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A Decision Support Framework for Science-Based, Multi-Stakeholder Deliberation: A Coral Reef Example

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Abstract We present a decision support framework for science-based assessment and multi-stakeholder deliberation. The framework consists of two parts: a DPSIR (Drivers–Pressures–States–Impacts–Responses) analysis to identify the important causal relationships among anthropogenic environmental stressors, processes, and outcomes; and a Decision Landscape analysis to depict the legal, social, and institutional dimensions of environmental decisions. The Decision Landscape incorporates interactions among government agencies, regulated businesses, non-government organizations, and other stakeholders. It also identifies where scientific information regarding environmental processes is collected and transmitted to improve knowledge about elements of the DPSIR and to improve the scientific basis for decisions. Our application of the decision support framework to coral reef protection and restoration in the Florida Keys focusing on anthropogenic stressors, such as wastewater, proved to be successful and offered several insights. Using information from a management plan, it was possible to capture the current state of the science with a DPSIR analysis as well as important decision options, decision makers and applicable laws with a the Decision Landscape analysis. A structured elicitation of values and beliefs conducted at a coral reef management workshop held in Key West, Florida provided a diversity of opinion and also indicated a prioritization of several environmental stressors affecting coral reef health. The integrated DPSIR/Decision landscape framework for the Florida Keys developed based on the elicited opinion and the DPSIR analysis can be used to inform management decisions, to

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reveal the role that further scientific information and research might play to populate the framework, and to facilitate better-informed agreement among participants.

Keywords Decision support framework · Environmental decision making · Environmental management · Multiple stakeholders · Elicitation · Scientific input · Valuation · Ecosystem services · DPSIR

Introduction

Government and private organizations regularly confront complex decisions that involve multiple parties, affect ecosystems and economies, and include choices made more challenging by limited scientific knowledge. Decisions are often made without appropriate consideration of scientific information, without knowledge of the uncertainty of the scientific information, without full representation of different stakeholder objectives, and without consideration of the value of ecosystem services (Costanza and others 1999; Lynam and others 2007; McNie 2007; Cowling and others 2008). We describe a decision support framework and methodology for science-based assessment and multi-stakeholder deliberation to better address these shortcomings.

The proposed decision support framework is based on the concept of decision analysis, which provides a course of action when there are conflicting desires and uncertainty in the consequences of alternative decisions (Keeney 1992; Clemen 1996). The framework is developed by combining: (1) an analysis to identify causal relationships among anthropogenic environmental stressors, processes, and outcomes with (2) an analysis to depict the legal, social, and institutional dimensions of environmental decisions. The second part of the framework also addresses the knowledge, values, and decision making of participants involved in aspects of the first part of the framework. The proposed framework draws from existing decision support tools for environmental assessment and management, such as integrated assessment and multiple criteria decision analysis, providing advancements relevant to each.

Much progress has been made in recent years to advance scientific understanding of different ecosystems, including their responses to stressors, their value to human wellbeing, and the sustainability of their goods and services provided to society. However, there is often a mismatch between scientific knowledge and the needs of agencies, businesses, and individuals making critical decisions that affect the environment. Improved decision support methods can be used to bridge this gap to: (1) guide scientists in the selection of targeted research studies and models responsive to the needs of decision makers and stakeholders; and (2) provide decision makers with the tools needed to interpret scientific results, understand uncertainties, draw relevant inferences regarding the decision problem, and identify further data collection and research needs. An existing tool for incorporating scientific information into a decision process is integrated assessment. Integrated assessment incorporates knowledge from two or more domains (e.g. environmental, social, and economic) into a single framework, often using quantitative models, in order to inform public policy (Rubin and others 1992; Dowlatabadi and Morgan 1993; Turner and others 2003; Matthies and others 2007). However, integrated assessment often lacks a multiple stakeholder context. The new framework proposed here incorporates identification of multiple stakeholder beliefs about scientific relationships between management options, anthropogenic stressors, environmental processes, and economic outcomes, as well as preferences for future environmental and economic outcomes, which can help to identify points of conflict and possible consensus. A better understanding of uncertainty in a decision problem will allow decision makers to either take action or target additional research needs. Uncertainty can include variability in current resource conditions or incomplete scientific knowledge regarding the causal relationships between management options and current resource conditions. Probabilistic techniques and expert elicitation are existing tools for analyzing uncertainty in a decision (Morgan and others 1990; Cullen and Frey 1999; Cullen and Small 2004). The new framework incorporates expert elicitation of beliefs and their associated uncertainty and identifies research gaps and information needs.

A decision support framework that encourages multi-stakeholder participation and deliberation can be used to build agreement around a preferred management action, especially among multiple decision makers and stakeholders who have differing objectives and beliefs regarding a problem (Cohen 1997; DeKay and others 2002; Renn 2006; Reed 2008). The National Research Council (National Academy of Sciences National Research Council 1996) described this democratization of risk and environmental policy decisions as an analytic-deliberative process, requiring a combination of *analysis* (input from the physical and social sciences) and *deliberation* (input from stakeholders). An existing tool for including multiple stakeholder objectives is multi-criteria decision analysis (MCDA), sometimes called multi-criteria decision making. MCDA is aimed at helping to evaluate the relative importance of multiple, possibly conflicting criteria in a decision scenario (Makowski and others 1996; Belton and Stewart 2001; Cohon 2004; Kiker and others 2005; Messner and others 2006). These criteria determine the basis for one particular choice or course of action over another. Often, management decisions must consider a wide range of criteria, especially when consensus is needed across groups with widely disparate interests. However, MCDA often lacks an explicit understanding of the scientific relationships between various aspects of a decision problem, such as management options, anthropogenic stressors, environmental processes, and economic outcomes. The new framework incorporates identification of these scientific relationships, which allows for better design and selection of objectives and preferred management options.

A decision support framework that incorporates the value and sustainability of ecosystem services could help to promote decisions that achieve a better balance between resource use, depletion or degradation, and preservation. Including ecosystem services in environmental decision making presents a way to incorporate benefits of the environment that may otherwise be overlooked (Costanza and others 2002; Hein and others 2006; Boyd and Banzhaf 2007; Turner and others 2010). Valuation of natural resources and environmental quality can be approached from a number of perspectives, including market and non-market measures of willingness-to-pay and contingent valuation (Bockstael and others 2000; Farrow and others 2000; Hanley and others 2007). For a variety of social, economic, and behavioral reasons, common environmental resources tend to be under-valued (Hassan and others 2005). As a result, land and resource use decisions have often been made to increase short-term economic opportunities with little attention to the long-term effects on goods and services, including human health, that are derived from natural ecosystems. The framework proposed here incorporates identification and weighting of impacts on ecosystem services associated with alternative decision options.

The principal contribution of the approach developed in this paper is to provide a framework within which the response of integrated physical, economic and social systems to alternative management options can be assessed, considering existing structures for decision making and decision support. The framework specifically addresses differences across stakeholders and participants in their values for different ecosystem and social outcomes, and their beliefs and uncertainties regarding anticipated system response, with a focus on identifying the scientific studies needed to reduce these uncertainties and enable future consensus on preferred management options. In this paper the new decision support framework is applied to the problem of assessing and managing coral reef stressors in the Florida Keys. A management plan for the National Oceanic and Atmospheric Administration Florida Keys National Marine Sanctuary (NOAA FKNMS) was developed through a public process from 1991–1996, implemented in 1996 and revised in 2005 and again in 2007. An expert elicitation of preferences for future environmental and economic outcomes and beliefs about scientific relationships between management options and outcomes was completed by volunteers participating in a US Environmental Protection Agency (EPA)-sponsored coral reef management workshop held in Key West in June 2009. The decision support framework for the Florida Keys was initially derived by integrating information drawn from this management plan and the workshop expert elicitation, and its effectiveness is discussed.

Background: Coral Reef Management in the Florida Keys

The Florida Keys are an archipelago that extends from Biscayne National Park south of Miami to the Dry Tortugas (Fig. 1). The coral reef tract extends nearly continuously along the 356 km shallow offshore waters of the Keys. Most of the reef tract lies within the boundaries of the 9,800 sq km FKNMS. The FKNMS partially encompasses the third largest barrier reef in the world.

Coral reefs provide important ecosystem services including regulating processes (shoreline protection, water quality maintenance, climate regulation), provisioning resources (fish, pharmaceuticals, and other marine natural products and chemicals), cultural benefits (tourism, recreation), and ecological support systems (nutrient cycling, habitat, nursery areas) (Hassan and others 2005). According to the United Nations Environmental Program (UNEP) coral reefs provide a total of US$100,000–600,000 in ecosystem services per sq km per year (UNEP 2006). Based on an approximately 1,250 sq km hardbottom reef area in FKNMS (Spalding 2001), this amounts to almost one billion dollars per year. Such an estimate appears reasonable for the Florida Keys, which support a commercial fishing industry worth several millions of dollars per year (NOAA 2010) and a tourism industry based mainly on marine resource-based activity worth one billion dollars per year (Leeworthy and Bowker 1997; Wheaton and others 2001).

A number of direct and indirect threats have been identified to coral reefs in general, and to the FKNMS in particular, though the importance of these are debated (Knowlton and Jackson 2008; Keller and others 2009). Factors mentioned include ocean warming and acidification associated with increasing atmospheric carbon dioxide (Orr and others 2005; Hoegh-Guldberg, and others 2007; Doney and others 2009); regional and local water pollution from sources such as municipal wastewater and agricultural runoff, including interactions with impacted waters from the Gulf of Mexico (Causey and others 2002; Kruczynski and McManus 2002; Lapointe and others 2004); altered freshwater flow regimes from the nearby Florida Everglades (Causey and others 2002; Porter and Porter 2002); harmful fishing practices and overfishing (Ault and others 2005; McClenachan 2009); and adverse physical contact and sediment resuspension from diving and boating activities (Jaap 2000; Shivlani and Suman

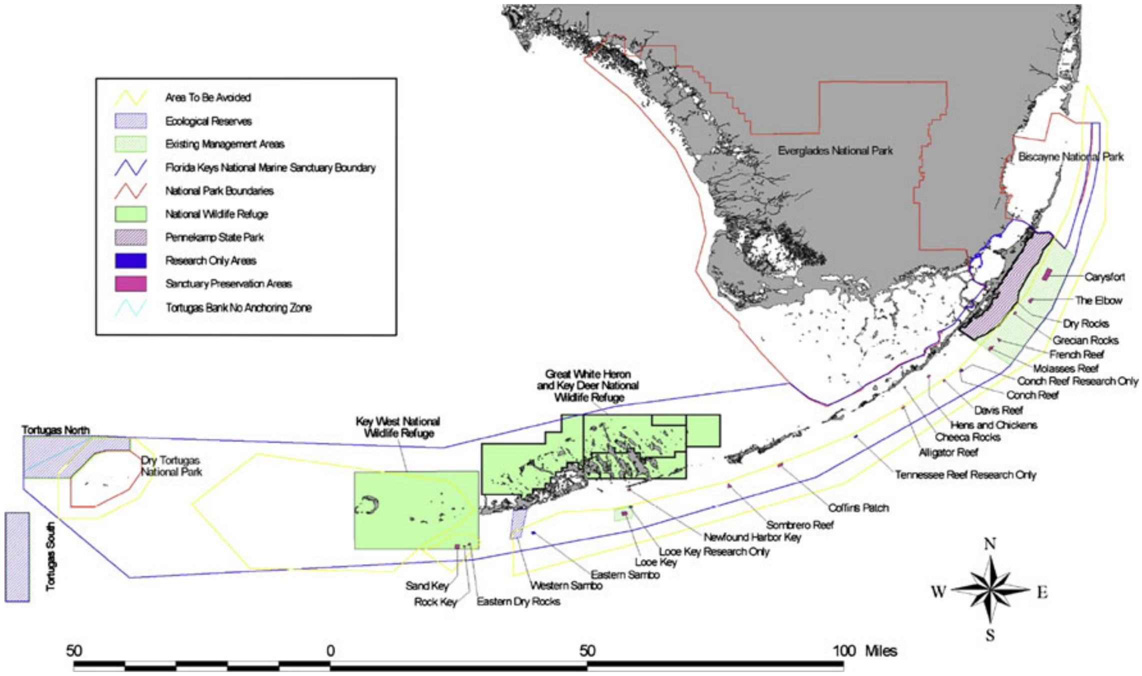

Fig. 1 Map of the Florida Keys national marine sanctuary (NOAA 2007) (Color figure online)

2000; Rouphael and Inglis 2002; Precht 2006). The individual and cumulative effects of these processes can be difficult to identify, particularly given the long-term shifts in coral community structure and coverage that are apparent in the geologic record, due to natural cyclic disturbances including hurricanes, winter cold fronts, and natural coral bleaching and disease stressors associated with ENSO cycles or other climate and weather factors (Precht and Miller 2007). Nonetheless, in recent decades coral bleaching has become more frequent, lasted longer, and been linked to dramatic declines in coral cover in the FKNMS (Manzello and others 2007; Eakin and others 2010). The loss of coral in the Florida Keys has prompted further consideration of the value of their ecosystem services, including economic benefits from tourism and fisheries, and possible losses in these that may be occurring (Leeworthy and Bowker 1997; Cesar and others 2003; Becken and Hay 2007; Hoegh-Guldberg 2010; Leeworthy and Loomis 2010a; Leeworthy and others 2010b).

Given these threats, a wide range of decision makers and stakeholders have recognized the priority and urgency for actions to protect and restore Florida's coral reefs (NOAA 2007). The Florida Keys National Marine Sanctuary and Protection Act of 1990 required a comprehensive management plan, and tasked the US EPA to work with the State of Florida and NOAA to develop a Water Quality Protection Program for the sanctuary. As part of a holistic-ecosystem based management approach, a citizen advisory council assisted the FKNMS in crafting a plan to protect the Sanctuary's natural resources, including coral reefs, seagrass, and mangroves (NOAA 2012). The FKNMS management plans (NOAA 1997, 2005, 2007) have been implemented in collaboration with parties such as the US EPA, Florida Department of Environmental Protection, Florida Department of Health, Florida Department of Community Affairs, the US Army Corps of Engineers, municipalities, and Monroe County, each with differing authority, constituencies and perceptions of environmental issues. Together, these agencies must consider options, such as wastewater treatment upgrades, marine zoning, restoration of damaged reefs, and stormwater management, to address the threats (NOAA 2007). These options require economic sacrifices by the Florida Keys community and likely tradeoffs with economic development. There are conflicting views among these parties and among their stakeholders on the severity of different threats, the potential to manage those threats, which actions should be taken, and their anticipated environmental and socioeconomic outcomes.

Decision Support Framework

The emerging decision support framework initiates the decision analysis process. The first part organizes the issue into identifiable steps and illustrates potential outcomes, intended or unintended, of different alternatives. It is achieved through application of a DPSIR (Driving Forces–Pressures–States–Impacts–Responses) conceptual approach (Fig. 2), which has been used to link ecological and socioeconomic factors and to scope the important causal elements

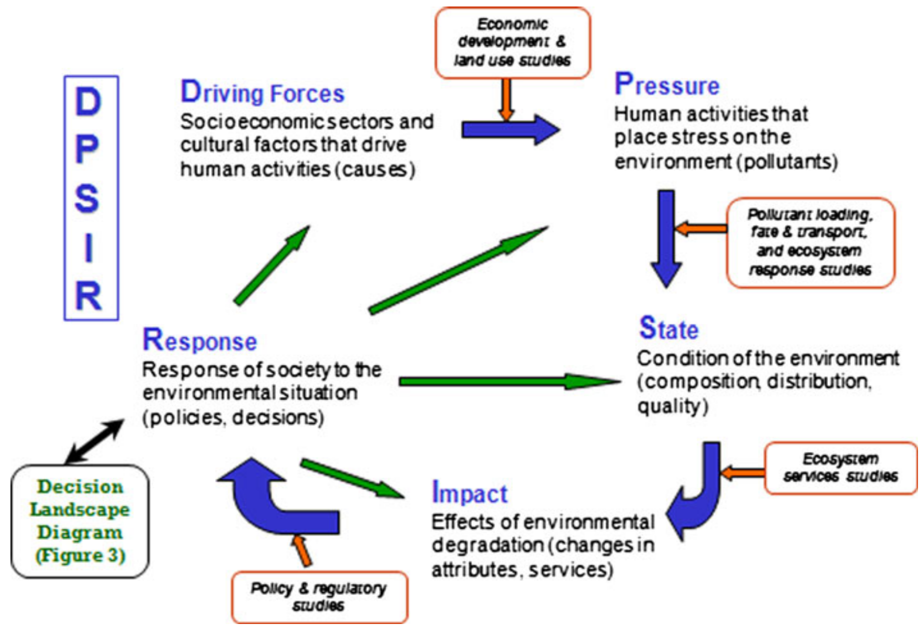

Fig. 2 The elements of DPSIR including links to scientific input (*orange boxes*) and the Decision Landscape (adapted from Fisher 2009; Bradley and others 2010) (Color figure online)

of environmental decision-making (European Environment Agency 2001; Brouwer and others 2003; UNEP 2007). The DPSIR framework provides a logical structure to house scientific information on relevant environmental and socioeconomic relationships. Scientific knowledge in the form of monitoring data, scientific studies, predictive models, or expert judgment can inform the relationships between components of the DPSIR framework (Fig. 2, orange boxes).

The second part of the decision support framework clarifies the decision situation and objectives and organizes management options. This is achieved through development of a Decision Landscape (Fig. 3), which builds on previous conceptual approaches to describe the relationships between environmental and social components in an environmental decision problem (Tonn and others 2000; Pyke and others 2007). The Decision Landscape analysis ensures that relevant legal, institutional, and social factors affecting a decision are recognized and considered. It addresses the knowledge, values, and decision making of participants in the various elements of the DPSIR process (Fig. 2, bottom-left). It informs stakeholders regarding decision makers and decision options (Fig. 3, components in green), system behavior and potential outcomes. It also identifies where scientific information regarding environmental processes is collected and transmitted to help improve knowledge about elements of the DPSIR and to support an improved scientific basis for decisions (Fig. 3, components in orange).

Together, DPSIR and the Decision Landscape provide a robust framework (DPSIR/DL framework) to incorporate relevant scientific knowledge, to weigh perceived and real environmental outcomes, to evaluate differences in ecosystem services and values, to recognize uncertainties in the assessments and even to identify monitoring or research projects to reduce that uncertainty.

Populating and Applying the Framework

Information from various sources can be used to populate the DPSIR/DL framework. In the examples presented here, ideas and concepts were collected from the FKNMS management plan (NOAA 2007) and from discussions at the EPA-sponsored Coral Reef Decision Support Workshop held in Key West in 2009. Presented below are: (1) preliminary DPSIR and Decision Landscape analyses of one example portion—the water quality portion—of the FKNMS management plan; (2) an expert elicitation of preferences and beliefs elicited from nine volunteers at the workshop regarding coral reef management and research needs in the Florida Keys; and (3) an overview of a proposed DPSIR/DL framework based on the results of the study that can be used to assist future planning for coral reef management in the Florida Keys. Water quality was selected for this analysis because of its greater potential for local and regional management than other larger-scale threats, such as climate change. Additionally, it was selected due to the following factors: (1) the US EPA and Florida Department of Environmental Protection have implemented a comprehensive Water Quality Protection Program that includes monitoring, research, corrective action, and outreach (EPA 2012), and (2) an ongoing extensive upgrade to wastewater treatment infrastructure in the Keys with a deadline set for July 1, 2015, which will significantly reduce wastewater loadings and impacts in the area (Office of National Marine Sanctuaries 2011).

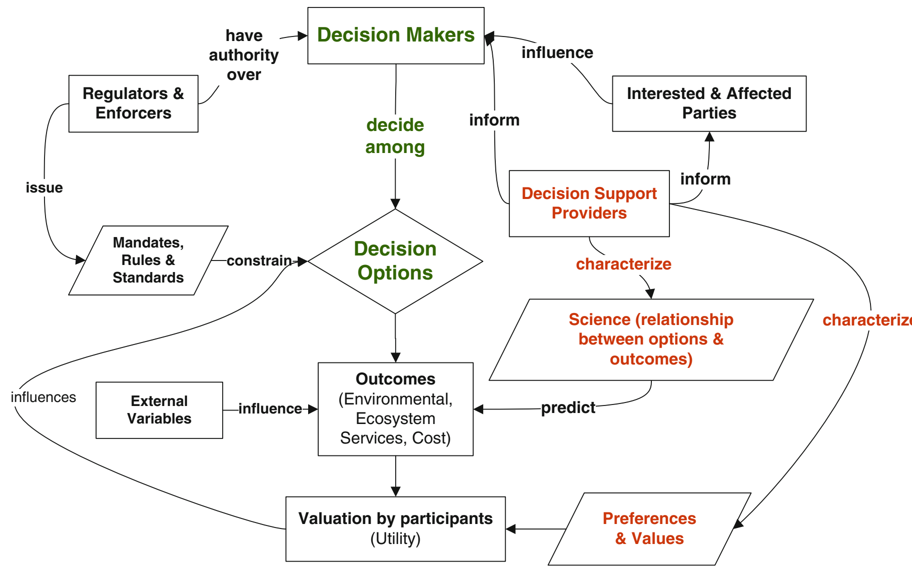

Fig. 3 Components and key relationships in an environmental management Decision Landscape (Color figure online)

Coral Reef DPSIR and Decision Landscape Analyses

Drawing from the management plan, the DPSIR analysis for water quality strategies portion of the FKNMS Management Plan included delineation of important drivers, pressures, "abiotic" (physical-chemical) and "biotic" (biological) states, and impacts on ecosystems services. For each of the DPSIR elements, existing knowledge and future research needs were identified (Table 1 illustrates an example for domestic wastewater discharges). Development of the Decision Landscape included delineation of important management actions, decision makers, and legal mandates that constrain decision options (Table 2 outlines important institutional components for the water quality strategies). Stakeholders involved in water quality strategies include environmental, fishing, and business and trade groups. Decisions are made by a variety of institutions (Table 2) and decision support is provided by institutions that prepare, implement and analyze monitoring programs and modeling studies that link pollutants and impacts, through various professional and news media reports (e.g. EPA, FDEP, NOAA FKNMS, National Coral Reef Institute, University of Miami, Miami Herald).

Expert Elicitation to Inform a DPSIR/Decision Landscape Framework

Nine volunteer respondents at the Coral Reef Decision Support Workshop were elicited for their preferences regarding different environmental and ecosystem services outcomes; beliefs regarding pressure-state-impact relationships for Florida's coral reefs; identification of alternative decision options; and research needed to reduce uncertainties related to environmental outcomes (Appendix). The methods used followed established procedures for MCDA (e.g. techniques for weighting criteria) and expert elicitation (e.g. techniques for gathering probabilistic subjective data, including a minimum of about ten experts, and providing anonymity of the respondents) (Morgan and others 1990; Belton and Stewart 2001). The respondents included decision makers, decision support providers, and an interested party. Five of the respondents held PhD degrees, two of whom had academic appointments, and one worked for a non-government organization (NGO). This was not a representative sample of stakeholders, as they tended to be better educated and less concerned about economic outcomes, and were probably more like scientific experts than stakeholders. Given the small sample size, no statistical analyses of the results were made. Rather, the elicitation results were used to provide an initial scoping of preferences and beliefs, to identify points of possible consensus, and to provide a basis for the construction of a DPSIR/DL framework.

Respondents were asked to weight the relative (%) importance of four outcomes for the Florida Keys region by allocating 100 points among them: coral reef health; water quality; tourism and economic growth; and fisheries health and vitality. Preferences for different outcomes (Fig. 4) were highest for good coral reef health (average of 34.5 %), followed by good coastal water quality and good fisheries health and vitality (averages of 27.5 and 27 % respectively), and finally high tourism and economic growth (average of 11 %).

The volunteers were also elicited regarding their beliefs about relationships between various pressures and environmental state in the Florida Keys. They were asked to estimate the probability of good coral reef health given different scenarios of water quality, climate change and fishing practices; these responses indicate the perceived uncertainty in the relationship between Pressure and State in the DPSIR framework (Fig. 5). There was a wide range of beliefs about the likelihood of good coral reef health. It varied from one

Table 1 Variables, current knowledge, and research needs for domestic wastewater discharges organized in the DPSIR framework derived from management plan

	Variables	Current knowledge	Research needs
Drivers	Economic Activity Industry Agriculture Recreation/tourism Waste disposal Culture (tourism and recreation) Housing	Bureau of econ. analysis/ census economic data Water, energy, material use (e.g. fertilizer)	Scenario development Future population Future economic activity
Pressures	Land use change Water use, diversion WW discharge rates N, P, BOD, TSS, toxics NPS loading rates Impingement Boating, diving, etc.	USGS land use/GIS data Inventories Cesspits, onsite systems, package plants, municipal plants NPDES permit data Compliance monitoring	Scenario development Water use Wastewater loading rates NPS loading rates Impingement projections Land use/land cover projection model
State (Abiotic)	Freshwater flow rates Ambient WQ N, P, Algal, DO, TSS, toxics	USGS flow monitoring Fed/state WQ data Habitat assessments	Biotic-abiotic interactions Uncertainties Climate change Variable rain patterns
State (Biotic)	Coral cover/health Fish species presence and abundance	Coral reef monitoring Fed/state programs Academic, NGO and volunteer programs	Stressor-response studies linking human activity to changes in coral condition Reef persistence modeling Linkage of coral reef attributes to ecosystem services
Impacts (Eco. Serv.)	Recreation/tourism value Fisheries products Shoreline protection	Socioeconomic monitoring program Recreation and tourist uses, values, attitudes and perceptions study (NOAA)	Improved quantification of ecosystem services Improved quantification of social preferences

USGS U.S. geological survey, *GIS* geographic information systems, *WW* wastewater, *N* nitrogen, *P* phosphorus, *BOD* biochemical oxygen demand, *TSS* total suspended solids, *NPS* non-point source (pollution), *NPDES* national pollutant discharge elimination system; *WQ* water quality

respondent who believed that the probability of good coral reef health was fairly low no matter what the underlying environmental conditions, to another who believed that the probability of good coral reef health was fairly high except for when there were no restrictions placed on fishing. With each of the environmental conditions of good water quality and low climate change, six out of nine respondents consistently believed that coral health would be improved, and one out of the nine did not see any effect in response to either of them. However, only four out of nine respondents consistently believed that coral health would be improved with restricted fishing. Differences in beliefs among participants could result from different notions regarding coral reef health, the relative importance of different stressors, or the potential for any environmental change to make a substantive difference. The average of the participant responses (dotted line in Fig. 5) indicates a general belief that coral reef health would improve with better water quality, less climate change and stronger fishing restrictions. The dotted line is not intended to suggest that policy makers should use the mean for policy purposes. Instead, it is presented to show a simple aggregation of the opinions and for use in gauging whether the opinions are consistent with existing data. As a group the respondents believed that improvements in water quality and in climate-related conditions (a close tie) would have the largest impact on coral reef health. However, the largest predicted increase in the likelihood of good coral reef health occurred when all three conditions were favorable.

The same nine volunteers were also asked to identify critical uncertainties in any factor affecting environmental quality and economic wellbeing in the Florida Keys, particularly those that limit the ability to identify effective management options. The critical uncertainties and research needs (Table 3), in order of how often they were mentioned (most often to least often),

Table 2 Decision options, decision makers, and legal mandates in the Decision Landscape for the water quality strategies portion of the FKNMS management plan

Decision options	Decision makers (and regulators/enforcers)	Legal mandates (rules/standards) (constraints)
Domestic wastewater strategies	Monroe County, Key Largo Wastewater Treatment district, FKAA, EPA, FDEP, FDCA, municipalities, FDOH, and Village of Islamorada	FL Sec 6 (Ch 99-395) which covers treatment and disposal standards
		Governor's Executive Order 96-108 (elimination of cesspits)
Stormwater strategies	Monroe County, Local municipalities, FDEP, FDOT, and SFWMD	40 CFR 122—The National Pollution Discharge Elimination System permitting and related regulations
		Best Management Practices
Florida Bay/external influence strategies	FKNMS:	FL Sec 62-043 Surface Water Improvement and Management Act
	EPA, FDEP, and NOAA Everglades/Florida Bay:	Sec 62-302 Surface Water Quality Standards Sec 403.021 of the Florida Statutes
	NPS, SFWMD, USACE, FDCA, USFWS, and Monroe County	Sec 62-303 Identification of Impaired Surface Waters
		PL 101-605 Florida Keys National Marine Sanctuary and Protection Act
		15 CFR 922, 929 & 937 Florida Keys National Marine Sanctuary Regulations, Final Rule
		16 USC 6401 Coral Reef Conservation Act
		33 USC 1251 Clean Water Act
		PL 106-541 Water Resources Development Act of 2000
Marina and live-aboard strategies	FWC, Monroe County, local municipalities, EPA, and NOAA	Florida Clean Vessel Act of 1994
		Sec 327.53 of the Florida Statutes
		No-Discharge Zones (City, State, Fed)
Landfill strategy	Monroe County, FDEP, U.S. Navy, and EPA	40 CFR 240-299 RCRA Regulations
Hazardous materials strategies	USCG, FDEP, NOAA, Monroe County, and FDCA	40 CFR 240-299 RCRA Regulations
		49 CFR 100-185 HAZMAT Regulations
Mosquito spraying strategy	FDA, consumer services (FDACS), and FDCA	40 CFR 150-189 FIFRA Regulations
Canal strategy	Monroe County, FDCA, SFWMD, EPA, FDEP, and municipalities	Same as applicable to Florida Bay/ External influence strategies above

FKAA Florida Keys Aqueduct Authority, *EPA* Environmental Protection Agency, *FDEP* Department of Environmental Protection, *FDCA* Florida Department of Community Affairs, *FDOT* Florida Department of Transportation, *SFWMD* South Florida Water Management District, *NOAA* National Oceanic and Atmospheric Administration, *NPS* National Park Service, *USACE* U.S. Army Corps of Engineers, *RCRA* Resource Conservation and Recovery Act, *USCG* U.S. Coast Guard, *FDACS* Florida Department of Agriculture and Consumer Services, *HAZMAT* Hazardous Materials, *FIFRA* Insecticide, Fungicide and Rodenticide Act

included studies to better understand causes of coral reef decline, conditions that promote effective restoration and recovery, current reef conditions in the Florida Keys, metrics of coral reef health, causal relationships between human activities and water quality, and the effect of educational efforts on attitudes and preferences.

Development of an Integrated DPSIR/Decision Landscape Framework

Based on the DPSIR analysis, the management plan, the elicitation, and deliberations of the workshop, an integrated DPSIR/DL framework for the Florida Keys began to emerge (Table 4). The framework identifies key relationships between DPSIR components and current scientific understanding, which were derived from the DPSIR analysis and workshop discussions. The framework also identifies stakeholder perceptions of that understanding, which were derived from the elicitation. Together, they can be used to predict the outcomes of management options and to identify future research needed to reduce critical uncertainties. As this process evolves, this should lead to support or rejection of hypotheses, and consequently, more agreement and confidence among stakeholders over scientific understanding and

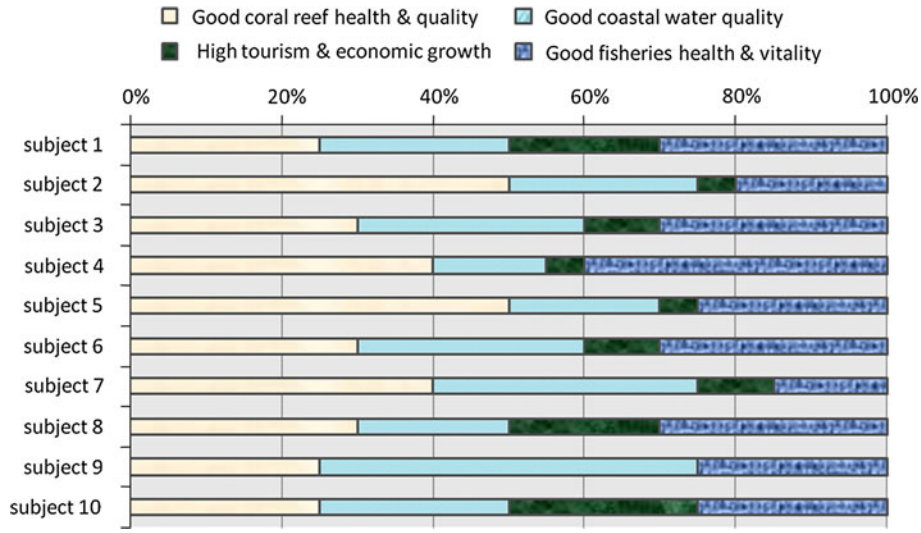

Fig. 4 Respondent preferences (relative weights) for different outcomes in the FKNMS region (Color figure online)

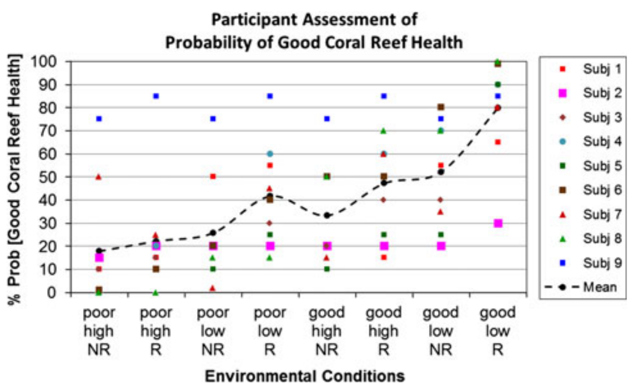

Fig. 5 Ratings of nine respondents (subj) regarding the probability (%) of good coral reef health based on various environmental scenarios involving (good/poor) local water quality, (high/low) potential for climate change (ocean warming and acidification), and restricted (R) or unrestricted (NR) fishing (Color figure online)

preferred management options. Therefore, the ability to project future outcomes should improve (Jaynes 2003). A wide range of information and research is needed to provide comprehensive decision support for coral reef management in the Florida Keys. As yet, an integrated model capable of linking human activities, water quality, coral reef health, fisheries, and ecosystem services does not exist for the region and could greatly benefit management planning there. Additionally, information provided in an organized framework could better inform the tradeoffs among decision options.

Discussion

The development of effective decision support for complex multiple stakeholder problems, such as coral reef protection and management, is challenging. It requires a broad range of pressures, management options, scientific information, and objectives to be aligned for a strategic delivery of relevant knowledge and information. Organizing the existing scientific research, associated uncertainties and research needs into the DPSIR framework facilitates the ability to forecast system responses and uncertainties. A Decision Landscape ensures that relevant constraints and flows of authority and information are recognized in the development of preferred management options.

The integrated DPSIR/DL framework is advantageous over other decision support tools because it allows prediction of the outcomes of management options and identification of future research needed to resolve uncertainties and conflicts among stakeholders. Some argue that a successful decision support tool should not be determined by its ability to build consensus, but instead, by its ability to structure decisions based on values and scientific information to gain insight and provide better informed recommendations (McDaniels and others 1999; Gregory and others 2001). Favorably, the DPSIR/DL framework's strength in aiding conflict resolution does not come at the expense of a critical exploration of the beliefs, values and objectives of participants. Like other tools, such as value-focused thinking and decision aiding, the DPSIR/DL framework supports an exploration of beliefs in developing management options, but it additionally supports delineation of scientific processes in a decision, which illuminates critical uncertainties and research needs, and ultimately, tends to lead to better-informed agreement among participants.

The application of the DPSIR/DL framework to coral reef management proved to be successful and offered several insights. Using information from a management plan, it was possible to capture the state of the current science in the DPSIR analysis and important decision options, decision makers and laws in the Decision Landscape analysis. Through discussions and elicitations at a Coral Reef workshop it was possible to scope participant preferences for outcomes, beliefs regarding pressure-

Table 3 Critical uncertainties and suggested research studies to reduce uncertainties identified by workshop participants (in order of how often they were mentioned—from most to least)

Critical uncertainties	Suggested research studies
1. Causes of coral reef decline	
A. Causes of "regional pandemic" coral diseases	Study to track the spatial distribution and conditions associated with coral bleaching and disease events
B. Mechanisms of coral disease transmission and spread, including probiotic vs. disease responses among corals	Probiotic/antibiotic studies to determine what makes some coral susceptible to disease and others resistant.
C. Improved understanding of coral spawning, recruitment and settlement.	Field studies of coral spawning, recruitment and settlement
D. Relationships between coral reef health and nutrient concentrations, algae, zooplankton, and higher food chain biota, such as fish	Laboratory and field studies of coral reef health under different conditions
2. Effectiveness of proposed reef protection and restoration strategies	
A. Effect of no-take areas on fish populations and coral reef health	Long-term monitoring of fish populations, catch, and coral reef health at and near designated no take zones
B. Effect of ecotourism (vs. current tourism practices) on coral reef health	Long-term monitoring of areas where coral reef contact is limited and ecotourism practices are maintained
C. Long-term success of reef restoration projects	Long-term monitoring of reef restoration sites
3. Current baseline information on reef condition in the FKNMS	Mapping and monitoring of reef ecosystems throughout the Florida Keys
4. The need for consistent, quantitative metrics to assess coral reef "health"	The reef science and management communities should actively pursue agreement on quantitative measures of reef ecosystem processes that relate to reef ecosystem "health"
5. Causal relationships between human activity and water quality in the Florida Keys	Integrated assessment of nutrient loads associated with agriculture, urban development, and wastewater, and the impact on water quality in the Florida Keys, conducted by biophysical and social scientists
6. Impact of education on preferences for coral reef protection and preservation of other ecosystem services	Study of response to information on coral reefs and ecosystem services presented to different segments of the population

outcome relationships, and the research needed to reduce important uncertainties in these relationships. Not surprisingly, the nine workshop respondents, who were mainly resource managers and not in business or commerce, most highly valued coral reef health and water quality. Had business groups participated in the study, they may have placed more value on economic objectives, such as tourism and fisheries. The framework succeeded in capturing a diversity of expert opinions regarding the relative importance of different environmental conditions that affect coral reef health. Despite the wide range of beliefs about the likelihood of good coral reef health, the respondents believed as a group that coral reef health will improve with better water quality, less climate change and stronger fishing restrictions, which is in agreement with existing studies (Kruczynski and McManus 2002; Ault and others 2005; Hoegh-Guldberg and others 2007). Belief in some synergy among the environmental factors needed to enable good coral reef health indicates a preference for a broad-based management strategy over a focus on only one or two of the environmental pressures. While the average of the expert opinions provides a simple way to aggregate the information, it tends to neglect differences due to differing backgrounds and experience among stakeholders, which could prove to be important in making management decisions. For example, resource managers may inherently see more complexity with respect to ecosystem degradation than other stakeholders. Participation of business groups in future studies would help to determine the extent to which these stakeholders have different objectives and scientific understanding of the system.

The framework succeeded in identifying a number of critical uncertainties from the respondents, all of which limit the ability to determine effective management options, and it is unlikely that any one organization, such as FKNMS and its collaborators, can mount a research strategy that addresses all of these issues. Thus, mechanisms for coordinating activities across a broad range of scientific researchers in the Florida Keys are needed, and plans for enabling these were also discussed at the Workshop.

The initial DPSIR/DL framework for coral reef management issues described in this study will be built upon and expanded in the future with the intent of contributing to a process that strategically incorporates critical scientific knowledge and multiple stakeholder preferences for outcomes into local and regional decisions. Next steps could involve using a larger and more diverse sample group (e.g. 10+ participants per group), including not only scientists,

Table 4 An overview of scientific understanding, stakeholder perceptions, and research needs for predicting outcomes of management options organized in the DPSIR framework

	Scientific understanding	Stakeholder perceptions	Research needs
Drivers → Pressures	Increased population and human activity leads to increased water use and pollutant loadings	Disagreement regarding the type and intensity of effects of population growth on coral reefs and economic growth	Economic input-output models Hydrologic and hydrodynamic non-point source pollution models Models to evaluate different decision scenarios
Pressures → Abiotic state	Sediment and nutrient discharges throughout the watershed add to pollutant loads reaching coral reefs and the coastal environment	Disagreement regarding the sources of pollutants in aquatic systems and the means to control them	General ambient water quality model Models to evaluate different scenarios
Abiotic state ←→ Biotic state	Multiple water-borne physical and chemical stressors lead to increased algae, decreased coral cover, and imbalance in number and diversity of fish	Disagreement regarding effects of pollutants on the condition of the coral reef community; effects of water-borne stressors relative to climate change stressors and damage by physical contact General agreement that coral condition can be improved by reduction of environmental stressors	Indicators explicitly sensitive to human disturbances Coral health/fisheries model Model to link water quality to ecological attributes Models to evaluate different scenarios
Biotic state → Ecosystem services	Changes in the amount and condition of coral reef ecosystems (coral, fish and other inhabitants) and delivery of ecosystem services	Disagreement on what constitutes an ecosystem service, what provides the service, the value of the service and how ecological state affects the delivery of the service	Rate functions that quantify ecosystem services Economic model to predict value of services from corals and fisheries Models to evaluate different scenarios Methods to incorporate stakeholder values
Integrated assessment	Activities to fulfill basic human needs result in use and alteration of coral reef ecosystems and services	Disagreement regarding quantifiable linkages among interacting human activities and consequent effects on coral reef ecosystem services	Development of an integrated model Educating and engaging stakeholders

resource managers, and education and outreach organizations, but also business groups, such as commercial fisherman and tourism organizations. This sample would allow for the ability to test whether differences in beliefs are a function of experience or background. Furthermore, the elicited expert information from the group could be entered into an influence diagram or graphical probabilistic model, which can be used to estimate the probabilities that various management options will have particular outcomes of interest and stakeholder valuations, better informing management decisions for protection of coral reefs (Stiber and others 1999; Borsuk and others 2001). Finally, future studies could examine whether proposed studies aimed at reducing uncertainty are likely to move stakeholders to more or less agreement about the state of current scientific understanding and preferred management actions.

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Appendix: Blank Elicitation Form for Florida Keys Workshop

Florida Keys Coral Reefs Workshop - June 2009

Pre-Workshop Stakeholder Assessment of Preferences and Beliefs for Resource Management

Name: ______________________________ Affiliation: ____

Note: Participants names or affiliations will not be identified in any presentation of results without your approval.

1. Beliefs Regarding Relationships Between Environmental Pressures and Outcomes. Here we would like your estimate of the effects of different environmental conditions on the following ecological and economic outcomes in the Florida Keys area: **a) coral reef health and quality**; **b) fisheries health and vitality**; and **c) tourism and economic growth**. For each of the combinations of environmental conditions (a row in each table), assign a percentage (between 0% and 100%) to reflect your belief in the likelihood of a good outcome. Good outcomes correspond to: a) healthy, high quality coral reefs; b) good fisheries health and vitality; or c) high levels of tourism and economic growth, for the respective tables.

a) Effect of Environmental Conditions on the Health and Quality of Coral Reefs

Environmental Conditions			Percent Chance that Coral Reef Health and Quality will be Good (assign value between 0% and 100%)
Water Quality (sediments, nutrients, algae, etc.)	Overfishing Occurs	Climate Change (increased ocean temperature and acidification)	
Poor	Yes	High	
Poor	Yes	Low	
Poor	No	High	
Poor	No	Low	
Good	Yes	High	
Good	Yes	Low	
Good	No	High	
Good	No	Low	

b) Effect of Coral Reefs and Climate Change on Fisheries Health and Vitality

Environmental Conditions		Percent Chance that Fisheries Health and Vitality will be Good (assign value between 0% and 100%)
Coral Reef Health	Climate Change (increased ocean temperature and acidification)	
Good	Low	
Good	High	
Poor	Low	
Poor	High	

c) Effect of Environmental & Economic Conditions on Tourism and Economic Growth

Environmental or Economic Condition			Percent Chance that Tourism and Economic Growth will be Good (assign value between 0% and 100%)
Land Use and Wastewater Restrictions	Fisheries Health and Vitality	Coral Reef Health	
No	Good	Good	
No	Good	Poor	
No	Poor	Good	
No	Poor	Poor	
Yes	Good	Good	
Yes	Good	Poor	
Yes	Poor	Good	
Yes	Poor	Poor	

2. Additional research studies involving data collection, experiments and modeling have the potential to provide improved characterizations of the relationships between the environmental and economic pressures and the environmental outcomes described above. Based on your understanding of current science and what information is needed to make management decisions, please respond to the following:
   a. I believe the following scientific uncertainties to be most important to resolve in the Florida Keys:

      ____

      ____

   b. I suggest the following study be conducted (what, how, by whom)? ____________

      ____

      ____

3. Preferences for Outcomes. Here we would like to understand the relative importance you place on coral reef health, water quality in coastal waters, tourism & economic growth, and fisheries health and vitality. Please assign value points to each outcome, so that the points sum to 100. For example, if you value each outcome equally, you will assign value weights of 25 to each. If you only value one of the outcomes, but not the other three, you will assign 100 points to the valued outcome and 0 points to the other three outcomes, etc.

	Outcome				
	Good Coral Reef Health & Quality	Good Coastal Water Quality	High Levels of Tourism & Economic Growth	Good Fisheries Health & Vitality	–> Σ Sum
Assigned Value Weight →					100

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