Environmental Management
DOI 10.1007/s00267-014-0422-8

Developing Objectives with Multiple Stakeholders: Adaptive Management of Horseshoe Crabs and Red Knots in the Delaware Bay

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Received: 22 November 2013 / Accepted: 5 December 2014

Abstract Structured decision making (SDM) is an increasingly utilized approach and set of tools for addressing complex decisions in environmental management. SDM is a value-focused thinking approach that places paramount importance on first establishing clear management objectives that reflect core values of stakeholders. To be useful for management, objectives must be transparently stated in unambiguous and measurable terms. We used these concepts to develop consensus objectives for the multiple stakeholders of horseshoe crab harvest in Delaware Bay. Participating stakeholders first agreed on a qualitative statement of fundamental objectives, and then worked to convert those objectives to specific and measurable quantities, so that management decisions could be assessed. We used a constraint-based approach where the conservation objectives for Red Knots, a species of migratory shorebird that relies on horseshoe crab eggs as a food resource during migration, constrained the utility of crab harvest. Developing utility functions to effectively reflect the management objectives allowed us to incorporate stakeholder risk aversion even though different stakeholder groups were averse to different or competing risks. While measurable objectives and quantitative utility functions seem scientific, developing these objectives was fundamentally driven by the values of the participating stakeholders.

Keywords Delaware Bay · Horseshoe crabs · Management objectives · Risk · Red knots · Structured decision making · Utility functions

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Introduction

Structured decision making (SDM) is an increasingly important tool for natural resources management (Williams et al. 2007; Gregory et al. 2012). At its essence, SDM is a value-focused decision-making process in which decision makers (1) set management objectives, (2) create a list of possible alternative actions, (3) predict consequences of those actions on the management objectives, (4) use this information to select the action that best meets the objectives, (5) implement the decision, and (6) monitor the outcome to determine if the objectives were achieved (Hammond et al. 2002; Gregory and Keeney 2002; Gregory and Long 2009). It is a way to structure problems and decisions to put the objectives first and foremost, before considering management choices or consequences (Arvai et al. 2001; Hammond et al. 2002; Gregory and Keeney 2002). Sometimes SDM leads to a full decision analysis and optimization, but in other instances, SDM functions to give clarity to management problems and decisions in a qualitative but structured way (Gregory et al. 2012).

Published online: 24 December 2014

SDM incorporates relevant stakeholders into the process, breaks the decision down into component parts, and integrates those parts through analysis of tradeoffs (Hammond et al. 2002). Adaptive resource management (ARM) is simply the application of SDM to recurrent decisions under ecological uncertainty (Williams et al. 2007), and the iterated nature of the decision provides the opportunity to learn about resource system dynamics and apply what is learned to future decisions (Williams et al. 2007; Runge 2011). Because SDM frameworks are built on value-focused thinking (Keeney 1992), setting clear and measurable objectives may be the most important step in the process.

Imperative to the success of an SDM process is identifying the fundamental objectives that describe the goals of management and incorporate the values of stakeholders (Hammond et al. 2002; Keeney and Gregory 2005). Setting objectives is not a science-based activity, but rather involves eliciting the values of key stakeholders and decision makers then translating those values into measurable quantities (Kirkwood 1997). However, because stakeholders often have competing concerns, agreeing to a common set of objectives can be difficult and sometimes adversarial. It is not necessary to eliminate competing objectives; on the contrary, the power of decision analytic frameworks like SDM and ARM stems from the ability to incorporate multiple value systems in a transparent manner. Ecological, economic, esthetic, spiritual, and other societal values are all legitimate concerns to consider and incorporate into management objectives. In many cases, SDM can help bridge differences among stakeholders, resolve or reduce conflict, and provide a way to simultaneously achieve multiple competing objectives.

Objectives must be stated in terms of performance measures so that the decision structure can be analyzed to identify optimal management strategies. With effective performance measures or measurable attributes, managers can evaluate both consequences of potential management actions before implementation and success of the management program after implementation (Keeney and Gregory 2005). Keeney and Gregory (2005) detail a set of guidelines and criteria to ensure that performance measures of an objective are useful in a decision analysis. Attributes useful for evaluation of objectives require five characteristics: (1) unambiguous—a clear relationship exists between the attribute and the desired consequences, (2) understandable—clear enough for the stakeholders to understand, (3) comprehensive—the attribute levels cover the range of possible outcomes, (4) direct—directly related to the outcomes stakeholders are trying to achieve, and (5) operational—able to be measured in the real world (Keeney and Gregory 2005). Articulation of well-crafted objectives and appropriate performance measures is a first step to combining the values and aspirations of stakeholders with a scientifically supported and defensible decision process (Williams et al. 2007). In complex management scenarios, pervasive in fisheries and wildlife management, performance measures can then be incorporated into a mathematical function, often called an objective function or reward function, used to calculate the expected rewards that will result from a management policy.

We worked with stakeholders and managers using an SDM approach to establish an ARM framework to manage horseshoe crab harvests in the Delaware Bay region (McGowan et al. 2009; McGowan et al. 2011a). Concern over harvest of horseshoe crabs grew because Red Knots, a migratory shorebird that eats horseshoe crab eggs during spring migration through Delaware Bay, exhibited steep population declines in the early 2000s, and many observers speculated that horseshoe crab harvest was the ultimate cause of Red Knot decline (Baker et al. 2004; Niles et al. 2009). The ARM framework we developed attempted to represent ecological uncertainty about the system to account for alternative hypotheses of system dynamics (i.e., in the form of competing models of the ecological relationship between horseshoe crab abundance and Red Knot population dynamics; McGowan et al. 2011a). An optimization analysis was used to find the best harvest actions given the stated management objectives, the set of possible horseshoe crab harvest actions, and ecological uncertainty (McGowan et al. 2009; McGowan et al. 2011a). We developed an objective function that accounted for the fundamental objectives of stakeholders (Gregory and Keeney 2002). The challenge in specifying the objectives was due to the stakeholders' strongly conflicting values and differing risk attitudes (Berkson and Shuster 1999; Odell et al. 2005). Our approach to developing an objective function was to start with qualitative descriptions of the fundamental objectives. After stakeholders agreed on qualitative objectives, these descriptions were combined into a single objective function using appropriate performance measures for the decision analysis.

In this paper, we describe the application of SDM to help multiple stakeholders develop management objectives within an ARM framework for horseshoe crab harvest in Delaware Bay. Using the five criteria presented by Keeney and Gregory (2005), we emphasize how our objectives evolved during the development of the decision framework from a qualitative statement to a quantitative objective function with unambiguous and more direct performance measures. The narrative serves as a successful case study for objectives setting in a multi-stakeholder, multi-objective management system with potentially adversarial stakeholders. We do not address other aspects of SDM in this paper. Further details on the other SDM aspects are included in McGowan et al. (2009), 2011a, and Smith et al. (2013); see also Gregory and Keeney (2002) and Runge (2011) for a general introduction to SDM/ARM, and Lyons et al. (2008) for the role of monitoring in SDM/ARM.

Objective Functions

At least two general approaches are available for incorporating multiple competing objectives into a single objective function, both based on multi-attribute utility theory (Keeney and Raiffa 1993): (1) identify a common currency for all objectives, such as dollars or "utilities," or (2) use a utility defined by one objective to affect the reward accrued by another objective (Nichols et al. 2007). In the first approach, an additive multi-attribute objective function for combined rewards from n different resources, which can be weighted to account for relative importance of each objective, may be

$$R = w_1u_1 + w_2u_2 + w_3u_3 + \ldots + w_nu_n,$$

where R is the total reward for a given management action, u indicates the utility of a management outcome on a common scale (often between 0 and 1) for a given objective, and w_i are the weights of each objective ($\sum_{i=1}^{n} w_i = 1$) representing the relative importance of different resources. In the first approach, the decision analysis optimizes the linear objective function. In the second approach, the decision analysis maximizes reward from one objective, but the optimization is constrained by other objectives. The second approach often uses thresholds to define the rewards (Martin et al. 2009). Lastly, it is possible to use some combination of the two approaches, where a multi-attribute objective function uses a common currency to combine the objectives in a measure of total reward which is constrained by one or more additional objectives. For example, a budget threshold ("cost constraint") may limit the cumulative benefits for multiple stakeholders in a watershed management project.

Multi-attribute utility theory not only facilitates tradeoffs among competing objectives but also makes it possible to accommodate the decision maker's attitude to risk when making decisions under uncertainty. We used informal methods similar to the "desirability curves" of Hammond et al. (2002) to construct utility functions. Utility functions and explicit risk management can be valuable tools in group decision making because risk-averse stakeholders may be unwilling to participate in a process that appears to increase risk (Hammond et al. 2002). Utility functions make the risk aversion and risk tolerance of the stakeholders transparent since the shape of a utility curve (derived from the utility function) is highly related to risk. For example, a simple linear function represents risk neutrality over changing values of the axes, while a stepwise (or threshold based) function represents extreme risk aversion (Goodwin and Wright 2004).

Stakeholders often have different views of how the system will respond to management actions when there is a lack of understanding of biological mechanisms involved, i.e., "structural uncertainty" (Williams 1997). When structural uncertainty can be articulated as competing hypotheses about system dynamics, it is possible to formulate multiple predictive models and find optimal solutions given the range of possible outcomes under alternative hypotheses. Multiple predictive models and well-designed monitoring programs provide the opportunity to learn about system dynamics over time, reduce uncertainty, and thus reduce risk to decision makers (Williams et al. 2007).

Application to Delaware Bay

Resource Management Background

Delaware Bay is an estuary in the mid-Atlantic Coast of the United States, which is globally important as both a spawning area for horseshoe crabs (*Limulus polyphemus*) and a migratory stopover site for a variety of shorebird species (Niles et al. 2009; Smith et al. 2009). Horseshoe crabs spawn on the sandy beaches of Delaware Bay by the millions during May–June annually, leaving behind billions of eggs which the migrating shorebirds consume during their epic, northward migration from South America to Arctic Canada (Niles et al. 2009; Smith et al. 2009). Intense, unregulated harvest of horseshoe crabs began in the 1980s and escalated in the 1990s as the crabs became increasingly important for use as bait in whelk fisheries (Kreamer and Michels 2009; Smith et al. 2009). Horseshoe crabs are also an increasingly important resource for the biomedical industry, which uses a lysate [Limulus amebocyte lysate (LAL)] derived from the crab's hemolymph as the worldwide standard to test for bacterial contamination in injectable drugs and implantable medical devices (Novitsky 2009). Following increased harvest during the 1990s, researchers reported steep declines of migratory shorebird populations that pass through Delaware Bay, especially the *rufa* subspecies of the Red Knot (*Calidris canutus rufa,* e.g., Baker et al. 2004; Mizrahi and Peters 2009). A series of scientific publications attributed the decline in Red Knot abundance solely to the unregulated harvest of horseshoe crabs (Morrison et al. 2004; Baker et al. 2004; Niles et al. 2009). At the same time, fishermen and LAL industry representatives advocated to maintain commercial harvest for economic and human health reasons (Kreamer and Michels 2009). Recently, a series of papers have identified other causes contributing to Red Knot decline, including arctic conditions and decline in wetland habitats range-wide (McGowan et al. 2011b; Karpanty et al. 2011; Fraser et al. 2013).

In 1998, the Atlantic States Marine Fisheries Commission initiated coastwide regulation of horseshoe crab harvest that recognized competing needs of fishermen and migrating shorebirds (ASMFC 1998; Smith et al. 2009). After several years of ad hoc multi-species management, many stakeholders were still dissatisfied and participants, seeking a more transparent and explicit approach, turned to SDM in 2007. The purpose of the SDM and ARM efforts in Delaware Bay was to find an optimal harvest policy that achieved explicit multi-species objectives.

Decision Makers and Stakeholders

The horseshoe crab fishery is managed coast wide by the Atlantic States Marine Fisheries Commission (ASMFC). ASMFC has a hierarchical set of committees with decision makers receiving information and analyses from multiple technical and advisory panels. At the top of the hierarchy, a management board comprised of representatives from each of the Atlantic coastal states and responsible federal agencies (U.S. Fish and Wildlife Service and National Marine Fisheries Commission) sets maximum harvest quotas, season lengths, and closures. The participating State governments can set their own harvest regulations up to, but not in excess of, the Commission's quotas. When the SDM/ARM framework was initially developed (beginning in 2007), the management board received technical advice from the Horseshoe Crab Technical Committee (HCTC), which comprised state and federal agency biologists and managers, including marine fishery and at least one shorebird scientist. The HCTC advised the board on scientific issues and provided data analyses and periodic stock assessments. The management board also received advice from the Horseshoe Crab Advisory Panel (HCAP), which comprised mainly of fishermen and representatives of the whelk and biomedical industries. Since 2010, the management board has received advice from the HCTC and HCAP, and the newly created Delaware Bay Ecosystem Technical Committee and Shorebird Advisory Panel.

Stakeholders concerned with horseshoe crab harvest management in Delaware Bay include commercial fishing industries for bait and LAL production, birdwatchers, environmental activists, eco-tourists, and Delaware Bay residents who have ecological or economic concerns (Odell et al. 2005). Horseshoe crabs are harvested along the Atlantic coast for use as bait in eel and whelk fisheries, and Delaware Bay has historically provided the largest share of the harvest (Smith et al. 2009). Additional mortality associated with the collection of horseshoe crab blood for the production of LAL has been reported to be from 5 to 30 % (Leschen and Correia 2010). Birdwatchers travel from across the country and the world to witness the hundreds of thousands of migratory shorebirds in Delaware Bay each spring. Estimated economic output (in 1999 dollars) along the Atlantic coast related to horseshoe crabs was \$7–\$10 million due to bird watching and eco-tourism in the Delaware Bay, \$73–\$96 million from the LAL industry, and \$13–\$17 million from whelk and eel pot fisheries (Manion et al. 2000). Stakeholders place different value on the economics of harvest or tourism, biodiversity, and beneficial use of LAL. Conflict arises when one stakeholder group places full value on one attribute to the exclusion of others or when the decision process does not appear to or in reality does not account for a complete set of stakeholders' concerns.

In addition to different values and concerns, stakeholder groups vary in how they understand the ecological system will respond to different management options. The groups that emphasize the value of biodiversity, birdwatching, and eco-tourism advocate for a restoration of the Bay's resources (specifically horseshoe crab populations) to historic levels that could support hundreds of thousands of migratory birds (Niles et al. 2009). These groups tend to believe that horseshoe crab harvest caused the observed decline in shorebird populations (Niles et al. 2009) and advocate for a full moratorium on horseshoe crab harvests until shorebird numbers have rebounded (e.g., Niles et al. 2009). In contrast, the groups that emphasize economic value of harvest and beneficial use of LAL advocate for a sustainable harvest of horseshoe crabs consistent with its role in the coastal ecosystem (ASMFC 1998). They tend to believe that either the shorebirds are not dependent on horseshoe crab abundance or that horseshoe crab harvest is not the sole cause of the observed decline in shorebird populations (Karpanty et al. 2011; Fraser et al. 2013), and some levels of harvest might be consistent with providing sufficient forage for shorebirds (Sweka et al. 2007).

At the request of ASMFC, the U.S. Fish and Wildlife Service convened a shorebird technical committee (STC) to account for multiple stakeholder concerns regarding shorebirds and to provide advice to the management board on how horseshoe crab harvest affects shorebird populations. The STC comprised wildlife and fishery biologists from state and federal agencies, non-profit environmental groups (e.g., Audubon Society), and academic institutions. The STC initially compiled data and conducted analyses on Red Knot (and other shorebirds) population trends and horseshoe crab egg availability on Bay beaches, then provided that information to the ASMFC and the US Fish and Wildlife Service. The HCTC and the STC were brought together in joint meetings to form a group known as the joint technical committees (JTC) to develop the SDM framework. This was the committee structure at the time of the ARM development and objectives elicitation as described herein. In 2010, the ASMFC dissolved the ad hoc JTC and replaced it with a permanent Delaware Bay Ecosystem Technical Committee and a Shorebird Advisory Panel (SAP) equivalent to the HCAP.

Establishing Management Objectives

The decision problem was framed as harvest management because the decision maker for harvest regulation is the ASMFC management board. The stakeholder and technical committees (JTC) developed the decision framework. The ASMFC management board then decided whether or not to adopt the framework.

Our SDM process incorporated the interests of many stakeholder groups, with the JTC representing the fishing industry, shorebird conservationists, and state agencies. Although not all NGOs had representatives on the JTC, shorebird advocates, fishery advocates, and all invested state and federal agencies were seated on the JTC. Furthermore, all meetings of the JTC regarding the SDM process were open to the public, and every meeting entailed public comment periods. Our approach assumed that the decision makers and stakeholders would be represented by the JTC members and by a limited number of additional representatives from the commercial industries and shorebird advocate groups.

The process began at a structured decision-making workshop held at the National Conservation Training Center in Shepherdstown, WV, where select stakeholders, taxa experts, and ecological experts were convened to begin analyzing the problem (Breese et al. 2007). The workshop and all subsequent meetings following the workshop used a rapid prototyping process (e.g., Blomquist et al. 2010). Rapid prototyping is an iterative process that involves a series of increasingly complex and realistic decision analyses to evaluate the decision space of a particular problem and to build increasingly useful management models to support decision making (Nicolson et al. 2002; Starfield and Jarre 2011; Gregory et al. 2012). An additional major benefit of prototyping is that the objectives, along with any component of the decision analysis, can be revisited and restructured with each prototyping iteration.

To develop our objective function, we followed the recommendations of Kiker et al. (2005) to acquire stakeholder input into the process; technical work and analyses were done by trained scientific contributors but management values and objectives were defined by stakeholders. The JTC held multiple meetings where objective statements and later mathematical objective functions were discussed, reworded, and refined to the point of consensus. These meeting were led by either the HCTC or the STC chairs, and consensus was reached in the meetings when no further edits or revisions were suggested by the participants. In between JTC meetings, the core modeling team (known as the ARM sub-committee) incorporated the revised objective statements and functions into the decision analysis structure. The ARM sub-committee, which reported to the JTC, consisted of ecologists, population modelers, data analysts, and taxa specialists from New Jersey, Delaware, and federal agencies. With this process, the objectives and the measurable attributes of the objects evolved over a period of 2 years.

The first step in developing management objectives was to seek common ground among the stakeholders and develop an agreeable qualitative objective statement. Everyone agreed that shorebird population conservation was a goal, and everyone could support horseshoe crab harvest as long as it did not interfere with shorebird conservation. The JTC started with a qualitative objective statement:

Manage harvest of horseshoe crabs in the Delaware Bay not only to maximize harvest but also to maintain ecosystem integrity and provide adequate stop-over habitat for migrating shorebirds (McGowan et al. 2009).

Our qualitative objective statement includes the essential values of the stakeholders for this decision problem, but the performance measures are ambiguous. For example, how would “ecosystem integrity” be measured? What constitutes “adequate stopover habitat for migrating shorebirds?”

Our qualitative objective statement referenced migratory shorebirds in general. For this management problem, Red Knots are considered an umbrella species (e.g., Lambeck 1997), and the JTC assumed that improving stopover habitat conditions for Red Knots would likewise improve conditions for other shorebird species. Henceforth, naturally measurable attributes of the Red Knot population served as proxy measures for the suite of migratory shorebird species that use the bay for stopover during migration (Keeney and Gregory 2005). Of the variety of shorebird species that use the bay and consume horseshoe crab eggs during the spring migration, the Red Knot seems to be the most dependent on horseshoe crab eggs because of their size, energetic requirements, and migration time constraints (Niles et al. 2009). Red Knots also have the most urgent need for management since populations have declined dramatically since the late 1990s (Baker et al. 2004; Morrison et al. 2004; Niles et al. 2008). With the focus on Red Knots, the objective statement was revised to “*Maximize the harvest of Horseshoe Crabs in the Delaware Bay if the Red Knot population achieves some desirable condition or state*.” This statement implies a utility threshold (when the reward associated with a resource changes; Martin et al. 2009) that constrains the reward associated with a given harvest level. In this case, the constraint is based on whether the Red Knot population achieves or exceeds some minimum desirable condition or state. If that population threshold is met, then harvest has full value, otherwise harvest has no value. Use of a utility threshold based on one objective as a constraint when maximizing or minimizing another objective can be a useful technique for developing quantitative objective statements when there are multiple and potentially competing management objectives (Johnson et al. 1997; Martin et al. 2009). However, the Red Knot population constraint needs to be fully defined within the objective statement to meet the unambiguous, direct, operational, or understandable properties proposed by Keeney and Gregory (2005).

Our initial approach to define and quantify the Red Knot constraint used energetic models to link harvest management decisions to horseshoe crab eggs. Energetics modeling and empirical data suggest that a Red Knot must weigh at least 180 g upon departure from Delaware Bay to survive the rest of the migratory journey to the arctic (Kvist et al. 2001; Piersma 2002; Baker et al. 2004). The objective focused on providing sufficient horseshoe crab eggs for an acceptable percentage of migrating Red Knots to reach 180 g of body mass (Martin et al. 2009; Niles et al. 2009). Stakeholders also desired to incorporate a temporal component to account for migration timing, arguing that problems for migrating shorebirds, especially Red Knots, could be occurring elsewhere in the migration route leading birds to arrive in the bay late and in poor condition. Such birds might not be able to attain needed body mass, regardless of the abundance of horseshoe crab eggs. The JTC agreed that the objective should focus on whether a specified percentage of birds arriving early in the Bay reached 180 g. If so, then the horseshoe crab harvest should be given full value. The objective statement following this modification read:

Maximize allowable harvest of horseshoe crabs with the constraint that 90 % of early arriving Red Knots reach 180 g by May 28th (Breese et al. 2007).

This objective statement links horseshoe crab and Red Knot populations by isolating the influence of horseshoe crabs, through their eggs, on Red Knot weight gain during stopover. However, the revised objective statement remains problematic for several reasons. First, measuring the percentage of the population that reaches the mass threshold is very difficult since birds are likely to depart the stopover site once they have achieved sufficient mass. Therefore, monitoring efforts would not be able to accurately measure the proportion of birds over 180 g, because many of the birds over 180 g might be unavailable for sampling; thus, the objective does not meet the operational property (Keeney and Gregory 2005). Second, the "early arriving" component of the statement is ambiguous. Attempts to define "early arrival" precisely led to disagreement about how much time birds need to gain sufficient weight, which is a function of food availability and thus the timing of the horseshoe crab spawning migration (Smith and Michels 2006). Because of these difficulties, this attribute of the objective statement was ambiguous and difficult to understand. Additionally, because of the issue of imperfect detection, measuring arrival time at a stopover site for migrating birds is difficult and highly uncertain (nonoperational). Lastly, and most importantly, the measurable attributes of the statement (% of the population above a mass threshold) are indirect and not expressed in terms of metrics that stakeholders truly cared about, namely, horseshoe crab harvest and Red Knot abundance. The revised objective statement implied that the Red Knot population could decline, but as long as at least 90 % of the remaining population reached 180 g, then the management objective would be achieved. Furthermore, if only a small proportion of birds arrived "early" the objectives would be met if most of these birds achieved the constraining mass threshold, even if this number represented a small proportion of the entire migratory population. Clearly, that was not the intended outcome of management, nor consistent with the initial qualitative objective statement.

The JTC continued to revise the objective statement so that it directly referenced Red Knot population size, because shorebird advocates desired to recover Red Knot populations to some historic abundance level. This modification reduced ambiguity, increased understandability, and put the associated attribute on a natural scale. The JTC explored a population viability approach to identifying a recovered population. A population simulation model (McGowan et al. 2011a) was used to find the population size required to reduce the risk of extinction for Red Knots to be less than 1 % over the next 100 years. However, reducing or nearly eliminating extinction risk did not meet the shorebird advocates' "recovery" objectives. The shorebird advocates desired to restore Red Knot populations to an abundance level equivalent to population sizes observed prior to the steep declines of the late 1990s. Concurrently, some participants noted that using Red Knot abundance as the only constraint on valuing horseshoe crab harvest exacerbated the risk of forgoing crab harvest if crab populations are not in fact limiting Red Knot populations. For example, effects of climate change on arctic nesting grounds or factors in places and times other than the stopover in Delaware Bay could contribute to Red Knot population declines (Karpanty et al. 2011; McGowan et al. 2011b; Fraser et al. 2013). If that hypothesis was correct, management actions to control horseshoe crab harvest would have no or limited capacity to achieve Red Knot management objectives, and horseshoe crab harvest would be unnecessarily restricted. The JTC agreed that there needed to be a mechanism to value horseshoe crab harvest if the crab population was large enough to sufficiently reduce the risk that food resources would not be limiting Red Knot population growth. In addition, the commercial industry, particularly the whelk industry, desired to decouple male harvest from the Red Knot population constraint, arguing that female crabs, not the males, produce the eggs that knots use as food. A second utility threshold applied to horseshoe crab populations was proposed for harvest of female horseshoe crabs if the crab population reached at least 80 % of carrying capacity based on population modeling (Sweka et al. 2007).

In March 2009, the JTC agreed to the following objective statement: *Maximize harvest of horseshoe crabs in the Delaware Bay with constraints that (1) harvest of female crabs is valued only when Red Knots exceed an abundance threshold* ***or*** *female horseshoe crabs exceed an abundance threshold. Below both thresholds, female HSC harvest has no value, and above either thresholds, female HSC harvest has full value; and (2) Harvest of males is valued only when additional males in the population will not increase HSC population growth rate*. This statement takes major strides toward meeting the unambiguous, operational, and direct properties of "good" attributes for an objective function (Keeney and Gregory 2005). The first part of the statement outlines the two utility threshold approaches based on population abundance for Red Knots or female crabs. This is an "or" conditional statement whereby if one or the other condition is met (i.e., one threshold or the other is exceeded) female harvest has value. When neither condition is met, female horseshoe crab harvest is not valued. The objective function defining under what conditions female horseshoe crab harvest is valued can be represented mathematically:

$$u_{\mathrm{HCF}} = \begin{cases} 1, & \text{if} N_{\mathrm{RK}} \geq N_{\mathrm{RK,c}} \quad \text{or} \quad \text{if} N_{\mathrm{HCF}} \geq N_{\mathrm{HCF,c}} \\ 0, & \text{otherwise} \end{cases}$$

where N_{RK} is the Red Knot population size, N_{HCF} is the female horseshoe crab population size, and the subscript c indicates a utility threshold population size (Martin et al. 2009). The term u_{HCF} is the utility of female harvest, and it is used as a multiplier in a reward function for the optimization analysis. For example,

$$R = u_{\mathrm{HCF}} H_{\mathrm{HCF}},$$

where R is the reward, and H_{HCF} is the number of female crabs harvested. An optimization analysis searches for the set of harvest policies that maximize the reward function, R.

The JTC also included a performance measure for crab sex ratio to address the concern that female-biased sex ratios could reduce crab population growth rates. The JTC believed that maintaining the population sex ratio at or above some male to female ratio would ensure that population growth is not limited by male abundance. This conclusion was based on published experiments on horseshoe crab fertility (Brockmann 1990; 2003), comparisons of adult sex ratios observed during spawning surveys and offshore trawl surveys of the Delaware Bay population (Smith and Michels 2006), equilibrium sex ratios in population models, and sex ratios in unharvested populations (Tauton Bay, ME and Seahorse Key, FL; Brockmann and Johnson 2011). Initially, there was disagreement on the sex ratio required for full fertilization of all the available female crabs. Some argued that an operational sex ratio (sex ratio observed on the spawning beach) should be at least 2:1 males to females, and others argued for 3:1. The 3:1 sex ratio argument was rooted in risk aversion and not scientific analysis. To accommodate this risk attitude, we created a sex ratio utility function where below 2:1 males to females, harvest utility was zero, above 3:1, harvest utility was 1, and in between 2:1 and 3:1, there was a sloped lined that added utility as sex ratio increases. However, we found through simulation that this linearly increasing utility function led to harvest policy recommendations that would allow female crab harvest even at abundance levels far below the utility thresholds for female harvest described above. With the gradually increasing utility function, the optimization routine recommended policies that would lead to male-skewed populations (i.e., harvesting females below the female utility thresholds described above), thereby increasing reward from male harvest. To avoid harvest of female crabs when the population is below the female crab threshold, we decided to use a simple knife edge utility function whereby below a 2:1 male to female operational sex ratio, harvest had zero utility and above it, harvest had a utility of one.

From the objective statement above, the JTC developed a conditional utility function for male harvest similar to the one developed for female harvest:

$$u_{\mathrm{HCM}} = \begin{cases} 1, \text{ if } \dfrac{N_{\mathrm{HCM}}}{N_{\mathrm{HCF}}} \geq r_{\mathrm{c}} \\ 0, \; if \; \dfrac{N_{\mathrm{HCM}}}{N_{\mathrm{HCF}}} < r_{\mathrm{c}} \end{cases}$$

where u_{HCM} is the utility of male crab harvest, N_{HCM} is male crab abundance, and r_{c} is the minimum sex ratio required to ensure full fertilization of deposited eggs. With this second male-focused utility function, the total reward function expanded to include utility from male harvest:

$$R = u_{\mathrm{HCF}} H_{\mathrm{HCF}} + u_{\mathrm{HCM}} H_{\mathrm{HCM}}.$$

The sex ratio constraint on male harvest was designed to allow harvest of males as long as the horseshoe crab population (and implicitly the Red Knot population) was growing toward the desired population thresholds. Specifically, sex ratio is intended to provide a measure of whether males are extraneous to population growth. Population growth rate itself may be a more direct measure; however, it is a retrospective metric, and using it as a performance measure to define the male harvest utility threshold was not possible because, to inform decision making, we needed to know current or future (not past) population growth. In that sense, using population growth rate as a performance measure is nonoperational (Keeney and Gregory 2005).

Agreeing upon specific population sizes and minimum sex ratio for the utility thresholds would be the last step to meet the unambiguous criterion for "good" attributes (Keeney and Gregory 2005). The agreed-upon objective statement utility functions reflected the tendency for the JTC to be risk averse with respect to Red Knot population viability. The group was attempting to avoid risk to Red Knots by valuing harvest constrained by Red Knot population thresholds. The perceived risks differed by stakeholder group in that the commercial horseshoe crab industry wanted to minimize the risk of unnecessarily limiting harvest, and the shorebird advocates wanted to minimize the risk of limiting Red Knot recovery.

Discussion

By following an SDM process, stakeholders have developed an objective statement that seeks to maximize horseshoe crab harvest but constrains harvest by Red Knot "recovery" targets, while managing risk resulting from ecological uncertainty about the links between Red Knot populations and horseshoe crab populations. There remains some dispute and discussion over the exact numerical values of the utility thresholds. Regardless, the ARM framework incorporated the concerns of the stakeholder groups and the ecological uncertainty surrounding the relationship between horseshoe crabs and Red Knots. The objective statement incorporated the fundamental objectives of maximizing harvest while constraining harvest by the Red Knot population and indirectly trying to restore Knots to some historic level of stopover population size in Delaware Bay. The objective statement also identifies clear performance measures, such as, population size and sex ratio, rather than immeasurable (nonoperational) or ambiguous terms, such as, ecosystem integrity.

Red Knot population size serves as a proxy metric for migratory shorebird species that rely on horseshoe crabs in the Delaware Bay ecosystem. Proxy attributes may not be a direct measure of fundamental objectives (Keeney and Gregory 2005). However, the umbrella species concept, which in this case assumes that Red Knots are representative of the shorebird community's needs, is widely used in multi-species conservation efforts (Wiens et al. 2008). Using an umbrella species inherently introduces an additional layer of uncertainty to our decision analysis because the fundamental objective is to conserve ecological integrity of Delaware Bay, and we are assuming that Red Knot abundance is a reasonable measurable attribute of ecological integrity. In theory, umbrella species provide a useful way to manage for multiple species or ecological communities by conserving a single species, but evidence indicates that in practice, the assumptions may not be met (Fleishman et al. 2001; Roberge and Angelstam 2004). Given that uncertainty, it is possible that management actions could ultimately succeed in achieving Red Knot target population sizes, but it fails to secure the ecological integrity of the Bay. Female horseshoe crab abundance and harvest rates serve as a direct, operational, unambiguous, understandable, and comprehensive attribute of the horseshoe crab harvest and population objectives. Horseshoe crab sex ratio serves as a proxy but natural metric to measure crab fertilization and population growth rates. All of these individual attributes when combined address the fundamental concerns expressed by the stakeholders.

There were two essential factors that allowed us to arrive at a complete and unifying multi-objective statement with these sometimes adversarial stakeholder groups. First, it was critical to establish objectives in isolation of other parts of the decision process, i.e., decompose the decision structure into discrete components following the recommendations of Gregory and Keeney (2002) and Gregory et al. (2012). Stakeholders may attempt to simultaneously consider management alternatives, models of system response and effects of decision thresholds, while defining management objectives (Gregory and Keeney 2002). If objectives are not developed in isolation of other parts of the decision process, the objective statement may be corrupted by hidden objectives designed, for example, to avoid a particular management action that is perceived to be undesirable (Gregory and Keeney 2002, Gregory et al. 2012). Hidden objectives reduce transparency of the process and frequently lead to actions that are suboptimal with respect to the objectives of at least some stakeholders. In our case, through much of the objective setting process described here, there was a tendency among some stakeholders to attempt to design a process that would ensure a particular policy, e.g., harvest moratorium or high harvest. Second, it was critical to emphasize that objectives are not scientifically based, but rather should reflect the values, desires, and preferences of stakeholders. The "stopover population restoration" concept was selected in our case because it more accurately reflected the preferences of shorebird advocates than the “extinction risk” concept, which relied more on available science. A failure to focus discussion on preferences and define objectives based on stakeholder values, separate from scientific concepts, may lead to unsatisfied stakeholders even if management is successful with respect to a stated “scientific” objective (Arvai et al. 2001; Keeney 1992; Pielke 2007; Kiker et al. 2005). In decision making for natural resource management, science can guide decision making through data analyses and building predictive models to evaluate management actions, but over-reliance on science when setting objectives can impede value-focused decision making (Pielke 2007). Value-focused thinking increases the probability that stakeholders and participants will be satisfied with a decision process and outcome (Keeney 1992). The process required patience and repetition of the points that discussion and definition of management objectives are not a science-based discussion but a value-based discussion. We think that in the end, we elicited the honest desires of all participating stakeholders and that those values are effectively captured using measurable attributes in our final objective statement and utility functions.

Participants need to enter into this type of process with the understanding that all stakeholder groups' objectives should be part of the analysis. Stakeholders likely do not, and do not need to, approach collaboration from the stand point of maximizing everyone's objectives given tradeoffs, but rather—quite naturally—approach collaboration as a means to meet their own objectives (Wondolleck and Yaffee 2000). However, as was the case here, as long as all stakeholders permit others' objectives to be part of the analysis (i.e., no objective weights = zero), then the SDM process provides the credible framework for common understanding and trust to emerge (Kirkwood 1997; Wondolleck and Yaffee 2000).

Our process allowed us to manage risk resulting from “ecological uncertainty” (e.g., the sex ratio utility threshold on male crab harvest). In decision making for natural resource management, ecological uncertainty is often addressed through multiple system models and formal adaptive management (Nichols et al. 2007). Our decision-making framework already included multiple system models representing uncertainty about the biological mechanisms linking crab and knot populations; computational limitations prohibited additional models to reflect every source of ecological uncertainty we identified in this system (Smith et al. 2013). Nevertheless, these sources of uncertainty were important considerations for some stakeholders. Our risk management using utility functions reflects the JTC's desire to avoid risk of extinction for Red Knot and risk of over harvest of horseshoe crab populations. Risk aversion compromises also occurred when the stakeholders agreed to include a second utility threshold on female crab harvest value, given the uncertainty in the relationship between crabs and knots and avoiding the risk of under harvesting crabs. We do not expect that risk management via utility functions will limit our capacity to manage the system effectively or learn about system function (i.e., the interaction between horseshoe crabs and Red Knots) through adaptive management. This strategy enabled us to avoid computational limitation in optimization software but much more importantly, we believe that incorporating risk aversion into the objective function enhanced the stakeholders' willingness to compromise and greatly furthered the SDM process.

Performance measures or measurable attributes in an objective statement are necessary to evaluate the success or failure of management actions, determine if the objectives have been met, and enable improvement of management and decision making in the future (Keeney and Gregory 2005). In our case, the attributes selected and defined in this paper represent the management objectives and serve as criteria by which success of management can be evaluated. In an adaptive management approach, such as the horseshoe crab harvest management problem (McGowan et al. 2011a), these metrics form the basis for identifying optimal actions.

The next steps were to take the agreed-upon objective statement, develop a list of alternative management actions, develop predictive models of the system to predict how each alternative is likely to affect the system, and determine which alternative best meets the management objectives, and finally evaluate ARM framework performance (Williams et al. 2007; McGowan et al. 2009; McGowan et al. 2011a; Smith et al. 2013). In the case of the Delaware Bay, in dealing with tremendous ecological uncertainty and complexity (e.g., McGowan et al. 2011a), the modeling and the evaluation required stochastic dynamic programming, an optimization analysis for recurrent decision problems, in order to evaluate the management alternatives (Lubow 2001; Nichols et al. 2007; Williams et al. 2007; McGowan et al. 2011a). Much of this work is ongoing in collaboration with the stakeholder groups that delineated the objective statements (McGowan et al. 2009; McGowan et al. 2011a; Smith et al. 2013).

Acknowledgments We thank the members of the Atlantic States Marine Fisheries Commission Horseshoe Crab Technical Committee, USFWS Shorebird Technical Committee, and the Management Board for their participation in and support of this process. We are grateful to the members of the Delaware Bay Adaptive Management Modeling Work Group (J. Brust, L. Niles, K. Kalasz, J. Sweka, R. Wong, J. Nichols, M. Kopfler, and B. Spear). We also thank the USGS and the National Fish and Wildlife Foundation for financial and logistic support of this work. Lastly, we thank C.T. Moore and other reviewers and editors of this paper for helping revise and improve this manuscript.

The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

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