of SESs for specific contexts and resource systems, and at specific scales. The heuristic model and conceptual framework presented herein can help unravel the direct and indirect drivers of change and assess the potential linkages and interdependence of factors associated with social-ecological sustainability. Such problem-oriented integrative research is imperative if society is going to make the transition to a more sustainable relationship with natural resources, services, and values, and the ecosystems in which they are embedded.

Responses to this article can be read online at:  
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