Evaluating a multispecies adaptive management framework: must uncertainty impede effective decision-making?

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Summary

1. Application of adaptive management to complex natural resource systems requires careful evaluation to ensure that the process leads to improved decision-making. As part of that evaluation, adaptive policies can be compared with alternative nonadaptive management scenarios. Also, the value of reducing structural (ecological) uncertainty to achieving management objectives can be quantified.

2. A multispecies adaptive management framework was recently adopted by the Atlantic States Marine Fisheries Commission for sustainable harvest of Delaware Bay horseshoe crabs *Limulus polyphemus,* while maintaining adequate stopover habitat for migrating red knots *Calidris canutus rufa*, the focal shorebird species. The predictive model set encompassed the structural uncertainty in the relationships between horseshoe crab spawning, red knot weight gain and red knot vital rates. Stochastic dynamic programming was used to generate a state-dependent strategy for harvest decisions given that uncertainty. In this paper, we employed a management strategy evaluation approach to evaluate the performance of this adaptive management framework. Active adaptive management was used by including model weights as state variables in the optimization and reducing structural uncertainty by model weight updating.

3. We found that the value of information for reducing structural uncertainty is expected to be low, because the uncertainty does not appear to impede effective management. Harvest policy responded to abundance levels of both species regardless of uncertainty in the specific relationship that generated those abundances. Thus, the expected horseshoe crab harvest and red knot abundance were similar when the population generating model was uncertain or known, and harvest policy was robust to structural uncertainty as specified.

4. *Synthesis and applications*. The combination of management strategy evaluation with state-dependent strategies from stochastic dynamic programming was an informative approach to evaluate adaptive management performance and value of learning. Although natural resource decisions are characterized by uncertainty, not all uncertainty will cause decisions to be altered substantially, as we found in this case. It is important to incorporate uncertainty into the decision framing and evaluate the effect of reducing that uncertainty on achieving the desired outcomes.

Key-words: adaptive resource management, *Calidris canutus rufa*, expected value of information, horseshoe crab, *Limulus polyphemus*, management strategy evaluation, multispecies management, red knot, stochastic dynamic programming

Introduction

Adaptive management is an increasingly important paradigm for natural resource management entailing recurrent decisions that are characterized by reducible ecological uncertainty (Walters 1986; McCarthy & Possingham 2007; Martin *et al.* 2009; Runge 2011; Williams & Brown 2012). Adaptive management, which is a special case of structured decision-making, is value focused and decomposes a decision problem to aid in identifying and solving impediments to making effective decisions (Gregory *et al.* 2012; Williams & Brown 2012). Central to adaptive management is a reward function that depends on how well objectives are met as determined by the state or condition of the natural resource system under management and on constraints or conflicting objectives (e.g. cost constraints) associated with policy options. Adaptive policies are found by optimizing the reward function over a specified period of management given uncertainty in the predicted system response (i.e. structural or ecological uncertainty). Structural uncertainty can be incorporated into the adaptive policies in two ways: passive or active adaptive management. Under both passive and active adaptive management, the structural uncertainty is potentially reducible by comparing the observed and predicted response of the system to management following implementation of actions after each decision point. Under passive adaptive management, the optimization conducted to select the appropriate management action is based on the relative degrees of faith in the different models at that point in time, assumed to be constant over the time horizon of the optimization. Under active adaptive management, learning (changes in degrees of faith in the different models) is anticipated in the optimization and projected through time. So learning occurs under each form of adaptive management, but is anticipated under active adaptive management, but not under passive adaptive management.

The adaptive management approach was used to develop a multispecies framework for the management of horseshoe crabs *Limulus polyphemus* and migratory shorebirds, in particular red knots *Calidris canutus rufa*, in Delaware Bay (McGowan *et al.* 2009; Atlantic States Marine Fisheries Commission (ASMFC) 2012). Horseshoe crabs are harvested as bait for American eel *Anguilla rostrata* and conch *Busycon spp.* and for a biomedical product (Kreamer & Michels 2009). Increased demand for bait by an increasing conch fishery during the 1990s corresponded to increasing harvest of horseshoe crabs (Smith, Millard & Carmichael 2009). The horseshoe crab population decline was followed by a decline of the *rufa* subspecies of red knot, which relies on horseshoe crab eggs during springtime migratory stopover (Baker *et al.* 2004; Karpanty *et al.* 2006; Haramis *et al.* 2007). Shorebird declines have been reported for many arctic-breeding species and across migratory flyways (Gratto-Trevor *et al.* 2011; Morrison *et al.* 2012; Ross *et al.* 2012). Recent evidence suggests that factors other than horseshoe crab eggs have contributed to population dynamics of red knots; these factors include changes in arctic conditions and in wetland habitats range-wide, which have affected shorebirds broadly (Gratto-Trevor *et al.* 2011; Karpanty *et al.* 2011; McGowan *et al.* 2011a; Fraser *et al.* 2013). However, Delaware Bay is a critical stopover for the *rufa* subspecies (Niles *et al.* 2008), and the management of horseshoe crabs is framed to harvest sustainably, while maintaining adequate stopover resources for migrating shorebirds (ASMFC 1998; McGowan *et al.* 2009).

The adaptive management framework was developed after a long period of applying traditional single-species harvest management (ASMFC 1998) that incorporated only conceptual linkages between the species and that was frequently mired by values conflict. The adaptive management approach provided an opportunity to find common ground and move from conflict to cooperation by incorporating stakeholder values and best available science, including uncertainty, into decision-making (McGowan *et al.* 2009; Williams & Brown 2012). After scientific peer review, advisory group input, and extensive public comment, the ASMFC formally adopted the adaptive management framework for harvest management in February 2012 (Jones *et al.* 2009; ASMFC 2012).

As part of the adaptive management framework, stochastic population models were developed for horseshoe crabs (Sweka, Smith & Millard 2007) and red knots (McGowan *et al.* 2011b), and these models were linked to predict the consequences of harvest on horseshoe crabs and red knots (McGowan *et al.* 2009). Structural uncertainty was represented by a set of models incorporating different relationships between horseshoe crab spawning, red knot weight gain and red knot vital rates (McGowan *et al.* 2011b). We used adaptive stochastic dynamic programming, implemented within the software ASDP (Lubow 2001; Martin *et al.* 2009), to develop optimal harvest recommendations from a predetermined set of possible harvest policy options based on a reward function that includes both harvest value for horseshoe crabs and red knot abundance. The policy was optimized using active adaptive management, as the state variables included model weights in addition to horseshoe crab and red knot abundance. We evaluated the adaptive management framework by applying management strategy evaluation to simulate the management system under different policies and assess the robustness of policy options to uncertainty (Butterworth & Punt 1999; Punt 2006; Haeseker *et al.* 2007; Mapstone *et al.* 2008; Bunnefeld, Hoshino & Milner-Gulland 2011). Our application of management strategy evaluation included the dynamic state-dependent harvest policy from stochastic dynamic programming as one of the policy options. The model weights were updated within the simulations based on a comparison of model predictions and simulated monitoring observations, thereby placing value on learning for the purpose of improved decision-making (McCarthy & Possingham 2007).

In this paper, we present results from a management strategy evaluation of the adaptive management framework developed for multispecies management of horseshoe crabs and red knots. The predictive model set included uncertainty in life-history parameters, partial controllability and structural uncertainty in the relationship between the species. The evaluation was designed to investigate certain choices and aspects of the management system, particularly the comparison of adaptive policies (i.e. state-dependent policies including structural uncertainty) to state-independent management strategies and the value of resolving structural uncertainty.

Materials and methods

The simulations were based on the model structure developed to predict the consequences of alternative harvest policies on the reward function. We review the components of the adaptive management framework for horseshoe crabs and red knots in Delaware Bay (McGowan *et al.* 2009; see Appendix S1, Supporting Information). We then describe the simulations and comparisons, which provide the results presented in this paper.

THE MULTISPECIES ADAPTIVE MANAGEMENT FRAMEWORK

The ASMFC sets annual harvest regulations for horseshoe crabs. Individual member states can enact more restrictive, but not less restrictive harvest than approved by ASMFC. Because the ASMFC is the decision-maker in this context, the problem was framed as a harvest decision, that is, how to sustainably harvest, including moratoria, given multispecies objectives. After a series of stakeholder meetings (McGowan *et al.* 2009), the consensus objective (reward) function was

$$R_t = v_{Ft}2H_{Ft} + v_{Mt}H_{Mt} \qquad \text{eqn 1}$$

where R_t is the reward in year t, H_F and H_M are number of female and male horseshoe crabs harvested in year t, and v_{Ft} and v_{Mt} are value functions determined by the level of female and male horseshoe crab harvest. The value function for females takes the value of one if red knot abundance exceeds 45 000 (i.e. 22 500 female red knot) or female horseshoe crab abundance exceeds 80% of carrying capacity (i.e. 11 million) and takes the value of zero otherwise. The red knot threshold of 45 000 was chosen to reflect historical abundances observed in Delaware Bay and is thought to be consistent with a recovering population (McGowan *et al.* 2009). The horseshoe crab threshold of 80% carrying capacity was chosen because it is thought to be consistent with adequate egg availability (Smith 2007; Sweka, Smith & Millard 2007). The value function for males is related to sex ratio, so that the function takes the value of zero when operational sex ratio (sex ratio on the spawning beach, expressed as males : females) is below 2 : 1, takes the value of one when operational sex ratio exceeds 3 : 1, and changes linearly in between those thresholds. The purpose of the value function for males is to value full fertilization and genetic diversity. The female value is multiplied by two because mature females are larger and considered better bait in the eel and conch fisheries; therefore, females have at least twice the market value. These value func-

tions and thresholds were developed through consultations and public meetings with managers and stakeholders with additional input from scientific experts on sex ratio and carrying capacity.

Harvest packages were defined by a stakeholder process as management alternatives (McGowan *et al.* 2009). Because male and female crabs differ in value to the fishery and in contribution to system function, sex-specific harvest quotas were defined (Table 1). In addition to harvest quotas, there are season closures, trip limits and a marine refuge off the mouth of Delaware Bay, but these are constant among the packages and not currently part of the annual decision process so are not considered further here.

The predictive model set was based on species-specific models with linkage between the species based on hypothesized effects of weight gain on red knot survival and fecundity (Sweka, Smith & Millard 2007; McGowan *et al.* 2011b; see Appendix S1, Supporting Information). Multistate modelling was used to parameterize the weight gain as a function of horseshoe crab spawning abundance during the shorebird stopover period (McGowan *et al.* 2011a). We used a threshold weight of >180 g to categorize red knots into two weight classes characterized by different survival and/or reproductive rates (McGowan *et al.* 2011b). We refer to birds that exceed the threshold as heavy and those that fall below the threshold as light.

Three red knot population models were parameterized to represent the range of hypothesized effects of weight gain on red knot survival and fecundity (Table 2). The No Effects model hypothesized equal survival and fecundity for heavy and light birds. The Moderate Effects model hypothesized weight-class-specific survival with estimates taken from McGowan *et al.* (2011b). The Strong Effects model hypothesized weight-class-specific survival with estimates taken from Baker *et al.* (2004). Fecundity was weight-specific in the Moderate and Strong Effects models with parameter estimates taken from McGowan *et al.* (2011b). Variances in the vital rates were from McGowan *et al.* (2011b,a). Model weights reflect the relative degrees of faith in each of the three models (e.g. Williams, Nichols & Conroy 2002). The initial model weights were set based on a consensus process of members of the ASMFC technical working group to 0·2, 0·4 and 0·4 for the No Effects, Moderate Effects and Strong Effects models, respectively (McGowan *et al.* 2009).

The reward function (eqn 1) was incorporated into a utility function, which was maximized using a backward recursion algorithm (stochastic dynamic programming), to determine optimal state-dependent policy (Williams, Nichols & Conroy 2002; see Appendix S1, Supporting Information). The algorithm was implemented within the software ASDP with an arbitrarily large time horizon (1000 years), as recommended by Lubow (2001), to effectively approximate an infinite time horizon. The algorithm con-

Table 1. Harvest packages within the adaptive management framework adopted by the Atlantic States Marine Fisheries Commission (2012)

Harvest package	Male harvest (×1000)	Female harvest (×1000)
1	0	0
2	250	0
3	500	0
4	280	140
5	420	210

Table 2. Red knot vital rates with coefficient of variation differentiating the model set in the adaptive management framework. Coefficient of variation includes parametric uncertainty and temporal variance. Fecundity is mean number of female fledglings per female

Model description	Initial model weights	Adult survival		Fecundity	
		>180 g	≤180 g	>180 g	≤180 g
No effects	0·2	0·91 (0·06)	0·91 (0·06)	0·28 (0·32)	0·28 (0·32)
Moderate effects (McGowan *et al.* 2011b)	0·4	0·92 (0·06)	0·89 (0·07)	0·40 (0·50)	0·05 (0·28)
Strong effects (Baker *et al.* 2004)	0·4	0·92 (0·16)	0·70 (0·21)	0·40 (0·50)	0·05 (0·28)

verged to a stable policy that we then used for harvest recommendations.

MANAGEMENT STRATEGY EVALUATION

The simulations used the fully stochastic and age-structured predictive model set from McGowan *et al.* (2009, 2011b) programmed in R (see Appendix S1, Supporting Information). Because ASDP is limited to relatively low-dimensional problems, for the purpose of policy optimization, much of the environmental variability and parametric uncertainty had been reduced from the models of Sweka, Smith & Millard (2007) and McGowan *et al.* (2011b), and the age-structured horseshoe crab model (Sweka, Smith & Millard 2007) had been converted to a stage-structured model. The survival probabilities in the age-structured model had been converted to transition probabilities in the stage-structured model; the resulting population growth rate was equivalent ($\lambda = 1.021$) for both structures. The stochasticity and age-structure were restored in the management strategy evaluation. Population dynamics were projected for 100 years and replicated 1000 times. The red knot model was female only (McGowan *et al.* 2011b). Initial adult population levels were 2·9 million female and 3·8 million male horseshoe crabs and 13 500 female red knots, which are consistent with initial values used by Sweka, Smith & Millard (2007) and McGowan *et al.* (2011b). These population levels correspond to abundance estimates reported by Niles *et al.* (2008) and Hata & Hallerman (2009). The state-dependent strategy from the ASDP optimization was used as a look up table to select the harvest package for each year when simulating the performance of the adaptive management framework. The look up table included the optimal action for each possible set of discretized species abundances and model weights. Model-predicted age-specific abundances were collapsed into stage classes and matched to the discretized abundance classes in the state-dependent strategy to determine harvest policy (see Appendix S1, Supporting Information). Partial controllability accounted for New Jersey's complete moratorium, which prohibits harvest of the New Jersey allocation, and uncertainty in actual harvest. Observation models simulated uncertainty in the monitoring process.

To approximate current monitoring (McGowan *et al.* 2009), observation models simulated abundance estimates with sampling error, and these estimates were used to look up state-dependent decisions. Because juveniles are not monitored for either species, juvenile abundances were based on model predictions. Model weights were updated using nonparametric likelihoods for red knot abundances computed by comparing observations to the distributions of 500 bootstrap predictions within each of the 1000 replications and time steps (Moore & Conroy 2006). The weight for the *i*th model in year $t + 1$ ($w_{i,t+1}$) was updated using Bayes'

Theorem by

$$W_{i,t+1} = \frac{w_{i,t}\,\mathrm{Pr}_i(N_{t+1}|N_t, A_t)}{\sum_{i=1}^{3} w_{i,t}\,\mathrm{Pr}_i(N_{t+1}|N_t, A_t)'} \qquad \text{eqn 2}$$

where $\mathrm{Pr}_i(\cdot)$ is the nonparametric likelihood based on the *i*th predictive model for red knot abundance in $t + 1$ (N_{t+1}) given abundance and harvest policy in year t (N_t, A_t). The model set representing structural uncertainty predicts red knot abundance in response to horseshoe crab abundance under three hypotheses; thus, only red knot abundances were informative for model weight updating.

Two versions of the value function on female horseshoe crab abundance were compared by running simulations separately for each version. The value function on female abundance determines the value placed on female harvest (υ_F) in the reward function (eqn 1). In the default version, which is currently used in the adopted adaptive management framework, the value was 1 in a year when female abundance exceeds 80% of carrying capacity and 0 otherwise. We called this the 'knife-edge' value function. In the alternative version, which was suggested in a peer review of the adaptive management framework (Jones *et al.* 2009), the value was 1 when female abundance exceeds 80% of carrying capacity, 0 when female abundance is below 50% carrying capacity, and linearly sloped in between. We called this the 'sloped' value function. In addition to the dynamic harvest policy based on the adaptive management framework harvest packages (Table 1), static harvest policies were simulated, including full moratorium and historical harvests of the Delaware Bay population in late 1990s reported to be 1 million females and 800 000 males per year (Kreamer & Michels 2009).

Within a simulation, one of the models from Table 2 was the *population generating model*, and the management performance was assessed in terms of species abundance, harvest and model weight. (We use the descriptive term population generating model or generating model synonymously for operational model, which is used in some literature on management strategy evaluation.) If adaptive management contributes to reduction in structural uncertainty, then model weights should move towards unity for the population generating model and zero for the other models.

The value of resolving structural uncertainty, termed the expected value of perfect information (EVPI), can be useful for determining when decision-making is impeded by uncertainty (Moore & Runge 2012). Calculation of EVPI followed several steps. First, we simulated the adaptive framework under each of the population generating models with the model weight fixed to be 1 for the generating model and 0 otherwise. This represented management with perfect information. The outcomes from the 'perfect information' set of simulations were averaged using the initial framework model weights of 0·2, 0·4 and 0·4. Secondly, we

simulated the adaptive framework under each of the population generating models with the model weights initially set to be 0·2, 0·4 and 0·4, but updated dynamically using eqn 2. This represented management under uncertainty. The outcomes from the 'with-uncertainty' set of simulations were also averaged using the initial framework model weights of 0·2, 0·4 and 0·4. Thirdly, the difference in the averaged outcomes (perfect information outcomes vs. with-uncertainty outcomes) was the EVPI.

Results

Red knot populations, simulated under the adaptive policy with model weights updated through time, increased to carrying capacity within 20 years for the No Effects model and within 50 years for the Moderate

Effects model (Fig. 1). However, for the Strong Effects model, red knot populations declined and remained well below levels under the No Effects and Moderate Effects models. Horseshoe crab population grew at nearly identical rates under No and Moderate Effects models and at a slightly higher rate under the Strong Effects model because more restrictive harvest packages were selected due to lower red knot populations (Fig. 1). Horseshoe crab population sex ratio tended to be slightly female-biased when harvesting under the No or Moderate Effects models, but not for the Strong Effects model. Harvest package 2 (male only, 250 K) was never selected under any model. Complete moratorium (package 1) was selected more frequently under the Strong Effects model.
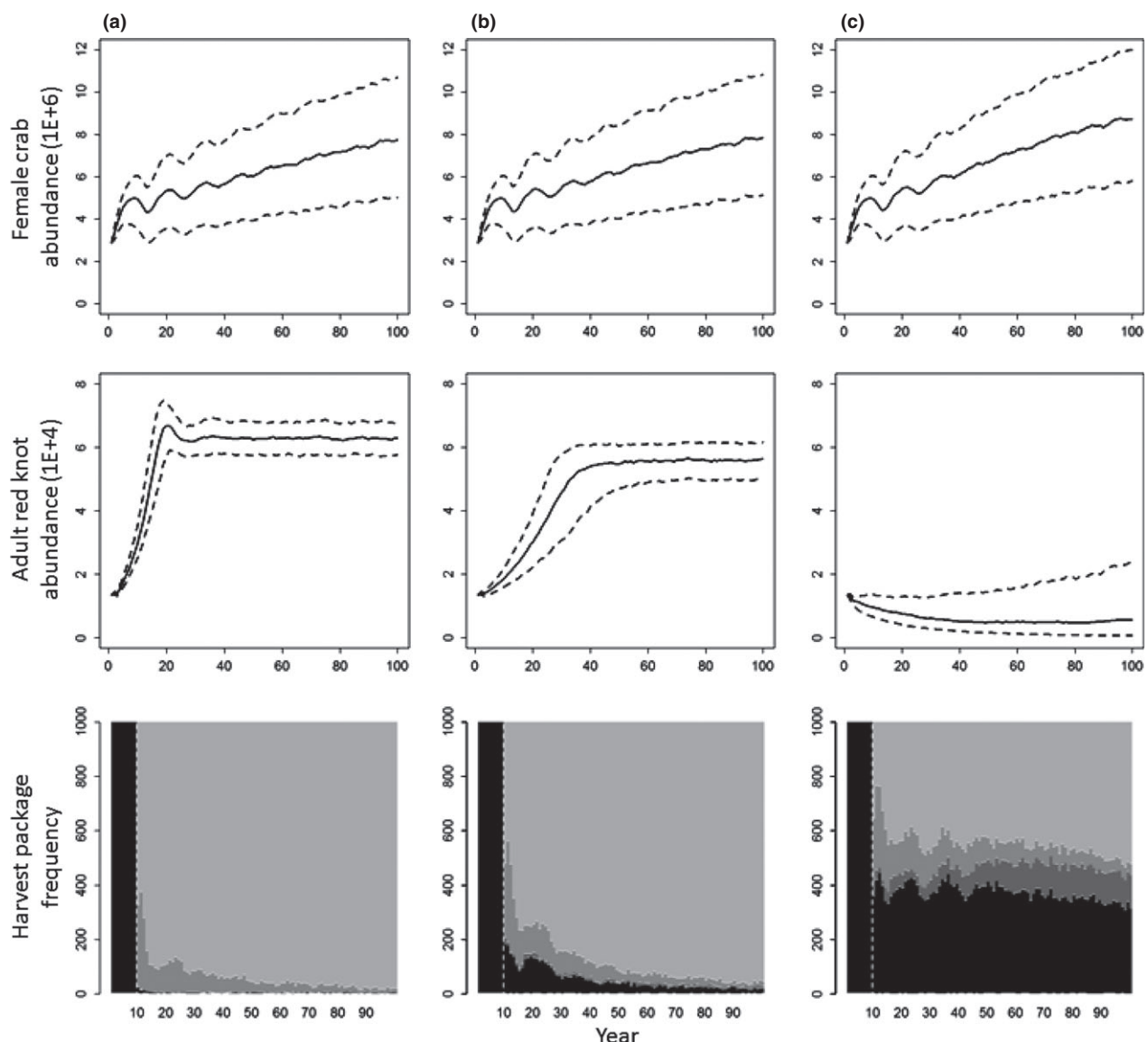

Fig. 1. Population trajectories for adult female horseshoe crabs and red knots and harvest package selection frequencies for simulations of the adaptive management framework. Red knot abundance is female only. Harvest policy is state-dependent accounting for uncertainty in the underlying population generating model. Results are shown for the No Effects (a), Moderate Effects (b) and Strong Effects (c) models based on initial model weights were 0·2, 0·4 and 0·4, respectively. Harvest packages are shown in shades of grey (cf Table 1) from black for harvest package 1 (moratorium) to lightest grey for harvest package 5. Note that harvest package 2 was never selected.
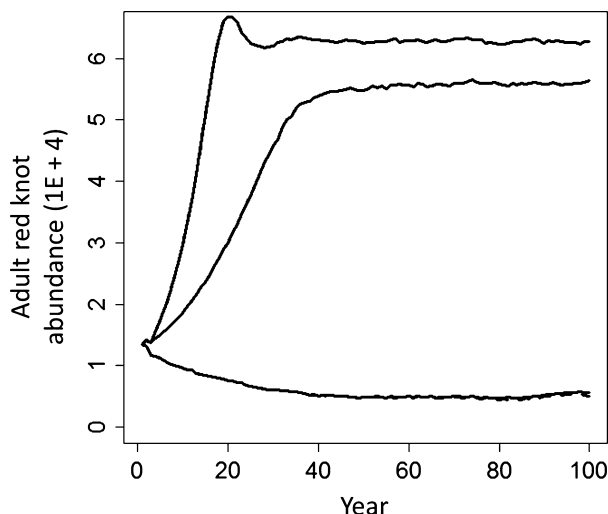
Fig. 2. Red knot abundance (median) for knife-edge (solid lines) and sloped (dashed line) value functions for No Effects, Moderate Effects and Strong Effects models (top to bottom). Red knot abundance is female only. Solid and dashed lines overlap for No Effects and Moderate Effects models.
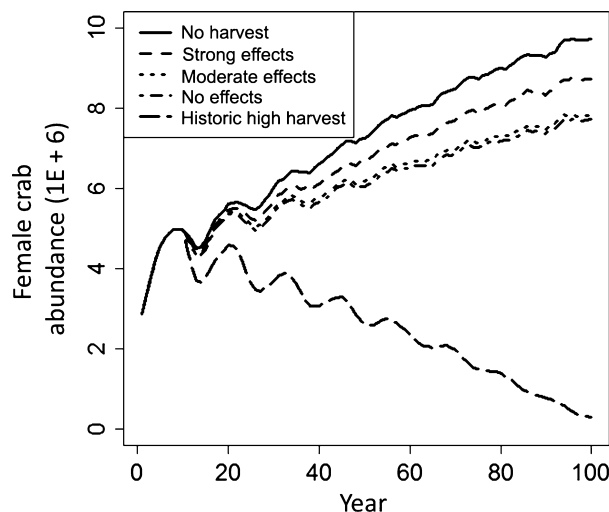

Fig. 3. Female horseshoe crab abundance (median) under scenarios of static and dynamic harvest. From top line to bottom line, the scenarios are (i) static no harvest, dynamic state-dependent harvest (ii) under the Strong Effects model, (iii) under the No or Moderate Effects models (overlapping) and (iv) static historically high harvest.

Package selection was mostly packages 4 and 5 under the No Effects model, packages 1, 4 and 5 under the Moderate Effects model, and packages 1, 3, 4 and 5 under the Strong Effects model.

Differences in red knot population trajectories between the Moderate and Strong Effects models reflected both the expected values and variances of model parameters (Table 2). In any simulated draw of adult survival rate, the probability of survival below 0·7 for heavy and light birds was 0·001 and 0·002 under the Moderate Effects model and was 0·09 and 0·46 under the Strong Effects model. The distribution of fecundity for heavy birds shifted lower as horseshoe crab abundance approached carrying capacity under the Moderate Effects model, which did not occur under the Strong Effects model.

Comparison between knife-edge and sloped value functions for female horseshoe abundance showed little effect on red knot trajectories (Fig. 2). Trajectories for the value functions under the No and Moderate Effects models completely overlapped. A slight separation of the trajectories appeared under the Strong Effects model with the trajectory for the sloped value function being lower than for the knife-edge value function.

Comparison between state-dependent harvest and static harvest policies showed that horseshoe crab abundance increased under the static, no harvest policy and the state-dependent harvest, but decreased under a static historically high harvest (Fig. 3). For the No Effects model as the generating model, red knot trajectory was not affected by harvest policy (Fig. 4). For the Moderate and Strong Effects models, red knot trajectories were similar under the static, no harvest policy and the state-dependent harvest. For the Moderate Effects model, the population increased and then declined under the static historical harvest. For the

Strong Effects model, the population declined throughout the time period under all simulated harvest policies, but faster under the static historical harvest.

Updated model weights based on monitoring adult red knots did not quickly converge on the generating model (Fig. 5). When either the No or Moderate Effects model was the generating model, weight on the Strong Effects model declined. When the No Effects model was the generating model, its weight increased throughout the time period. When the Moderate Effects model was the generating model, its weight increased early in the time period, but decreased after red knot abundance reached carrying capacity. When the Strong Effects model was the operating model, the model weights did not change consistently, on average. Trials of different sets of initial model weights simply shifted the elevation of average model weights without changing the shape of how the model weights changed over time. The failure to converge could be attributed to the similarities of parameter distributions between the No and Moderate Effects models and the high variance in parameter distributions in the Strong Effects model.

The EVPI was relatively small (Table 3). The reward function (eqn 1) would be expected to increase by 0·1% over the entire time horizon if the generating model was known. In terms of red knot abundance at the end of the time period (year 100), abundance would be expected to increase by only 0·2% if the generating model was known. Note that the average reward in year 100 (rightmost column in Table 3) was higher for the Moderate Effects model under uncertainty than under certainty, which was an anomaly that we attribute to stochastic simulation. The difference was relatively small (0·3%), and this had occurred for other generating models in other simulations.
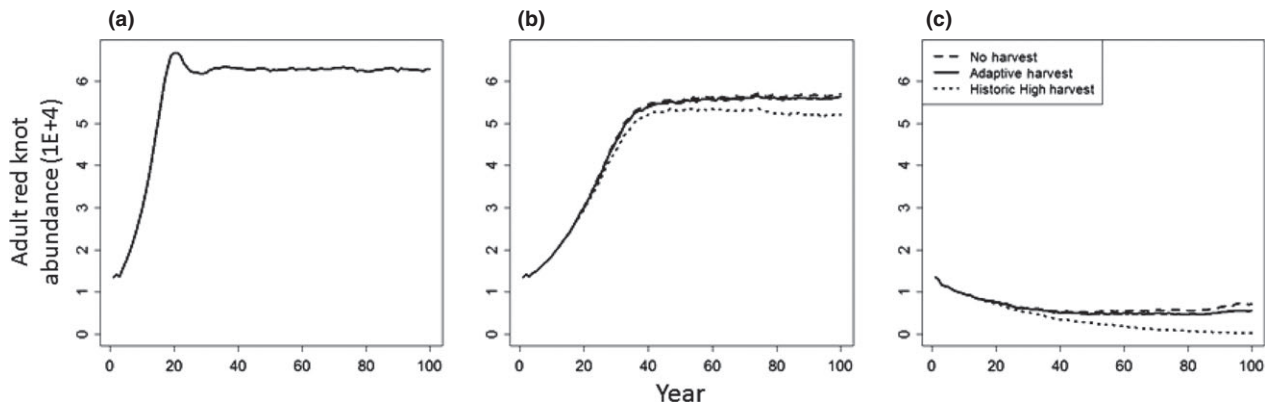
Fig. 4. Red knot abundance (median) under scenarios of static and dynamic harvest for generating models (No Effects – left, Moderate Effects – middle, Strong Effects – right). Red knot abundance is female only. From top line to bottom line, the scenarios are (i) static no harvest, (ii) dynamic state-dependent harvest and (iii) static historically high harvest.
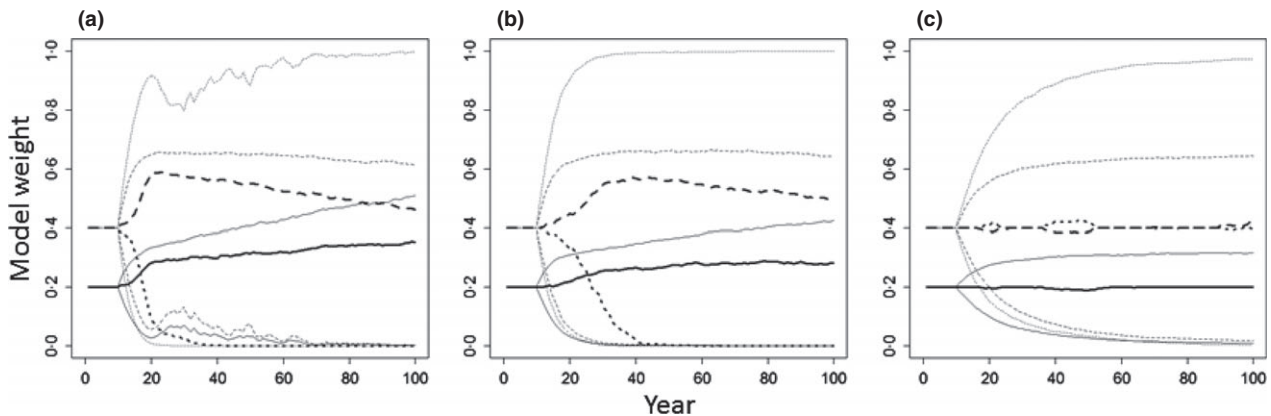

Fig. 5. Model weight updating for the population generating models. Within each panel, updated model weights are shown for the No Effects model (solid lines), the Moderate Effects model (dashed lines) and the Strong Effects model (dotted lines). Bold lines are medians and light lines are 25th and 75th percentiles. Although model weights sum to one across the model set within each replicate and year, a median across replicates did not necessarily sum to one for all years.

Table 3. Expected value of perfect information (EVPI). Expected value is mean outcome averaged over model weights. EVPI is expected value when uncertainty is resolved first minus expected value under model uncertainty. Red knot abundance is female only

Outcome	EVPI	Expected value	Resolve uncertainty first	Generating model	Initial model weight	Outcome at year 100 averaged over 1000 reps
Reward function (eqn 1)	27 792	32 009 763	Yes	No effects	0·2	52 100 705
				Moderate effects	0·4	40 103 937
				Strong effects	0·4	13 870 119
		31 981 971	No	No effects	0·2	52 091 350
				Moderate effects	0·4	40 222 479
				Strong effects	0·4	13 686 773
Adult red knots at year 100	72	40 247	Yes	No effects	0·2	62 592
				Moderate effects	0·4	54 236
				Strong effects	0·4	15 085
		40 175	No	No effects	0·2	62 592
				Moderate effects	0·4	54 285
				Strong effects	0·4	14 856

Discussion

This study combines simulations for policy evaluation (Butterworth & Punt 1999; Mapstone *et al.* 2008; Bunnefeld, Hoshino & Milner-Gulland 2011) with state-dependent strategies from dynamic programming (Nichols, Johnson & Williams 1995; McCarthy & Possingham 2007; Rout, Hauser & Possingham 2009). We found the combination

to be useful for evaluating policy performance and testing underlying assumptions. Although the scenarios tested were not exhaustive, the basic approach is available to evaluate modifications of the adaptive management framework (Williams & Brown 2012).

Harvest policy ought to be precautionary (Hilborn *et al.* 2001). The adaptive management framework presented here includes a long-term planning horizon, identifies and seeks to avoid undesirable outcomes (e.g. red knot abundance <45 000), responds to annual changes in state variables, incorporates uncertainty in the effect of horseshoe crab harvest on both horseshoe crabs and red knot populations, and establishes institutional processes for review and revision. In addition, the population trajectory for red knot under the adaptive management framework almost matched that of a fixed moratorium (the most precautionary policy) under any hypothesized relationship between red knot and horseshoe crabs because the dynamic, state-dependent harvest strategies maintained population growth for horseshoe crabs. Thus, in terms of conservation benefits for red knots, sustainable harvest under the adaptive management framework is precautionary, and simulations indicate that the framework will produce the desirable objective of managing crab harvest, while allowing for red knot recovery.

Value of information can be an effective guide to prioritize information-gathering activities (e.g. research and monitoring), but it is assessed rarely (Hansen & Jones 2008; Rout, Hauser & Possingham 2009; Moore & Runge 2012). We assessed EVPI for this framework and found a slow rate of learning and a relatively low value for reducing the structural uncertainty regarding the precise relationship between horseshoe crabs and red knots. We note that our EVPI is conditional on the uncertainty quantified by the initial set of model weights and is thus directly applicable to our specific management programme. We attribute the low EVPI to (i) state-dependent policy that is responsive to abundance of both species regardless of population generating model, (ii) the similar red knot survival rates under the No Effects and Moderate Effects models permitting population growth and (iii) the inability of even extreme management (harvest moratorium) to induce population growth under the Strong Effects model. All natural resource decisions are surrounded by uncertainty. However, not all uncertainty would cause decisions to be substantially altered. In some cases, the best decision remains the same in spite of large uncertainties. The important task is to incorporate uncertainty in the decision frame and assess the value of reducing uncertainty to the desired outcomes.

The predictive model set represents the competing hypotheses about the relationship between red knots and horseshoe crabs. The No Effects model is a special case from a family of predictions in which red knot trajectory is independent of horseshoe crab abundance. Within that family, red knots could decline, remain stable or increase depending on other factors linked to vital rates. The special case included in the adaptive management framework is nearly indistinguishable from the Moderate Effects model with respect to the red knot trajectories. Considering the survival estimates in the Moderate Effects model based on multistate analyses from McGowan *et al.* (2011a), red knot population growth and viability may be limited primarily by fecundity. Little is known about red knot productivity and how, if at all, Delaware Bay stopover ecology affects breeding propensity and success (McGowan *et al.* 2009, 2011b; Fraser *et al.* 2013). The trajectory for the Moderate Effects model is quite optimistic, while the trajectory for the Strong Effects model is quite pessimistic. If the Strong Effects model approximates red knot dynamics, then substantial abundance increases are unlikely under any harvest policy.

Adaptive management anticipates the need for revising the framework to adapt to new information through what is termed double-looped learning (Williams & Brown 2012). The adaptive management framework under ASMFC guidelines incorporates double-loop learning at least on a 4-year cycle. The double-loop process allows managers and researchers to recast the framework, including objectives, harvest options, system models and key uncertainties to improve effective management. Our evaluation will be an important tool for identifying programme components in need of revision or reconsideration.

The management strategy evaluations and EVPI computations presented here will be useful in guiding future efforts in our Delaware Bay management programme. We also believe that these exercises lead to broad considerations relevant to other programmes of informed management, including adaptive management. For example, relatively small EVPI does not necessarily argue against the expenditure of funds and effort on monitoring. In addition to resolving uncertainty, monitoring data are used to make state-dependent decisions and to assess management progress, two uses of information that were not incorporated into our classical EVPI metric. One logical response to small EVPI is reconsideration of the specific forms of structural uncertainty that we seek to reduce. We came to this conclusion about our specific system, and more generally, we believe that this is a valuable insight contributed by EVPI analysis. Our management strategy evaluations provided a sobering reminder of the limits to management in the Delaware Bay system. Two of our models (No Effects and Moderate Effects models) showed relatively small differences in overall survival rates of red knots. Under the pessimistic predictions of the third model, even extreme management (horseshoe crab harvest moratorium) failed to generate adequate red knot population growth. Such limits to management are being encountered more frequently in conservation (Nichols 2012) and argue strongly for explicit, model-based projection of the consequences of management actions. Knowledge of such limits is important, as inadequacy of proposed conservation efforts motivates search for additional management actions.

In conclusion, we found that resolving the uncertainty regarding the effects of red knot body mass on subsequent survival (and hence the effects of horseshoe crab spawning on red knot population dynamics) was not an important impediment to effective management. The harvest policies depend on observed abundances of both species and are less sensitive to uncertainty regarding the relationship between horseshoe crab and red knots. Thus, harvest policy tended to be more restrictive when red knot and horseshoe crab abundances were low and less restrictive when abundances were high regardless of the structural uncertainty. This was reinforced by the value of information (i.e. EVPI), which indicated that rewards were similar when underlying generating models were uncertain or known (Table 3). However, this conclusion carries two important caveats. First, it is specific to the uncertainties expressed in our three models of mass-specific red knot survival. Two of these models are very similar, and rewards are extremely limited for all management options under the third model. Secondly, the conclusion does not suggest that our basic approach to management be changed. Optimal state-dependent decisions are still the recommended approach to management, and monitoring information is still needed to inform this approach, even if such information is not as important for learning. In addition, the incorporation of an adaptive (learning) component seems wise, given the possibility of altered system dynamics associated with climate change.

Acknowledgements

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Additional detail on the components of the adaptive management framework developed to sustainably harvest Delaware Bay horseshoe crabs while providing adequate stopover habitat for migrating shorebirds.