Application of Structured Decision Making to Multi-Species Management of Horseshoe Crab and Shorebird Populations in Delaware Bay

A Case Study from the Structured Decision Making Workshop
9-13 July 2007
National Conservation Training Center, Shepherdstown, WV, USA

Authors: Greg Breese[1], Dave Smith[2], Jim Nichols[3], Jim Lyons[4], Anne Hecht[5], Nigel Clark[6], Stew Michels[7], Mike Millard[8], Annette Scherer[9], Brad Spear[10], Donna C. Brewer[11], Anthony M. Starfield[12], Michael C. Runge[13].

During July 9-13, 2007 a training workshop on application of structured decision making (cf. Hammond et al. 1999) to conservation problems was held at the USFWS National Conservation Training Center. The workshop provided training on rapid prototyping a complex problem as a technique to get started on structured decision making. The workshop included four teams who worked separately on case studies representing real-world conservation problems. A team of managers and researchers involved in the management of horseshoe crabs (*Limulus polyphemus*) and migratory shorebirds in Delaware Bay participated in the workshop to learn about structured decision making and to work through an example. This report documents the example that the team worked through and produced. While we believe components of this rapid prototype can be usefully built upon, this product should be viewed only as a possible starting point.

Decision Problem

The overall problem can be divided into four decisions involving 1) harvest regulation, 2) shoreline protection, 3) control of disturbance, and 4) endangered species status.

On a periodic basis, the Atlantic States Marine Fisheries Commission (ASMFC) and member states regulate harvest of horseshoe crabs within Delaware Bay and along the Atlantic coast by level, area, and season consistent with continued use by current and future generations of the fishing and non-fishing public, migrating shorebirds, and other dependent wildlife, including federally listed sea turtles.

On a periodic basis, state agencies in New Jersey and Delaware decide where and how to protect shorelines within Delaware Bay using shore-parallel structures (e.g., bulkheads) and beach nourishment.

[1] USFWS Delaware Bay Estuary Project, Smyrna, DE, Gregory_breese@fws.gov
[2] USGS, Leetown Science Center, Kearneysville, WV, drsmith@usgs.gov
[3] USGS, Patuxent Wildlife Research Center, Laurel, MD, jim_nichols@usgs.gov
[4] USFWS, Migratory Bird Office, james_lyons@fws.gov
[5] USFWS, Endangered Species Office, Sudbury, MA, anne_hecht@fws.gov
[6] British Trust for Ornithology, Norfolk, UK, Nigel.clark@bto.org
[7] DE DFW, Dover, DE, stewart.michels@state.de.us
[8] USFWS, Northeast Fishery Center, Lamar, PA, mike_millard@fws.gov
[9] USFWS, New Jersey Field Office, Pleasantville, NJ, Annette_scherer@fws.gov
[10] ASMFC, Washington DC, bspear@afmsc.org
[11] USFWS National Conservation Training Center, Shepherdstown, WV, USA
[12] University of Minnesota, St. Paul, MN, USA
[13] USGS Patuxent Wildlife Research Center, Laurel, MD, USA

On a periodic basis, state agencies in New Jersey and Delaware decide whether and how to control disturbance of migrating shorebirds during the stopover. Sources of disturbance can be human or non-human.

In an ongoing process, the USFWS reviews the status of the red knot (*Calidris canutus rufa*) and the immediacy and magnitude of threats to the species to determine whether and how urgently listing as a threatened or endangered species under the Endangered Species Act is warranted.

Concern over the decline of shorebird populations using Delaware Bay, coupled with a decline in the horseshoe crab population during the mid 1980s through the late 1990's when harvest rates increased dramatically, led to a series of harvest restrictions and intense debate. In 2006, ASMFC implemented a two-year, "male only" harvest; see Addendum IV to the Interstate Fishery Management Plan for Horseshoe Crab for the full set of restrictions. This "male only" harvest under the ASMFC sets a minimum standard that the states need to meet; the states can be more restrictive if they choose. NJ and DE chose to enact a full moratorium for two-years, though recently DE's was overturned in court. The timing and frequency of the states' regulations are limited only by their own internal regulatory processes and timelines. By September 2008, the ASMFC must decide whether to let the two-year restrictions (Addendum IV) expire or continue in some form.

Background

Legal, regulatory, and political context

Starting in the late 1990s New Jersey and Delaware began restricting harvest of horseshoe crabs due to concern over their perceived decline due to overharvest and the need for eggs by migratory shorebirds. In addition the states requested help from the Atlantic States Marine Fisheries Commission (ASMFC) in regulating this inter-jurisdictional species.

The ASMFC adopted a Fishery Management Plan for the Horseshoe Crab in 1998, which included a requirement that NJ and DE maintain their recently reduced harvest. The Atlantic States Marine Fisheries Commission was formed by the 15 Atlantic coast states in 1942. The Commission serves as a deliberative body, coordinating the conservation and management of the states shared near shore fishery resources for sustainable use. The goals of the Fishery Management Plan for Horseshoe Crab are to "…provide for their continued use by: 1) current and future generations of the fishing and non-fishing public, 2) migrating shorebirds, and 3) other dependent wildlife, including federally listed sea turtles". There are several important constraints to meeting these goals:

1) Lack of historical perspective on the size of sea turtle, shorebird, and horseshoe crab populations.
2) The 9-12 years needed for horseshoe crabs to reach maturity means management actions on the spawning population will result in changes to recruitment to the breeding population a decade or more later. [Note: One effect of the Shuster reserve was to protect pre-recruits and new-recruits from harvest. Thus, the resulting 'time lag' to see a population effect of the reserve was potentially much shorter than the 9-12 years.]

3) While the parameters related to egg consumption by shorebirds and how many eggs are needed to increase shorebird body mass are known, it is still uncertain how many and what density of spawning horseshoe crabs are needed to support a given number of shorebirds. First, habitat use by horseshoe crabs and shorebirds must coincide spatially and temporally. The timing of spawning is known to vary annually due to temperature and weather variations, whereas shorebird migration is more predictable. Although horseshoe crabs are widely distributed throughout Delaware Bay, shorebirds forage on only a subset of spawning beaches. Second, the proportion of deposited eggs that become available to shorebirds is affected by density of spawning crabs and wave energy. Eggs that reach surface sediments due to bioturbation are rapidly exhumed and transported within the swash. Also, eggs exposed on sediment surfaces dry out, are consumed by other birds, fish and other organisms, and are washed away without being consumed. Finally, disturbance by people, gulls, and other factors can disrupt foraging activity, reducing the ability of shorebirds to make optimum use of available eggs.
4) Some portion of the shorebird population in recent years appears to be arriving late which suggests that the South American stopovers may be playing a role in shorebird population decline. It is unknown how much of a role this may play in shorebird weight gain in any given year.
5) There is little quantitative data on the South American stopover, wintering, and breeding ground quality for shorebirds.

In 2000, the ASMFC further reduced State quotas for horseshoe crabs harvested for the bait industry by 25% from the agreed upon Reference Period Landings; sponsored a bait workshop, and recommended a no harvest zone.

In 2001, NOAA established a 1,500 square mile no-take sanctuary at the mouth of Delaware Bay (i.e., the Carl N. Shuster, Jr. Horseshoe Crab Reserve).

In 2003, the State of New Jersey implemented restrictions on hand harvest of horseshoe crabs and closed key Delaware Bay spawning / foraging beaches to public access. The State of Delaware implemented similar regulations for the 2004 fishing season.

In 2004 the ASMFC further reduced quotas in the states of New Jersey, Delaware, and Maryland along with a seasonal harvest restriction based upon findings from the Shorebird Technical Committee.

In 2005, the States of New Jersey and Delaware took additional regulatory action to ensure that the horseshoe crab harvest did not adversely impact the red knot or other migratory shorebirds. In addition to the regulations already in effect for 2005, and in response to the late arrival of the red knots in Delaware Bay, New Jersey imposed an emergency moratorium temporarily halting the hand harvest of horseshoe crabs until June 23, 2005, to allow the birds continued unencumbered access to foraging areas.

The State of Delaware also supplemented its regulations in 2005 by instituting mandatory horseshoe crab check stations, in addition to its established mandatory reporting requirement.

Although the horseshoe crab harvest season in Delaware was scheduled to remain open until June 30, the State reached its 150,000 quota earlier, closing all harvest effective June 24, 2005. Delaware closed the harvest season from May 1 to June 7, 2006.

In the fall of 2005, the States of Delaware and New Jersey addressed the ASMFC and proposed a 2-year moratorium on horseshoe crab harvest in the Delaware Bay. The Board approved the following harvest restrictions effective from October 1, 2006 to September 30, 2008: (1) for New Jersey and Delaware there is a prohibition on harvest and landing of horseshoe crabs from January 1 through June 7, harvest of males only is allowed from June 8 through December 31, and harvest is limited to no more than 100,000 male horseshoe crabs per state per year; (2) in Virginia, the harvest season is closed from January 1 through June 7, no more than 40% of harvest can be from outside state waters, and there is a minimum male to female ration of 2:1; and (3) in Maryland the season is closed from January 1 through June 7. NJ and DE chose to enact a full moratorium for two-years, though recently (June 2007) DE’s was overturned in court and consequently DE is presently operating under regulations consistent with Addendum IV. NJ’s two-year moratorium preceded the adoption of Addendum IV and is presently set to expire in December 2007.

There has been discussion about the role of the Migratory Bird Treaty Act and the Atlantic Flyway Council in this arena. The Migratory Bird Treaty Act (40 Stat. 755; 16 U.S.C. 703-712) (MBTA) is the only current federal protection provided for the red knot. The MBTA prohibits “take” of any migratory bird, which is defined as: “to pursue, hunt, shoot, wound, kill, trap, capture, or collect, or attempt to pursue, hunt, shoot, wound, kill, trap, capture, or collect.” However, other than for nesting sites, which are not located in the United States, the MBTA provides no authority for protection of habitat or food resources. Human disturbance is cited as one of the major threats to red knots throughout it migratory range within the United States. The MBTA does not afford shorebirds protection from human disturbance on migratory and wintering areas. The Atlantic Flyway Council’s historic focus has been on waterfowl and other harvested species. Recently the Council has been considering its role in relation to non-game species, and shorebirds specifically.

The US Fish and Wildlife Service has responsibility for administration of the Endangered Species Act. Through the Listing Program, the Service determines whether to add a species to the Federal lists of endangered and threatened wildlife and plants. Species awaiting listing are considered candidate species and do not receive substantive or procedural protection under the Act. Once listed, a species is afforded the full range of protections available under the Endangered Species Act, including prohibitions on killing, harming, harassing, or otherwise "taking" a species. In some instances, species listing can be avoided by the development of Candidate Conservation Agreements which remove threats facing the candidate species. The US Fish and Wildlife Service recently completed an internal candidate species status review for the red knot and in August 2006 concluded that listing the red knot was warranted, but precluded by higher priority listing actions. Concurrent with the Service’s review, three petitions were filed requesting that the Service consider immediate emergency listing for the red knot. The Service determined that emergency listing was not warranted, in large part due to abatement of threats through conservation actions implemented by the ASMFC and the states of DE and NJ. A lawsuit has been filed against the Service regarding its emergency listing decision.

Non-governmental shorebird conservation organizations have been very vocal participants in the debate, primarily in support of reduced or eliminated horseshoe crab harvest. Commercial watermen and seafood processors have been equally active in supporting a continued fishery at some level.

There have been various efforts aimed at modeling the dynamics of horseshoe crabs or shorebirds separately (see below). To date, a multi-species model that explicitly relates the species' dynamics has not been developed. However, a conceptual model has been developed, which incorporates basic components and factors.

Existing species-specific models for horseshoe crab population dynamics include:

1) HCrab Age (Stage) Structured Model
2) HCrab Surplus Production Model
3) HCrab Catch-Survey Model (proposed)

In addition, there has been an effort to model horseshoe crab nest disturbance as a function of spawning density, which is an important component of the process that determines egg availability for shorebirds.

Existing species-specific models for shorebird population dynamics and behavior include:

4) SESA vs LESA Weight Gain Comparison
5) Stillman Behavioral Model
6) Wintering Area Specific Red Knot Survival Models
7) Pradel Recruitment Models from Banding Data
8) Ruddy Turnstone & Sanderling Survival Models
9) Shorebird Stopover Duration Analysis

Monitoring programs that provide data for building and evaluating predictive models include:

10) HCrab Spawning Survey
11) HCrab Trawl Survey
12) DE Bay Trawl Surveys
13) HCrab Tagging Studies
14) HCrab Egg Availability Survey
15) Shorebird Weight Gain (# Reaching Threshold Weight)
16) TdF Winter Shorebird Survey
17) 10% Individually Marked Shorebird & Resighting
18) Delaware Bay Shorebird Aerial Survey

Ecological context

Delaware Bay hosts the largest spawning population of horseshoe crabs in the world and the second largest population of migrating shorebirds in North America. Delaware Bay is designated within the Western Hemisphere Shorebird Reserve Network as having the highest reserve status. Over eighty percent of the Western Hemisphere's population of red knot depends upon horseshoe crab eggs to double their weight in two weeks before flying to the Arctic to nest. These migrants depend on the eggs of spawning horseshoe crabs for a major portion of their diets

(50 to 90 percent) each spring before migrating from the Delaware Bay beaches to Artic nesting grounds. The vast majority of HSC eggs utilized by shorebirds are eggs which have been brought to the surface via physical and biological processes and thus would not have contributed to HSC production in the absence of bird predation.

In addition to providing the principal food source for migratory birds in Delaware Bay, horseshoe crabs are believed to be an important part of juvenile loggerhead turtle diet in the Chesapeake Bay and nearby coastal waters, with some studies of gut contents indicating that horseshoe crabs were the most common item found (Lutcavage and Musick 1985). Loggerhead turtles are federally listed as threatened under the Endangered Species Act; principal responsibility for the species is vested with the National Marine Fisheries Service.

Migratory shorebirds on the Delaware Bay beaches have declined in recent years. The local threats that have been identified include reduced food availability, human disturbance, predation, loss of sandy beaches and suitable roost sites, and risk of oil and hazardous materials spills. The high harvest of horseshoe crabs through the late 1990s has reduced the crab population and may have led to declines in migratory shorebirds including red knot, sanderling (*Calidris alba*), semipalmated sandpiper (*Calidris pusilla*), ruddy turnstone (*Arenaria interpres*). Human disturbance associated with recreation is another serious threat to migratory shorebirds. A significant threat to habitats here is risk of oil and hazardous materials spills: Delaware Bay is the second largest port for oil transport on the East coast, so oil spills (such as the Athos I in 2004) are a documented threat to habitats and animal populations. Erosion of beaches and roosting “islands” has been an ongoing concern, potentially affecting their suitability and use by spawning horseshoe crabs, with the potential to cause a decline in egg development. Shoreline loss due to bulkheads and jetties is also a concern. Some beach area has been restored by beach replenishment operations, and work is underway to improve the design for horseshoe crab and shorebird needs.

Given the vast migration of red knots, there are also documented and potential threats in other parts of the red knot’s range in the Western Hemisphere. Threats include variations in habitat conditions in Arctic breeding areas and variations in habitat conditions, adverse habitat alteration within wintering habitats and South American stopovers and changing wind patterns during migration. Climate change could be playing a role in any or all of these as well, affecting such factors as snow melt, temperature, and food resources. In addition, oil and other development in South America wintering and stopover areas potentially threaten the populations with pollution. Conversion of shoreline in northern South America and harvesting of shorebirds for human consumption have also been raised as potentially important factors. Most importantly, weight gain data at Delaware Bay indicates that a portion of the population has arrived later in recent years. The reason for this late arrival, and the role it plays in survival and breeding success is not known. The Shorebird Technical Committee and Peer Review Panel concluded that late arrivals and egg abundance were probably factors that worked together and varied in importance from year to year.

See U.S. Fish and Wildlife Service Species Assessment and Listing Priority Assignment Form for further information (http://ecos.fws.gov/docs/candforms_pdf/r5/B0DM_V01.pdf).

Decision Structure

Alternative actions

Potential management actions include 1) regulating harvest, 2) habitat management, 3) control of disturbance both human and non-human, and 4) listing of red knot as an endangered species.

1) Alternative harvest actions include level of harvest for males and/or females, how long to maintain the moratorium, when and how (gear type) to harvest within the season (e.g., no harvest prior to 7 June), and how to regulate biomedical harvest.
2) Alternative habitat management actions include beach nourishment, mitigating effects of shoreline protection, and creating habitat for 'hot spots'.
3) Alternative disturbance-control actions include control of human disturbance through periodic beach closure, and control of red knot predators and competitors.
4) Alternative actions under the ESA include whether or not to list red knot as a threatened or endangered species and whether a higher or lower listing priority is warranted.

In this initial exercise, we chose to focus on harvest of females as the management action of interest. Consideration of different actions would lead to different statements of the objective function (e.g., different ways of expressing costs of other management actions) and different models that included the effects of these other actions.

Objectives

Objective statement (qualitative): Ensure sufficient eggs for shorebirds, including red knots, taking into account environmental uncertainty while allowing surplus horseshoe crabs to be harvested.

Objective statement (quantitative): Maximize allowable harvest of horseshoe crabs with the constraint that 90% of early arriving red knots reach 180g by 28 May. [Comment: The 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 the stopover.]

Objective function:

$$\max \sum_{t=1}^{\infty} u_t H_t$$

where

u_t = Utility of harvesting horseshoe crabs, which is a function of whether there are sufficient eggs for red knots

H_t = Number of horseshoe crabs harvested

The time-specific harvest utility (u_t) is a function of red knot weight gain and population size relative to a recovery threshold. For example, while red knot population size is below a recovery threshold, the utility becomes 0 when the horseshoe crab population is not likely to result in 90% of early arriving birds reaching adequate weight (e.g.,180g) before a set departure date (e.g., 28 May) from Delaware Bay (Figure 1 and left panel of Figure 2). While red knot population size is above the recovery threshold, the utility is >0 for smaller proportions of knots reaching weight (right panel of Figure 2). Note that this objective function is based on an infinite time horizon. The effect of this long-term view is to assign equal value to current and future harvest, thus incorporating a conservation ethic and a long-term interest in future crab populations and red knot.

Figure 1. Graphical representation of the objective statement. The solid line represents the number of horseshoe crabs required per red knot. The dashed line allows for a margin of safety. The shaded region represents the range of population abundances where HSC harvest could be allowed.

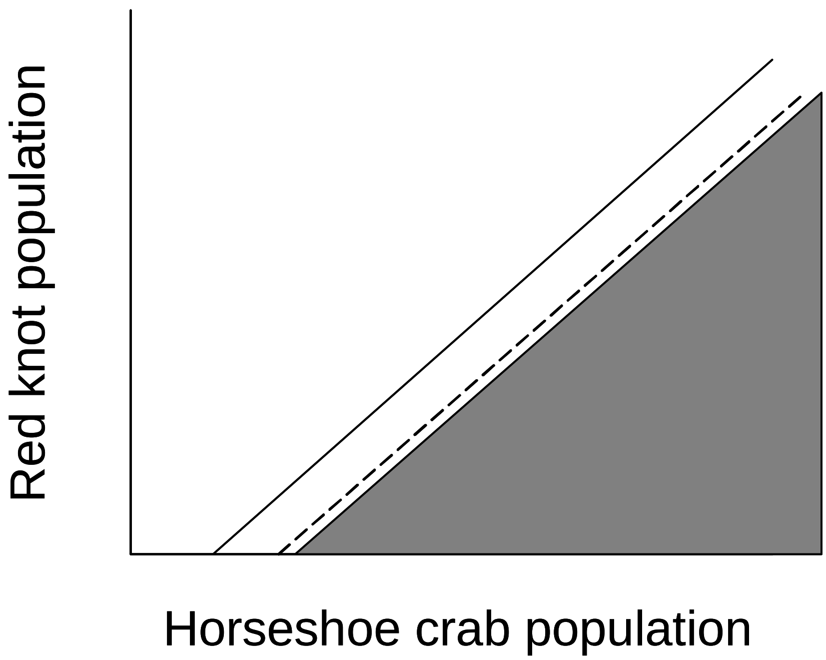
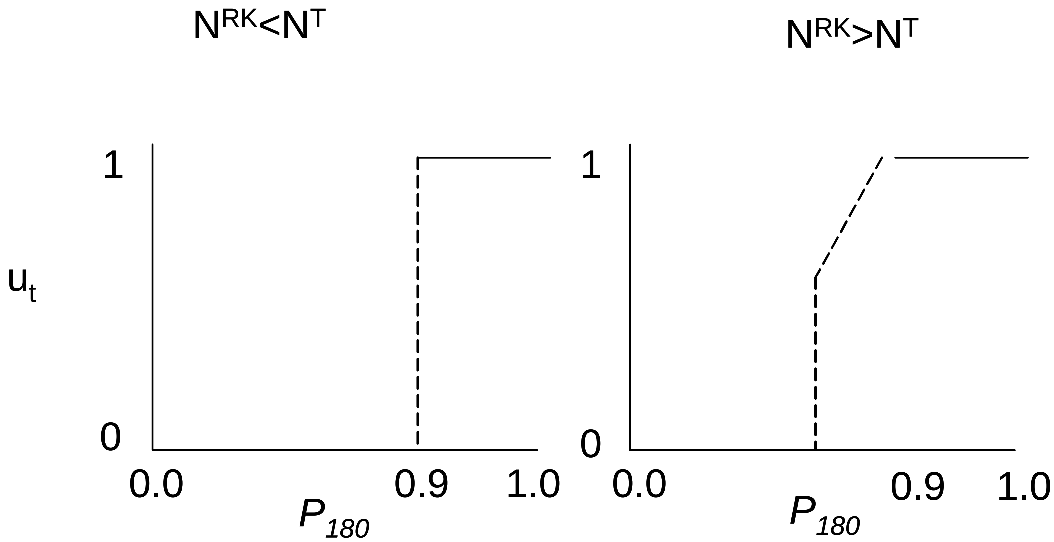


Figure 2. An example of a utility of harvesting horseshoe crabs as a function of the proportion of early arriving red knots that reach 180g by 28 May (P_{180}). The shape of the utility differs if the red knot population (N^{RK}) has reached a recovery threshold (N^{T}). This change in the utility is shown in the difference between the two panels. The left panel is operative when red knot population is below the recovery threshold ($N^{RK} < N^{T}$) and is analogous to Figure 1. The right panel is operative when the red knot population has exceeded the recovery threshold ($N^{RK} < N^{T}$), and some utility is assigned to harvest even when fewer than 90% of the birds are predicted to reach 180g, reflecting the hypothesis that a recovered red knot population can likely tolerate such suboptimal weight gains without jeopardizing the population.



Predictive model

The predictive model has four components:

1) a horseshoe crab population dynamics model,
2) a model that links horseshoe crab abundance to egg availability,
3) a model that links egg availability to the proportion of early arriving red knots that reach 180g by 28 May,
4) a red knot population dynamics model that includes the relationship between the proportion making weight and both red knot adult survival and reproduction.

Figure 3. A schematic of the horseshoe crab component of the model.

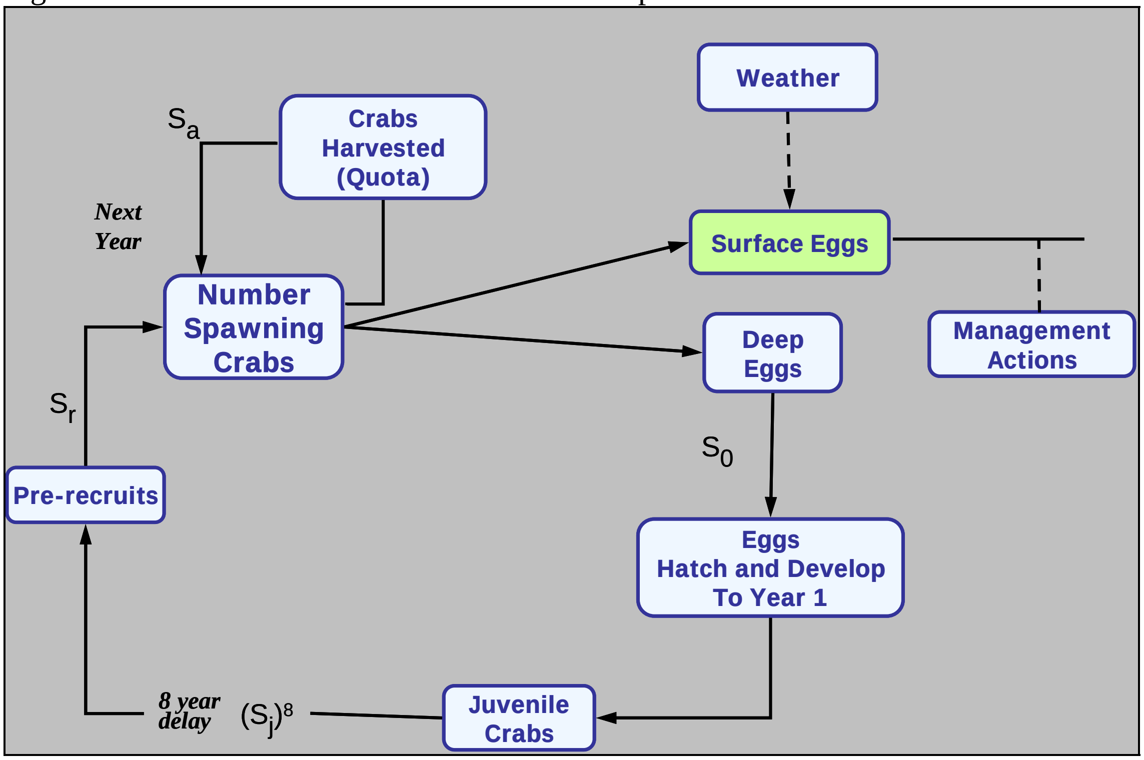
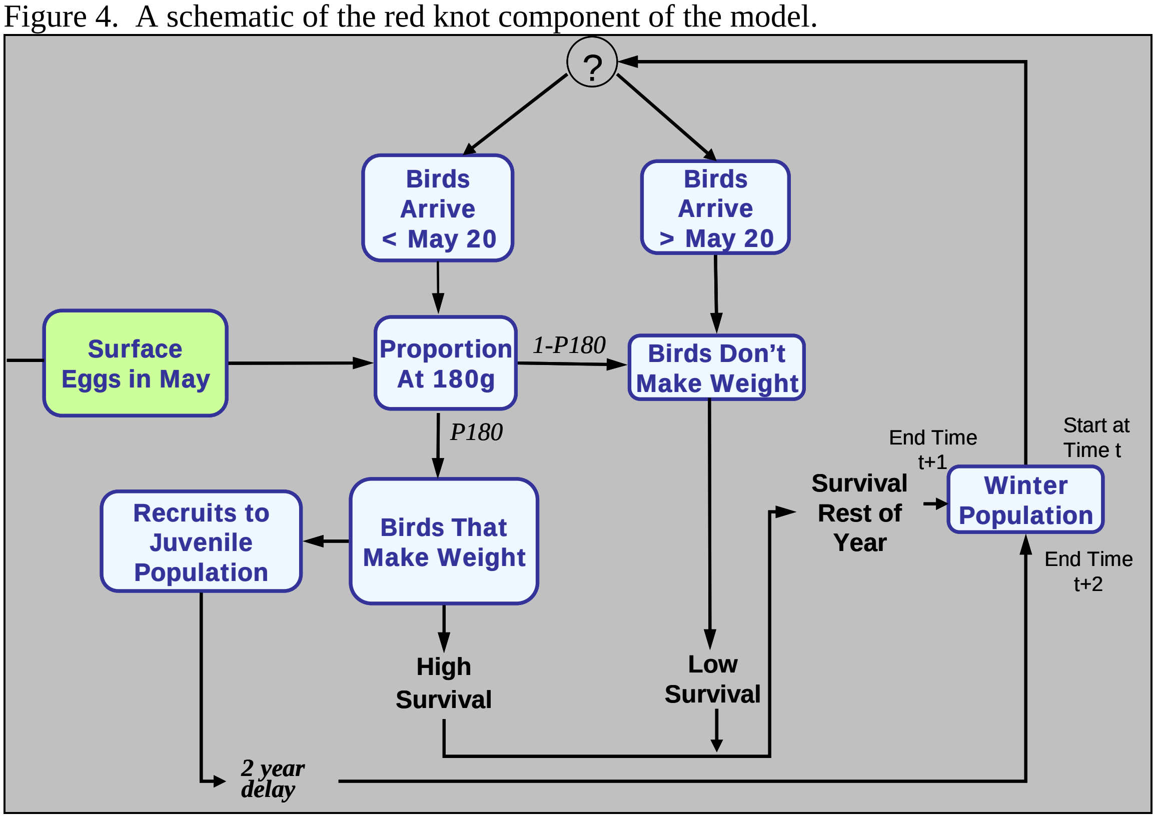


Figure 4. A schematic of the red knot component of the model.



The team developed the model for the special case where the decision focuses on female harvest:

1) HSC population dynamics model

$$N_{t+1}^{HSC} = N_t^{HSC} + f(H_t)$$

2) Model linking HSC abundance to egg availability

$$N_t^{EGGS} = f(N_t^{HSC})$$

3) Model linking egg availability to proportion making weight

$$P_{180,t} = f(N_t^{EGGS})$$

4) Red knot population dynamics model(s)

$$N_{t+1}^{AdRK} = N_t^{AdRK} + f(P_{180,t})$$

where

N_t^{HSC} = Abundance of adult female horseshoe crabs that spawn in Delaware Bay

H_t = Harvest of female horseshoe crabs from Delaware Bay

N_t^{EGGS} = Number of eggs in Delaware Bay available to shorebirds

P_{180} = Proportion of early arriving red knots that reach 180 g by 28 May

N_t^{RK} = Abundance of adult red knots

The horseshoe crab dynamics model is a modification of the catch-survey model, which was endorsed by the Horseshoe Crab Technical Committee (Millard et al. 2000), and a age-structured model developed by Sweka et al. (2007):

$$N_{t+1}^{HSC} = \left(N_t^{HSC} - H_t\right)S_{Ad,t}^{HSC} + R_t^{HSC} S_{R,t}^{HSC}$$

$$R_t^{HSC} = \left(S_{0,t}^{HSC} F^{HSC} \big/ 2 \right) N_{t-10}^{HSC} \left(S_{J,t}^{HSC}\right)^8$$

$$S_{0,t}^{HSC} = \max\left\{1 - \left[b \ln\left(N_{t-10}^{HSC}\right) - a\right], 0\right\}$$

where

$S_{Ad,t}^{HSC}$ and $S_{R,t}^{HSC}$ = Survival rates for female horseshoe crabs that are adult and one - year from maturity, respectively

R_t^{HSC} = Abundance of female horseshoe crabs one - year from maturity

$S_{0,t}^{HSC}$ = Density - dependent survival rate from egg to 1 year old

F = Fecundity

The model linking abundance of female horseshoe crabs and egg availability is based on a simulation study of density-dependent nest disturbance (Smith 2007).

$$N_t^{EGGS} = \gamma * \left(I_t^{HSC}\right)$$

$$I_t^{HSC} = \frac{C * N_t^{HSC}}{A * T}$$

where

γ = The model parameter for the relationship between average number of spawning females per m of shoreline per night and available eggs. The parameter (γ) must be scaled to be relevant to the shorebird models.

I_t^{HSC} = Average number of spawning females per m of shoreline per night as measured by the Delaware Bay spawning survey

C = Average frequency that a spawning female will spawning

A = Amount (m) of shoreline suitable for spawning habitat in Delaware Bay

T = Number of nights in a spawning season

The models linking egg availability to shorebird dynamics are based on results from Atkinson et al. (2003), Baker et al. (2004), Gillings et al. (2007), and Atkinson et al. (2007).

$$P_{180} = \frac{\exp\left(a + b * N_t^{EGGS}\right)}{1 + \exp\left(a + b * N_t^{EGGS}\right)}$$

$$S_{Ad,t}^{RK} = \frac{\exp\left(a_1 + b_1 * P_{180}\right)}{1 + \exp\left(a_1 + b_1 * P_{180}\right)}$$

$$\lambda_t^{RK} = \frac{\exp\left(a_2 + b_2 * P_{180}\right)}{1 + \exp\left(a_2 + b_2 * P_{180}\right)}$$

$$N_{t+1}^{RK} = N_t^{RK} S_{Ad,t}^{RK} + R_t^{RK} S_{R,t}^{RK}$$

$$R_{t+1}^{RK} = N_{t-1}^{RK} \lambda_{t-1}^{RK} S_{R,t-1}^{RK} S_{R,t}^{RK}$$

where

N_t^{RK} = Abundance of adult red knot

R_t^{RK} = Abundance of juvenile red knot

$S_{Ad,t}^{RK}$ and $S_{R,t}^{RK}$ = Survival rates for adult and juvenile red knot, respectively

λ_t^{RK} = Ratio of juvenile and adult red knot = $\frac{R_t^{RK}}{N_t^{RK}}$

<u>If the decision involves both male and female harvest, then several steps would be required to incorporate male harvest into the model:</u>

1) add abundance of males to the horseshoe crab population dynamics model
2) make survival of eggs (S_0) a function of the sex ratio

3) make the slope of the relationship between spawning density and egg availability or spawning density and P_{180} a function of sex ratio or male abundance

Table 1. Data and information needs required by the predictive model and the decision structure. State variables are the subset of variables that can be used to represent the state of the system that is comprised of the horseshoe crab and red knot populations. Ongoing monitoring program needs are designated with “*”.

Data need	Existing data	State variable
*Horseshoe crab abundance (adults)	Annual spawning survey (estimates spawning density) Annual offshore benthic trawl survey (estimates relative abundance)	Yes
*Horseshoe crab abundance (pre-recruits)	Annual offshore benthic trawl survey (estimates relative abundance)	Yes
*Harvest	State-specific harvest records (subject to reporting error)	No
Horseshoe crab adult survival	Adult survival to be estimated from tagging study	No
Horseshoe crab juvenile survival and egg development	Parameters from literature (Carmichael et al. 2003)	No
Horseshoe crab fecundity	Parameters from literature (Shuster and Botton 1985, Brockmann 1990, Leschen et al. 2006) And to be estimated from Weber (unpublished data)	No
Relationships between spawning density and egg availability, and then between egg availability and P_{180}	Parameters from literature (Gillings et al. 2007, Smith 2007); high uncertainty	No
Relationship between spawning density and P_{180}	Parameters to be estimated from existing data (8 years)	No
*Proportion of early arriving birds that reach 180g by 28 May (P_{180})	Catch data	Yes
*Red knot survival	Annual band and resighting studies	No
Red knot recruitment	Annual band and resighting studies	No
*Red knot abundance	Annual winter counts from aerial surveys (estimates of relative abundance)	Yes

Decision Analysis

The problem has been developed as an optimization problem. The objective function would be maximized across feasible ranges of the state variables (i.e., horseshoe crab and red knot abundances). The product of the analysis would be a decision matrix similar to Table 2. The values for the state variables and harvest levels are shown qualitatively.

Table 2. A decision matrix of optimal harvest levels for year *t*, conditioned on horseshoe crab and red knot population sizes (year *t*) as determined by the objective function and predictive model.

	Red knot population			
Horseshoe crab population	Low	Medium	…	Very high
Low	moratorium	moratorium		moratorium
Medium	moratorium	conservative		conservative
⋮				
Very High	conservative	moderate		liberal

Uncertainty

The team evaluated the sources of uncertainty and speculated on the influence of uncertainty on the predictive model. Table 3 presents a summary of the sources of uncertainty that are likely to be highly influential on the predictive model.

Table 3. Sources of uncertainty highly influential to the predictive model and decision structure. Types of uncertainty include environmental variation, process or structural uncertainty, and sampling error. Environmental variation is pervasive and reduces the certainty that management action will have the predicted outcome. Process uncertainty takes into account multiple predictive models or more than one parameterization of a predictive model. Sampling error includes imprecision in estimates and bias due to partial observability (e.g., catchability in trawl surveys or visibility bias in aerial surveys). To various degrees, the identified sources of uncertainty are potentially subject to all the types of uncertainty.

Source of uncertainty
1) Relationship between spawning density and egg availability, and then relationship between egg availability and P_{180} or 2) Relationship between spawning density and P_{180}
3) Relationship between departure weight and red knot survival and recruitment
4) Relationship between horseshoe crab abundance and spawning density
5) Horseshoe crab spawner-recruit relationship including density-dependence of egg survival
6) Horseshoe crab adult survival

Discussion

Value of decision structuring

This workshop demonstrated to the team how a structured decision approach could be applied to multi-species management of horseshoe crabs and shorebirds. Over the past few years there has been growing awareness that the ongoing studies and assessments of horseshoe crabs and shorebirds must be integrated for effective management. The structured decision making approach is a useful tool for moving forward with that integrative assessment.

There proved to be considerable value in keeping the focus on the structure of the process, i.e., decision problem, objectives, alternatives, predictive models, and analysis. The process enabled the team to isolate the important elements of the problem and to gain real insight into how the species-specific dynamics could be linked in a way that is relevant to management alternatives and decisions.

The fundamentally transparent process will be important as the team works to gain acceptance of a structured decision making framework. Stakeholders involved in horseshoe crab and shorebird management will place high value on an open process, where all the steps are documented and understandable. Transparency will be needed to build trust among the stakeholders.

Further development required

Although the team felt that real progress was made on conceptualizing and beginning to piece together predictive models, the product from the workshop requires substantial further development with input from a much wider group of stakeholders. The team attended the workshop knowing that a joint meeting of the ASMFC's horseshoe crab and shorebird technical committees was planned for October 2007. The purpose of the joint meeting was to work towards a formal multi-species assessment to aid management decisions. The team viewed this workshop at NCTC as an opportunity to prepare for the joint meeting.

This workshop at NCTC was also valuable for setting the team's expectations for what can be accomplished at the joint meeting. Based upon this experience, the team has set its goals for the meeting as reaching consensus on the management objective, alternative management actions, and a conceptual model. We expect that the technical committees will task a smaller working group to build the predictive models with periodic reporting to the larger committees.

Prototyping process

The use of "rapid prototyping" was effective because it allowed the team to go through the whole process in a small amount of time. This allowed the team to do rudimentary sensitivity testing, make modifications to the model, create a conceptual model, look at next steps for implementation, and consider how best to present the process and results to stakeholders and decision makers.

The strategy of using real world case studies was very helpful. It forced the team to deal with unavoidable complexities including missing information and uncertainty. It also gave the team an opportunity to make progress on a real and difficult problem.

Recommendations

Offer this workshop as often as possible. Without a doubt, others will find this workshop highly valuable and relevant.

Literature Cited

Atkinson, P.W., Clark, N.A., Bell, M.C., Dare, P.J., Clark, J.A. & Ireland, P.L. (2003) Changes in commercially fished shellfish stocks and shorebird populations in the Wash, England. Biological Conservation, 114, 127–141.

Atkinson, P.W., Baker, A.J., Bennett, K.A., Clark, N.A., Clark, J.A., Cole, K.B., Dekinga, A., Dey, A., Gillings, S., González, P.M., Kalasz, K., Minton, C.D.T., Niles, N.J., Piersma, T., Robinson, R.A. & Sitters, H.P. 2007. Rates of mass gain and energy deposition in Red Knot on their final spring staging site is both time- and condition-dependent. Journal of Applied Ecology 44:885-895.

Baker, A.J., González, P.M., Piersma, T., Niles, L.J., de Nascimento, I.L.S., Atkinson, P.W., Clark, N.A., Minton, C.D.T., Peck, M.K. & Aarts, G. (2004) Rapid population decline in red knots: fitness consequences of decreased refuelling rates and late arrival in Delaware Bay. Proceedings of the Royal Society of London, Series B, **271**, 875–882.

Brockmann, H. J. 1990. Mating behavior of horseshoe crabs, Limulus polyphemus. Behaviour 114:206–220.

Carmichael, R. H., D. Rutecki, and I. Valiela. 2003. Abundance and population structure of the Atlantic horseshoe crab, Limulus polyphemus, in Pleasant Bay, Cape Cod. Marine Ecology Progress Series 246:225–239.

Gillings, S., P. W. Atkinson, S. L. Bardsley, N. A. Clark, S. E. Love, R. A. Robinson, R. A. Stillman, and R. G. Weber. 2007. Shorebird predation of horseshoe crab eggs in Delaware Bay: species contrasts and availability constraints. Journal of Animal Ecology

Hammond J. S., Keeney R. L., Raiffa H. 1999. Smart Choices: A Practical Guide to Making Better Life Decisions. Broadway Books, New York.

Leshen, A. S., S. P. Grady, and I. Valiela. 2006. Fecundity and spawning of Atlantic horseshoe crab, Limulus polyphemus, in Pleasant Bay, Cape Cod, Massachusetts, USA. Marine Ecology 27: 54–65.

Lutcavage, M. and J. A. Musick. 1985. Aspects of the biology of sea turtles in Virginia. Copeia 1985:449-456.

Millard, M.J., D.R. Smith, S. Michels, J. Brust, and J. Berkson. 2000. Stock assessment of Atlantic coast horseshoe crabs: a proposed framework. Horseshoe Crab Stock Assessment Committee, Report to the Atlantic States Marine Fisheries Commission, Washington, D.C.

Shuster, JR., C. N. AND M. L. Botton. 1985. A contribution to the population biology of horseshoe crabs, Limulus polyphemus (L.), in Delaware Bay. Estuaries 8:363–372.

Smith, D. R. 2007. Effect of horseshoe crab spawning density on nest disturbance and exhumation of eggs: a simulation study. Estuaries and Coasts 30(2):287-295.

Sweka, J. A., D. R. Smith, and M. J. Millard. 2007. An age-structured population model for horseshoe crabs in the Delaware Bay area to assess harvest and egg availability for shorebirds. Estuaries and Coasts 30(2):277-286.