

## Joint Horseshoe Crab and Shorebird Technical Committees Report

September 3-4, 2008

The ASMFC Horseshoe Crab and USFWS Shorebird Technical Committees (TCs) met jointly on September 3<sup>rd</sup> and 4<sup>th</sup> at the St. Jones Reserve in Dover, Delaware. The purpose of the meeting was to receive updates from the Adaptive Resource Management Work Group (AWG) and to make decisions or recommendations to guide the AWG's work. The following is a summary of the meeting.

**Note:** Most of the work noted in this report and the attached presentations is 'in progress'. The general structure and direction of this process will likely remain as is but details of the objectives, management alternatives, modeling, and analysis will continue to evolve.

### **Attendees**

|                         |                          |
|-------------------------|--------------------------|
| Gregory Breese (USFWS)  | Anne Hecht (USFWS)       |
| Brad Spear (ASMFC)      | Alicia Nelson (VA)       |
| Mike Millard (USFWS)    | Linda Stehlik (NMFS)     |
| Dave Smith (USGS)       | Amanda Dey (NJ)          |
| John Sweka (USFWS)      | Larry Niles (CWF – NJ)   |
| Jim Lyons (USFWS)       | Humphrey Sitters (IWSG)  |
| Connor McGowan (USGS)   | Jon Bart (USGS)          |
| Rick Robins (HSC AP)    | David Mizrahi (NJAS)     |
| Kevin Kalasz (DE)       | Jeff Brust (NJ)          |
| Stew Michels (DE)       | John Maniscalco (NY)     |
| Steve Doctor (MD)       | Rich Wong (DE)           |
| Alison Leschen (MA)     | Allen Burgenson (HSC AP) |
| Robert Gorrell (NMFS)   | Michael Oates (Anew Inc) |
| Annette Scherer (USFWS) | Nellie Tsipoura (NJAS)   |

### **General Updates**

The Horseshoe Crab Management Board met on August 21<sup>st</sup> to select management options contained in Addendum V. The Board chose to extend for one year the provisions of Addendum IV: delayed harvest of up to 100,000 male crabs in New Jersey and Delaware; delayed harvest in Maryland; and multi-measure approach in Virginia. The Board also added a provision that gives it the ability through a vote at one of its meetings to extend the provisions of Addendum V for up to one year.

Attendees were interested in a break down, by month and gear, of the number of horseshoe crabs harvested for biomedical purposes. Those data are confidential and are not available. However, crabs harvested in the Delaware Bay region are harvested primarily in the fall using a combination of trawling and hand harvest.

The group also heard an update on the Red Knot Candidate Status Review. Numbers of red knot *rufa* subspecies have continued to decline in the two years since the original status assessment

was completed. A revised *Calidris canutus rufa* Species Assessment and Listing Priority Assignment Form is under review by the USFWS.

A proposal to look at the taxonomy of red knot using techniques such as genetic markers has been accepted. Funding through the Science Support Program, which draws on expertise within USGS to address scientific questions important to USFWS, will be provided to Tim King (USGS) to examine the taxonomy of red knot population that overwinters in Florida. The work will be done in collaboration with Allan Baker.

The ruddy turnstone population that uses the Delaware Bay as a stopover has declined since 1998. The peak count observed in the Bay that year was around 100,000 birds. It has dropped to about 20,000 in 2008, a decline that is commensurate with that of the Red Knot. It is not known whether the decline in numbers in Delaware Bay is also reflected in the American ruddy turnstone population as a whole or whether the birds have simply changed their migration route in response to the declining food supply. Ruddy turnstones mainly spend the winter in small flocks so a large-scale decline may not have been noticed.

Ruddy turnstones feed on horseshoe crab eggs when stopping over in the Bay. They are different than other species that feed on the eggs in that they dig and defend pits to get eggs. Over 1998-2008 the weights of ruddy turnstones in Delaware Bay have shown a significant year-on-year decline but it is at a lower scale of decline in weights of red knots. There is also evidence that individual turnstones have suffered significantly reduced rates of mass gain in years when eggs were in particularly short supply, as in 2003. Investigations are continuing, especially to establish whether there has been a decline in the flyway turnstone population.

### **Overview of Adaptive Resource Management**

Structured decision making (SDM) is a formal method for analyzing a decision by explicitly identifying what you want to achieve (objectives), what management alternatives you have, and how to rank your alternatives. The specific tools and techniques depend upon the specific problem being addressed, the uncertainty, risk tolerance, and knowledge/data available. The system can be set up so management can adapt over time as monitoring and learning occurs, Adaptive Resource Management. The key elements of adaptive management are: 1) well defined objectives; 2) management alternatives; 3) model(s) of system response to management actions; 4) measures of model credibility; and 5) monitoring program to estimate system state and other relevant variables.

Monitoring is crucial to adaptive management. It allows evaluation of management performance toward objectives and allows managers to learn about system dynamics through comparison of actual monitoring data with model-based predictions. Models can then be revised and/or weighted according to how well they make predictions.

This process has been used successfully in North America in waterfowl management and for fisheries in Australia.

The ARM modeling process will include potentially multiple alternative hypotheses. First and foremost the models will include two hypotheses (1) that red knot survival/population viability is

strongly linked to HSC abundance and (2) that red knot survival/population size is weakly/not linked to HSC abundance. The former hypothesis will initially be more heavily weighted due to prevailing professional opinion and available data and the model weights will be revised over time based on new data future analytical results.

For more details, please see Attachment A (Jim Lyons' presentation, Principles of Adaptive Management).

### **Objectives and Management Alternatives**

The goal of management, as developed so far by the TCs, is to recover and maintain populations of red knots and other shorebirds that forage on horseshoe crab eggs to sustainable levels while allowing for sustainable harvest of horseshoe crabs for bait and biomedical purposes.

To begin setting up a decision structure, an objective statement was drafted as follows: to maximize allowable harvest of horseshoe crabs, constrained by the condition that 90% of early arriving red knots reach 180 grams by May 28<sup>th</sup>. Equations or functions were presented to represent this mathematically. There were concerns about the definition of 'early arriving' and the specifics of the proposed function over infinite time. The AWG will revisit these issues and report back to the TCs.

There was also a suggestion to develop an objective without the shorebird constraint (i.e., simply maximize HSC harvest over time while maintaining a sustainable population) for states without significant horseshoe crab-shorebird interactions.

The AWG presented a suite of management alternatives for consideration by the TCs. The alternatives will be evaluated and presented in a decision matrix to help managers see what an 'optimal' decision might be. The options incorporate only a total harvest number for DE Bay crabs, as opposed to considering various state-by-state allocation scenarios. Management alternatives are centered on the current ASMFC regulations in NJ, DE, MD, and VA, and considered various sex ratios in the harvest. The alternatives ranged from a full moratorium (male and female) to a maximum feasible harvest of 330K females and 990K males.

Based on what is biologically and politically feasible, the TCs paired down the AWG's list of alternatives to include a lower bound of a full moratorium and an upper bound harvest of 330K females and 495K males. The list also included harvest similar to current levels, which also coincides with a 2:1 male to female harvest ratio for the region (140K female, 280K male) and an alternative for a male only harvest in NJ, DE, and MD or those three states plus VA (0 female, 270K/420K males). The AWG will develop 1 or 2 more alternatives to complete the suite of alternatives. The model is focused on the Delaware Bay horseshoe crab population; the geographic scope of the model as it relates to management at the state level may require additional analysis of tagging data.

These alternatives assume that the harvest numbers do not include crabs harvested for biomedical purposes. Also, the alternatives do not incorporate time or area closures. It is assumed they will continue because changes to current time and area restrictions will likely not be changed in the near term.

For more details, please see Attachment B (Dave Smith's presentation, Objectives and Alternatives).

### **HSC Population Model**

The age-structured model incorporates life history parameters to predict horseshoe crab abundance and egg availability to shorebirds over time. It is based on the model published by Sweka et al. 2007 and has since been updated to include males. An alternative set of survivorship parameters was calculated for crabs up to age-8 based on DE's 16-foot trawl survey data (Wong 2008). The alternative estimates shows higher survival rates ( $S$ ) than used by Sweka et al. (2007) and wider variability between years. In addition, sensitivity analysis shows that age-0 survival is the most influential parameter.

The different survival estimates led to several issues and suggestions that the AWG will address:

- (1) Would incorporating a range or error of  $S$  come at a cost to the structured decision making process?
- (2) Additional mortality might occur during the first two instars which are not captured by the trawl, so is it possible to use Sweka et al.'s age-0  $S$  for the first couple months and Wong's for the last months to get an annual  $S$ .
- (3) Can you change the shape of the distributions of  $S$  to incorporate a full range of observed values?
- (4) Should the AWG incorporate two competing models to evaluate which approach is better or should it incorporate uncertainty in values of a single model?

A male-only harvest management strategy is being used in a portion of the DE Bay region. The AWG will also consider at what point the harvest of males begin to influence spawning success? Currently, the model is set up that if the proportion of mature females is less than or equal to 0.5, then all eggs are fertilized. Jane Brockman is conducting studies to link operational sex ratios to fertilization rates. This information might help inform this modeling effort and the AWG will consider how to treat this issue in the model.

The TCs supported continued development and use of the age-structured model to simulate the horseshoe crab portion of the multi-species model. However, debate continues regarding how to model the link between the HSC population and red knots. Two approaches were discussed: 1) the red knot bioenergetics approach models egg availability to link the two; and 2) the empirical approach directly links HSC abundance to red knot survival and the proportion of birds that make weight (P180g). The empirical approach is preferred because it eliminates the large amount of uncertainty that exists in egg availability. However, there is concern with this approach because eggs represent the functional link between the two species, and bypassing this link might completely mask important relationships. The AWG can move forward by evaluating both approaches.

The AWG is also investigating the surplus production model to predict HSC abundance. It has fewer parameters than the age-structured model, and captures other parts of population dynamics better than the age-structured model. One suggestion is to estimate  $r$  and  $K$  in a simplified

growth function with a time lag of 10 years. The AWG will need to critically review which model it uses because it might significantly affect SDM results.

For more details, please see Attachment C (John Sweka's presentation, HSC Population Modeling).

### **Linking HSCs to Red Knot Weight through Population Models**

Evidence indicates that annual survival of red knots is dependent on mass at the time of departure from DE Bay. HSC eggs are their primary food source in the Bay during northward migration. Logically, HSC abundance determines HSC egg availability for red knots. This relationship is being modeled through development of a 'multi-state open robust design mark-recapture/resight survival analysis.' The goals of the analysis are to estimate: 1) annual survival of knots contingent upon weight at the end of DE Bay stopover period; 2) weight at end of DE Bay stopover period; and 3) the relationship between probabilities that birds transition between mass classes and HSC abundance.

The survival analysis will rely on extensive mark-recapture/resight data, particularly the 200+ within season re-traps, along with HSC population metrics such as the benthic trawl and spawning surveys. The sampling framework will include four 8-day 'windows' over multiple years (1998-2008) to track birds within and across years. If weight transition rates are high enough, shorter windows could be used. It is proposed to use three weight classes of red knots that reflect likelihood of survival and making it to the arctic. It was suggested that 133 grams would be an appropriate reference weight because that is the approximate weight where physiological changes in knots allow them to more quickly add weight.

A question of how resighting effort affects estimates came up. Effort is variable across the DE Bay. Are there differential capture/resighting probabilities? The AWG will consider incorporating this into the model, which would increase the number of parameters to estimate. It was also recommended that the AWG correct for weight loss caused by capture and holding time. Using weight classes will help reduce this effect. Also, individuals who were re-caught very soon after initial capture won't be used. It's difficult to tell how big of a problem this is until the AWG begins working up the data. In the meantime, the coded model is being run with simulated data and checked for errors.

The multi-state survival and transition analysis can be run with covariates. The AWG will use HSC surveys as covariates to capture HSC abundance and timing of peak spawning, both keys to red knot weight gain. There was a question of how timing of spawning can be evaluated in the model. The AWG plans to use the proportion of spawning that occurs during the stopover.

Questions about how to use the HSC egg density data came up. Should it be incorporated as baywide or state-specific? How do we deal with the lag between spawning and availability of eggs to shorebirds? How do we model behavioral responses of birds moving to DE beaches where density is higher? There are no firm answers yet. However, as noted earlier, there is so much variation in the egg data, it might not be useful to use them in the model. The AWG is considering simply using information on when the eggs are available.

A question was brought up about how availability of other food sources (e.g., mussels, *Donax*) would affect the model. This could be accounted for as stochastic variability in transition probabilities or as a separate variable with its own mean and error distribution. It was noted that alternative food sources won't solve the knot's problem, but it might minimize the impact on birds in years of very low egg availability.

Little data are available to quantify the relationship between fecundity of knots in the arctic and mass at departure from DE Bay. The AWG proposed using a 'decision sensitivity analysis' that creates hypothetical (high, medium, low) functions of fecundity at a given P180. This allows an evaluation of how sensitive the model results are to each function. Time-permitting the AWG might look at available data to get a better picture of fecundity.

In addition to annual adult survival, HSC egg abundance likely affect Red Knot annual productivity, probably by reducing the probability of breeding for birds that does not make weight. Measuring productivity is quite difficult for Red Knots because of their remote arctic breeding habitat and measuring recruitment to either the Tierra Del Fuego winter population or to the Delaware Bay migratory population might be alternative avenues of estimation. There was concern about how to estimate recruitment of knots to the juvenile stage because there is no established method for doing so. Complicating this issue is the two-year lag from when juveniles recruit to the population to when they are seen in winter populations. Lots of factors (other than HSC abundance/egg availability in DE Bay) could affect recruitment. The goal may be to use some measure of DE Bay population birds rather than arctic or wintering ground counts. Alternatively the AWG suggested a decision sensitivity analysis approach to examine how changes in modeled Red Knot productivity affect optimal decision analysis. The sensitivity analysis will guide future research on Red Knot recruitment and its relation to HSC populations in the Delaware Bay.

There were questions about whether the SDM utility function will use P180 or an alternative metric for indexing the state of red knots departing DE Bay. The AWG believes it will be some function of red knot weight gain but not necessarily P180. The AWG will revisit this at its next meeting.

For more details, please see Attachment D (Conor McGowan's presentation, Linking Red Knot and HSC Populations).

### **Optimization**

Optimization is part of decision analysis that helps managers find the 'best' management action given the objectives and the state of the system. Each alternative is ranked based upon how well it achieves the management objectives, or the return associated with a management action given the system state and post-action state. The highest-ranking alternative action (i.e., the one with the best return) will be identified for a given system state (i.e., population).

The AWG will likely use stochastic dynamic programming to determine optimization. It starts at the end of an infinite time series (i.e., what is the best management action to take in the last time step) and works backwards to find what action to take in the current year.

The utility function (i.e, quantitative objective) is based on the qualitative objective. It is the equation that produces the return. The utility function is how societal values (such as supporting bird populations and allowing a sustainable harvest) are incorporated into the decision analysis.

There was a question of whether optimization results have standard errors. This was based on the concern that if we used similar inputs, would we find different optimization results. TC members would like to see in the decision analysis some sort of grading or confidence intervals for each outcome. The AWG will look into this. One way might be to simulate the analysis a number of times to see how results differ.

### **Timelines and Expectations**

The next AWG meeting is scheduled for October 9<sup>th</sup> and future meetings will occur roughly every two months after. The goal for the AWG is to present the joint TCs with preliminary results in March 2009. With input and guidance from the TCs, the AWG would present preliminary results to the Management Board in May 2009. A peer review is being scheduled for Fall 2009 to review the horseshoe crab stock assessment as well as a review for the ARM modeling work.

There was concern among the group to make sure there is buy-in from all stakeholders. All TC and Board meetings are open to the public. Specific individuals that TC members believe should attend TC meetings can receive personal invitations. TC or AWG members can present this work at meetings outside of the ASMFC process (e.g., NE Directors meeting). There is also the possibility of web-based presentations.

# Principles of Adaptive Management

Jim Lyons

USFWS Division of Migratory Bird Management

Joint Meeting of the ASMFC  
Horseshoe Crab and Shorebird  
Technical Committees  
3-4 September 2008



# Structured Decision Making

- A formal method for analyzing a decision, by breaking it into components
- “A formal application of common sense for situations too complex for the informal use of common sense.”--R. Keeney
- Helps to
  - identify where the impediments to a decision are
  - focus effort on the right piece
- Provides a wide array of analytical tools for dealing with particular impediments

# Structured Decision Making: Two Key Features

- Problem decomposition
  - Break the problem into components, separating policy from science
  - Complete relevant analyses
  - Integrate the parts to make a decision
- Value-focused
  - The objectives (values) are discussed first, and drive the rest of the analysis
  - This is in contrast to our intuitive decision-making, which usually jumps straight to the alternatives

# Key Elements of Adaptive Management

1. Objective(s): what do you want to achieve?
2. Management alternatives: actions you can take
3. Model(s) of system response to management actions (for prediction)
4. Measures of model credibility
5. Monitoring program to estimate system state and other relevant variables

# Key Element #1: Objectives

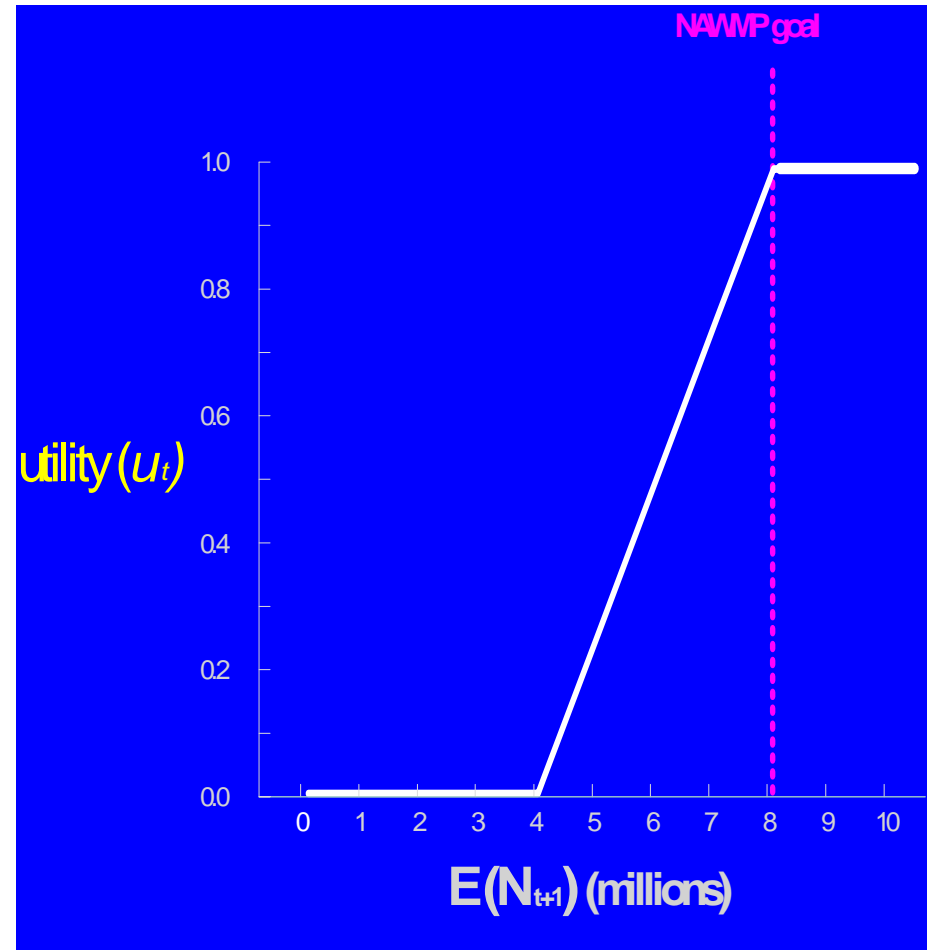
- Explicit statement allows focused discussion, negotiation, and evaluation
- The objective drives management process
- Focus on setting objectives first, before discussing alternatives
- Ultimately, objectives reflect societal values (legal mandates and policy are relevant)

# Key Element #1: Objectives

- Competing objectives handled by
  - Finding common currency, or
  - Using constraints, e.g.

$$\max \sum_{\tau=t}^T u_{\tau} H_{\tau}$$

- Expressed in terms that can be evaluated using monitoring data



## Key Element #2: Management Alternatives

- Different options should result in different benefits and costs (“a real choice”)
- Practically, the set of options should be limited, and remain static for some period of time
- Determined by managers and other stakeholders, based on feasibility and (political) palatability

# Mid-continent mallard regulations as alternative actions

|           |   | ATL                            | MIS | CEN | PAC |
|-----------|---|--------------------------------|-----|-----|-----|
| hours     |   | 1/2 hr before sunrise - sunset |     |     |     |
| dates     |   | Oct 1 - Jan 20                 |     |     |     |
| days      | R | 30                             | 30  | 39  | 59  |
|           | M | 40                             | 40  | 51  | 79  |
|           | L | 50                             | 50  | 60  | 93  |
| basic bag | R | 3                              | 3   | 3   | 4   |
|           | M | 4                              | 4   | 4   | 5   |
|           | L | 5                              | 5   | 5   | 6   |

# Key Element #3: Predictive Models

- Predictive models link actions to outcomes that are relevant to the objectives
- Modeling is not optional – even subjective prediction is a model
- Generating Competing Models
  - Ecological Theory
  - Empirical Experience with Alternative Actions
  - Disagreement about System Dynamics
  - Stakeholder Preferences



## Key Element #3: Predictive Models

- Models should be few and as simple as possible
- Models should bound uncertainties
- Models should differ in predicted responses to management actions.

# Four population models

Density Dependence

Weak

Strong

Additive

★ additive hunting  
★ weakly d-d recruitment

(SaRw)

★ additive hunting  
★ strongly d-d recruitment

(SaRs)

Hunting Mortality

Compensatory

★ compensatory hunting  
★ weakly d-d recruitment

(ScRw)

★ compensatory hunting  
★ strongly d-d recruitment

(ScRs)

## Key Element #4: Measures of Model Credibility

- Weights reflect relative credibility and sum to 1 for all members of the model set
- Models with higher weights have more influence over future decisions
- Some kinds of decision processes permit learning, as reflected in changing model weights

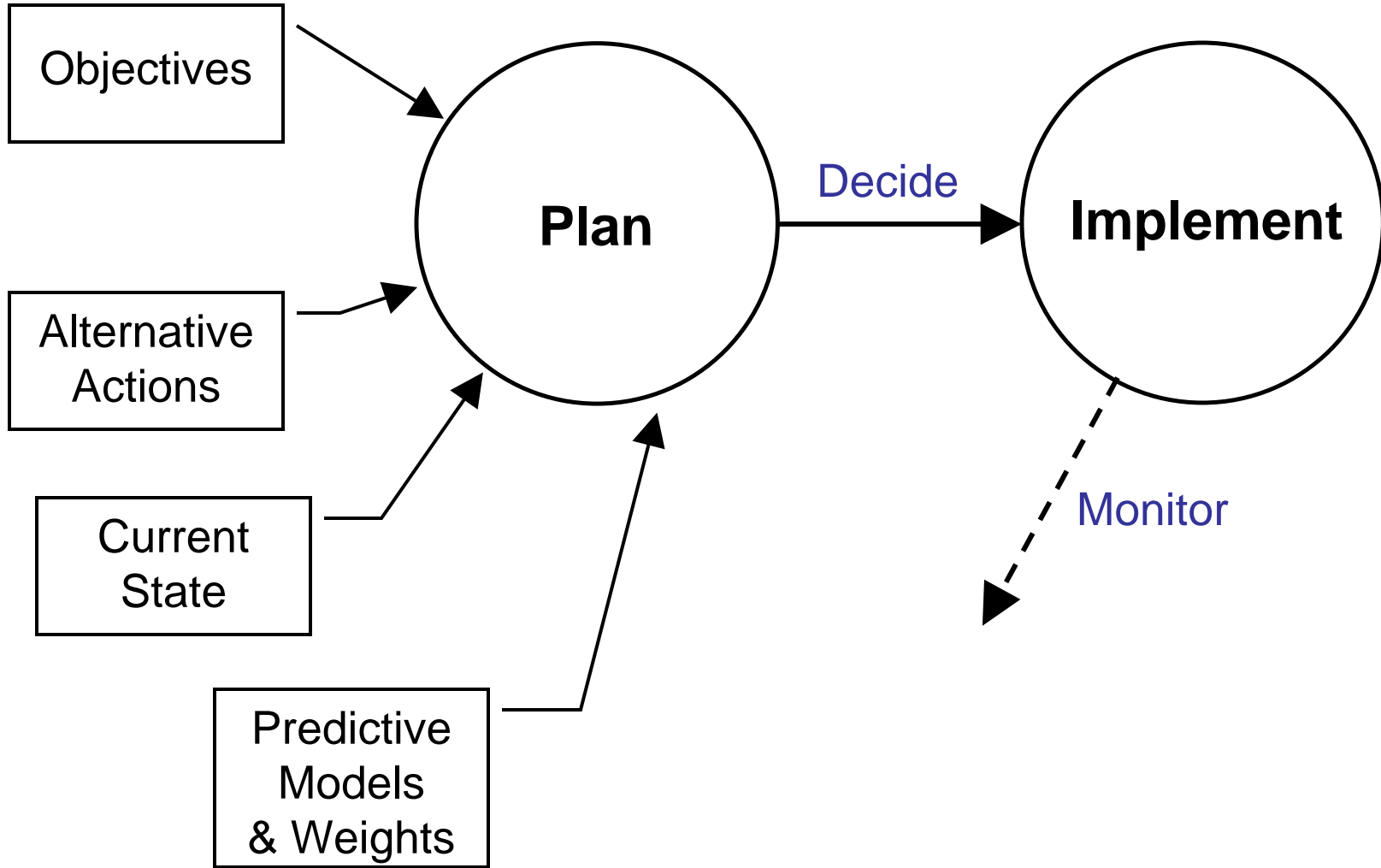
# Key Element #5: Monitoring

- Monitoring for management should focus on precisely the information that will be most useful in making management decisions
- Monitoring can play 3 roles...

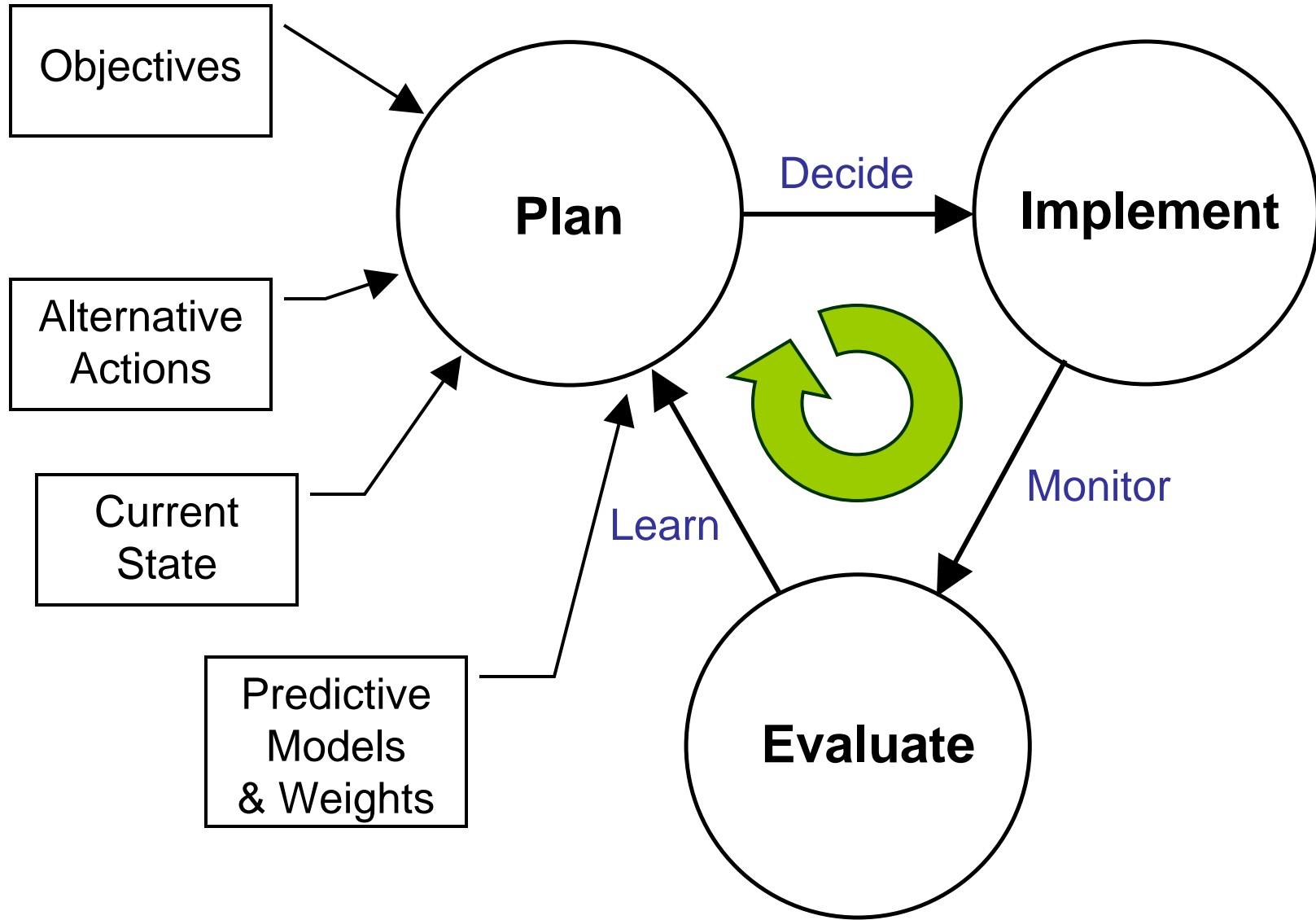
# Role of Monitoring in Management

- I. Determine system state for state-dependent decisions
- II. Evaluate management performance toward objectives
- III. Learn about system dynamics via comparison of monitoring data with model-based predictions (i.e., do science)

# Adaptive Management



# Adaptive Management



# Roles of Monitoring I: Identify System State

- Optimal decision =  $f(\text{system state})$
- Example: different harvest decisions depending on whether population size is too small, too large, or at desired level



# State-dependent Decision Matrix

|                     |   | Ponds (thousands) |   |   |   |
|---------------------|---|-------------------|---|---|---|
|                     |   | 2                 | 3 | 4 | 5 |
| Mallards (millions) | 4 |                   |   |   |   |
|                     | 5 |                   |   |   |   |
|                     | 6 |                   |   |   |   |
|                     | 7 |                   |   |   |   |
|                     | 8 |                   |   |   |   |

## Roles of Monitoring II: Evaluate Management Performance

- Monitoring of goal-related variables permits performance assessment
  1. Conservation setting: goals may be functions of the system state variable(s)
  2. Exploitation setting: goals may include functions of other variables estimated from the monitoring program (e.g., accumulated harvest)

# Roles of Monitoring III: Learning about System Dynamics

- Requirements:
  - Models and their predictions
  - Replication over space and/or time
  - Monitoring program
- Model Weights are updated over time as function of
  - 1) Current weights
  - 2) New data (observed state – predicted state)
- Learning is reflected by changes in model weights representing model credibility

# Updating Model Weights: Bayes' Theorem

$$Pr(\text{Model } i \mid \text{data}) =$$

$$Pr(\text{Model } i) Pr(\text{data} \mid \text{Model } i)$$

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$$Pr(\text{data})$$

$$\sum_j Pr(\text{Model } j) Pr(\text{data} \mid \text{Model } j)$$

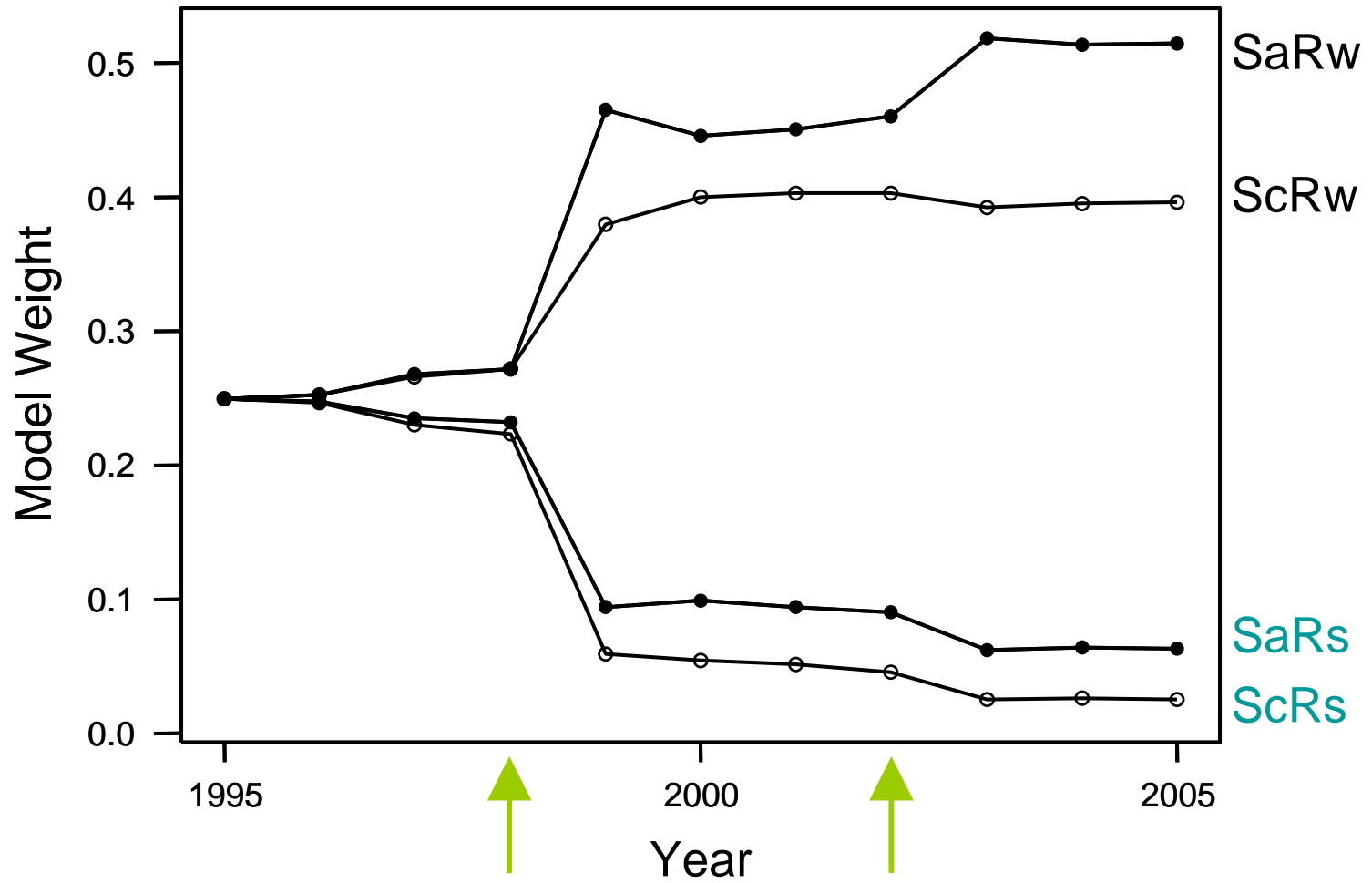
# Updating Model Weights Based on New Data

|                | Model weight | Likelihood of Data | New Model Weight |
|----------------|--------------|--------------------|------------------|
| Model <i>A</i> | 0.25         | ?                  |                  |
| Model <i>B</i> | 0.25         | ?                  |                  |
| Model <i>C</i> | 0.25         | ?                  |                  |
| Model <i>D</i> | 0.25         | ?                  |                  |

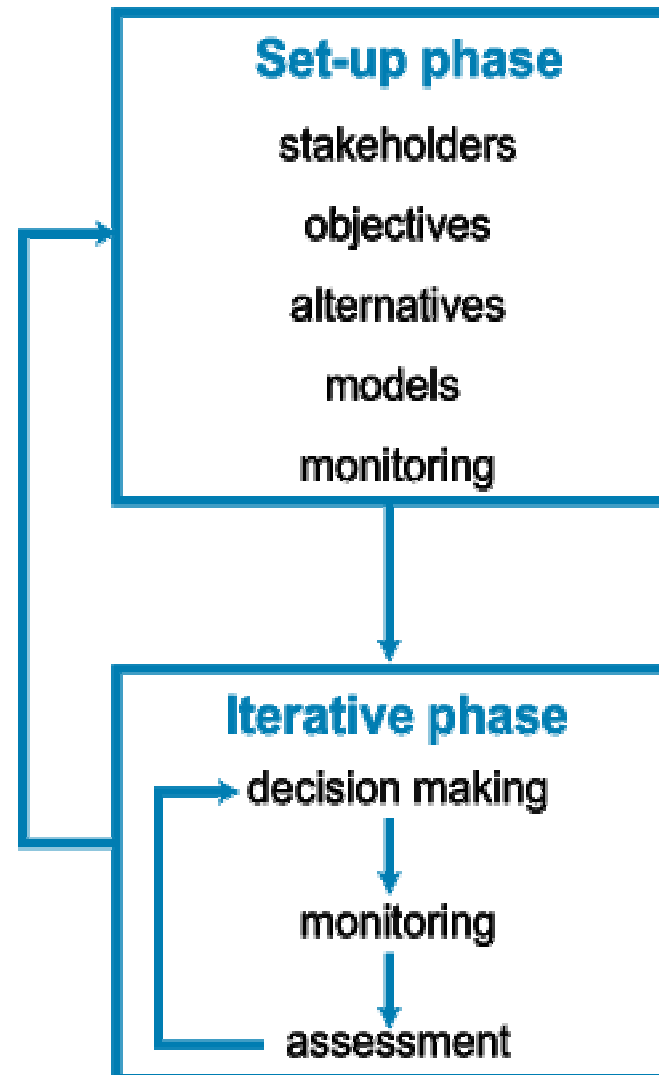
# Updating Model Weights Based on New Data

|                | Model weight | Likelihood of Data | New Model Weight |
|----------------|--------------|--------------------|------------------|
| Model <i>A</i> | 0.25         | 0.98               | 0.31             |
| Model <i>B</i> | 0.25         | 1.15               | 0.36             |
| Model <i>C</i> | 0.25         | 0.74               | 0.23             |
| Model <i>D</i> | 0.25         | 0.32               | 0.10             |

# AHM Learning



# Adaptive Management: “Double-loop Learning”





# Key Elements of Adaptive Management


1. Objective(s): what do you want to achieve?
2. Management alternatives: stuff you can do
3. Model(s) of system response to management actions (for prediction)
4. Measures of model credibility
5. Monitoring program to estimate system state and other relevant variables

# Role of Monitoring in Management

- I. Determine system state for state-dependent decisions
- II. Evaluate management performance toward objectives
- III. Learn about system dynamics via comparison of monitoring data with model-based predictions (i.e., do science)



# Adaptive Management: Outline of Iterative Process

- Derive & implement optimal management action based on:
    - Objective function
    - Available management actions
    - Model set and model weights
    - Current state of system
    - Derive and implement optimal management action
  - Iterative process
    - Observe new state of system
    - Update model weights
    - Derive optimal management action
    - Implement optimal management action
- 

# Role of Monitoring: Informing Models of System Dynamics

- Monitored quantities include state variables, goal-related variables and model parameters
- Estimates of state (and other) variables obtained from monitoring are compared against model-specific predictions (science)
- Process leads to updating of model weights (learning)

# Role of Monitoring: Informing Models of System Dynamics

- Updating parameter estimates for members of model set (e.g., revised estimates of distribution of harvest rates resulting from different hunting regulations)
- Updating of the model set itself

# Recommendations: Why Monitor?

- Monitoring is most useful when integrated into efforts to do science or management
- Role of monitoring in science
  - Comparison of data with model predictions is used to discriminate among competing models
- Role of monitoring in management - determine system state for:
  - State-specific decisions
  - Assessing success of management relative to objectives
  - Discrimination among competing models

# Model weights

|       | Wetland<br>management action |      |      | Model weight |
|-------|------------------------------|------|------|--------------|
|       | early                        | late | none |              |
| $M_1$ | +                            | 0    | -    | 0.34         |
| $M_2$ | -                            | 0    | +    | 0.33         |
| $M_3$ | 0                            | -    | 0    | 0.33         |



# Bayes' Formula

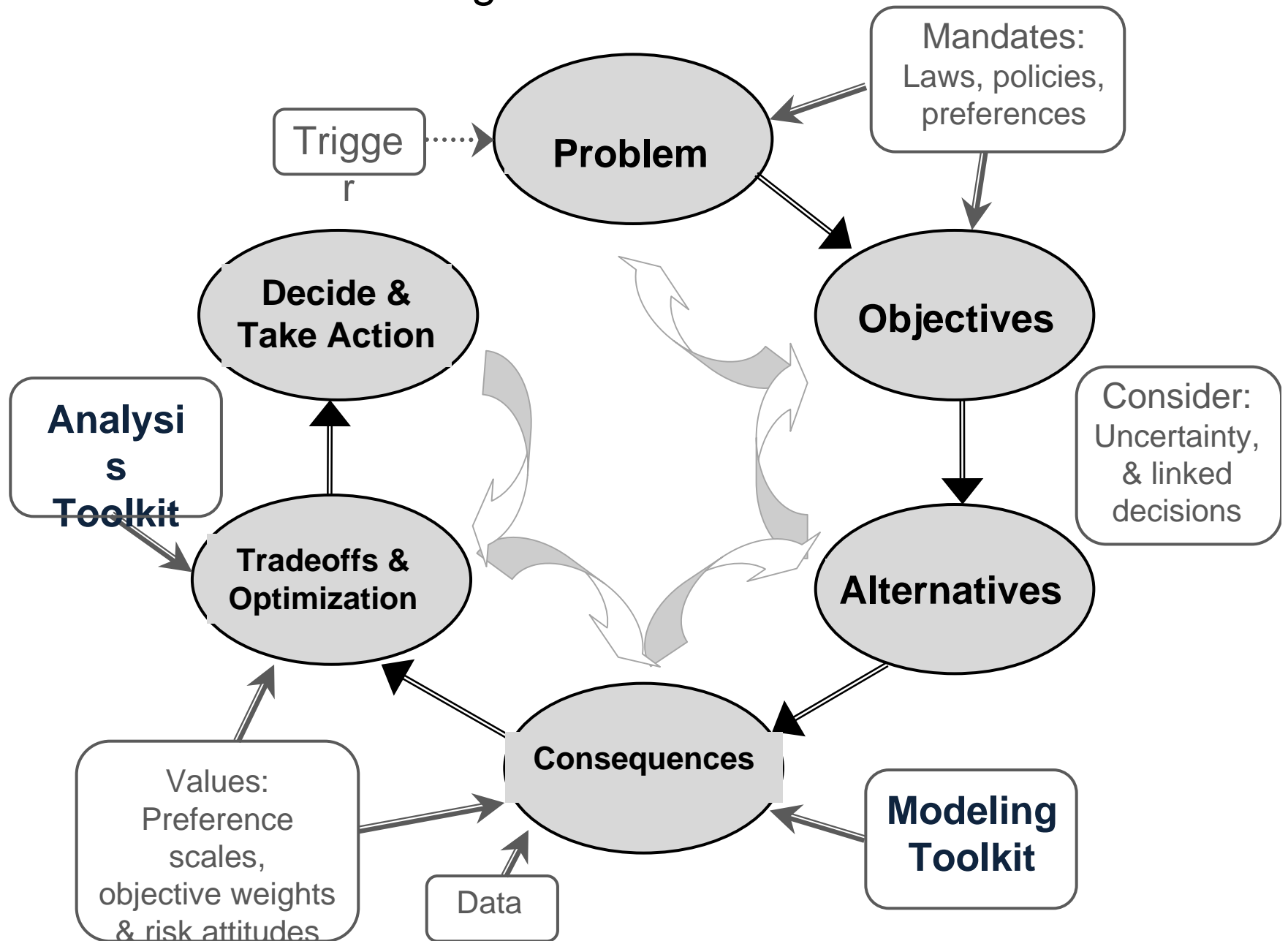
$$p_{t+1}(\text{model } i \mid \text{data}_{t+1}) =$$

$$p_t(\text{model } i) P(\text{data}_{t+1} \mid \text{model } i)$$

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$$\sum_j p_t(\text{model } j) P(\text{data}_{t+1} \mid \text{model } j)$$

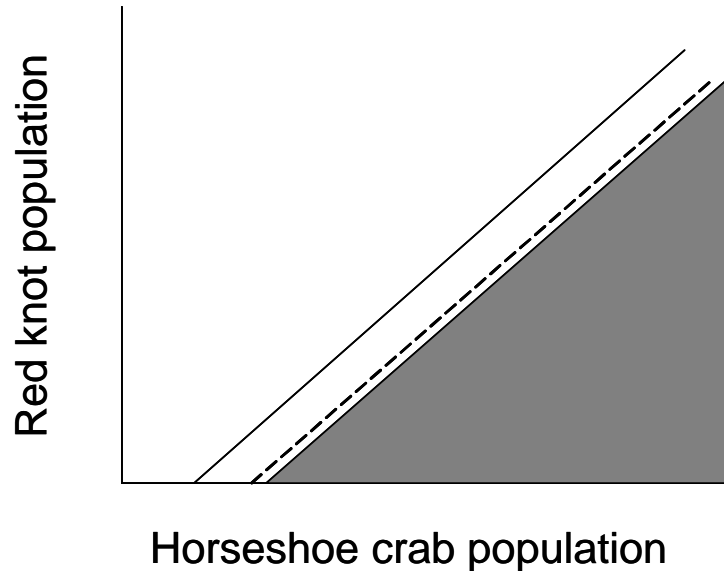
# Structured Decision Making



# Goal and Objective Statements from the Oct 07 Joint Mtg

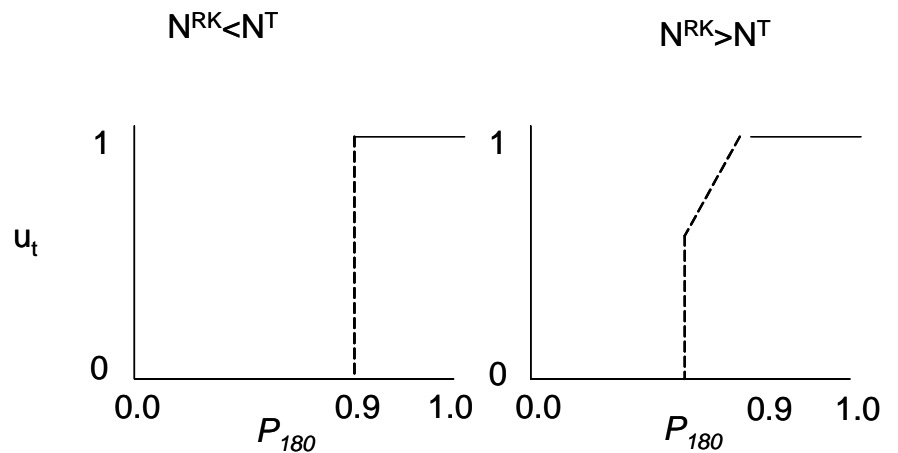
- **STATEMENT OF GOAL:** Recover and maintain populations of red knot and other shorebirds that forage partially or wholly on horseshoe crab eggs to sustainable, healthy, economically important levels, while allowing for sustainable harvest and biomedical use of horseshoe crab populations.
- **STATEMENT OF OBJECTIVE:** Regulate a sustainable harvest of horseshoe crab populations to provide sufficient horseshoe crab eggs to support population recovery goals for Delaware Bay shorebirds (e.g., population target of 80,000 for the red knot) which forage partially/wholly on horseshoe crab eggs.
  - \*It is implicit that to achieve this objective, horseshoe crab populations need to increase (from 2007 population levels).

# Decision Structure: *Objectives*



Objective statement: Maximize allowable harvest of horseshoe crabs constrained by 90% of early arriving red knots reaching 180g by 28 May.

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



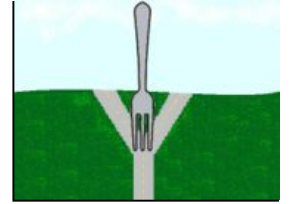
# Management alternatives from Oct 07 Joint Mtg

- Management alternatives should:
  - result in different benefits and costs;
  - be based on feasibility and political palatability; and
  - be limited in number and remain static for some period of time.
- The group agreed that management alternatives should include:
  - No harvest
  - Less than current Delaware Bay population harvest
  - Current Delaware Bay population harvest
  - More than current Delaware Bay population harvest
  - Record Period Landings (RPL)
- There was consensus that putting numbers to these management alternatives was a task for the ARM work group.

# Management alternatives from ARM work group

- **Management alternatives outlined at the October workshop uses the current regs as a pivot point. Thus, we needed to specify current regs.**
- **The current harvest regs by state are**
  - **NJ: moratorium**
  - **DE: male-only; 100k; June 8 to Dec 31**
  - **MD: Harvest June 8 to Dec 31; quota**
  - **VA: Harvest June 8 to Dec 31; <40% of harvest from outside state waters; minimum male to female ratio of 2:1; quota**
  - **The harvest level for Del Bay hsc depends on the percentage of MD and VA ocean landings that are of Del Bay origin. For example,**
    - **Under the assumption that 100% of MD and VA ocean landings are of DelBay origin, then harvest level projected for 2007 is 143k females and 195k males.**
    - **Under the assumption that 50% of MD and VA ocean landings are of DelBay origin, then harvest level projected for 2007 is 72k females and 147k males.**

# Management alternatives from ARM work group



- **The ARM work group will focus on alternative harvest levels for the population that spawns in DB regardless of allocation. Allocation of harvest among the states will be determined through the ASMFC process.**
- **Reference period landings seemed too high to be politically or biologically feasible, so we considered an alternative upper limit. Reasoning that bait needs were met during the years of 2000-2003, we averaged harvest during that time assuming that 100% of ocean landings in MD and VA were of Del Bay origin. The level that resulted was 330k females and 500 males.**
- **Because there is considerable interest and uncertainty regarding the affect of sex ratio of the harvest, we considered 2 ratios of male:female harvest. The ratios were 1.5:1, which reflects current harvest, and 3:1, which is consistent with a move to male-only or male-dominated harvest.**

# Management alternatives from ARM work group

- **Specific alternative harvest levels for evaluation:**
- **There might be too many alternatives for the optimization routine given the complexity of the population models. Thus, we might need to trim the list.**

| Alternatives         | Harvest level<br>(1,000s) |      |
|----------------------|---------------------------|------|
|                      | Female                    | Male |
| Moratorium           | 0                         | 0    |
| Less than<br>current | 35                        | 53   |
|                      | 35                        | 105  |
|                      | 70                        | 105  |
| Current              | 70                        | 210  |
|                      | 140                       | 210  |
| More than<br>current | 140                       | 420  |
|                      | 235                       | 353  |
|                      | 235                       | 705  |
| Max<br>feasible      | 330                       | 495  |
|                      | 330                       | 990  |



# Management alternatives from ARM work group



- **Things to discuss:**
- **Min and max alternative**
- **Sex-specific harvest alternatives**
- **Assumptions regarding mixture of coastal harvest**

| Alternatives         | Harvest level<br>(1,000s) |      |
|----------------------|---------------------------|------|
|                      | Female                    | Male |
| Moratorium           | 0                         | 0    |
| Less than<br>current | 35                        | 53   |
| Current              | 35                        | 105  |
|                      | 70                        | 105  |
| More than<br>current | 70                        | 210  |
|                      | 140                       | 210  |
| Max<br>feasible      | 140                       | 420  |
|                      | 235                       | 353  |
|                      | 235                       | 705  |
|                      | 330                       | 495  |
|                      | 330                       | 990  |

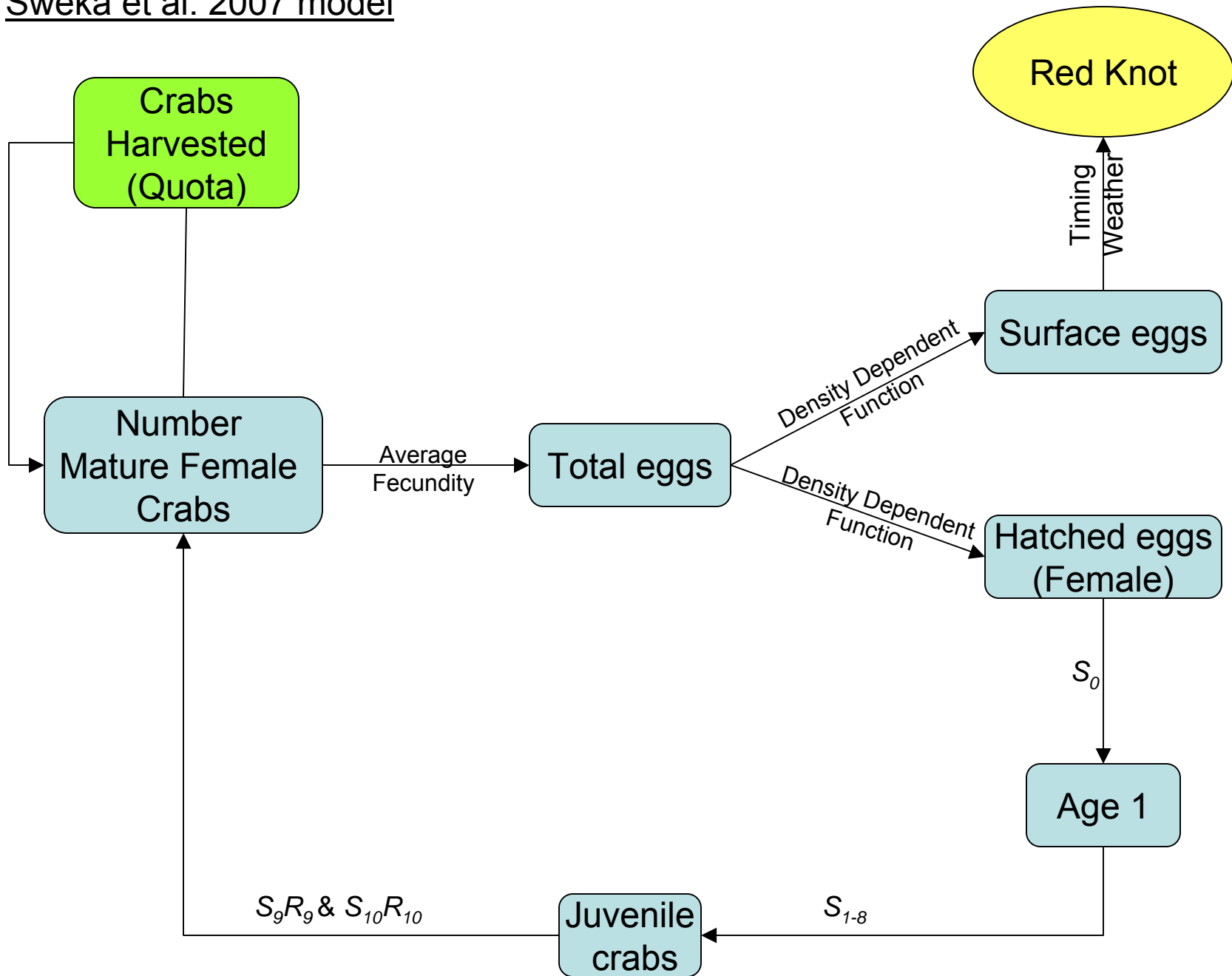
# Discussion

# Horseshoe Crab Age-Structured Model

Based on:

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. *Estuaries and Coasts* 30: 277-286.

Sweka et al. 2007 model



## Life History Parameters

| <b>Age</b> | <b>S</b> | <b>Source</b>  | <b>Partial Recruitment</b> |
|------------|----------|--|----------------------------|
| 0          | 0.00003  | Botton et al. 2003   | 0.0                        |
| 1 – 8      | 0.9738   | Carmichael et al. 2003 (Table 13)                          | 0.0                        |
| 9 – 10     | 0.7994   | Mean on 1 – 8 and 11 – 17 (assumption)                     | 0.5                        |
| 11 – 17    | 0.6250   | Carmichael et al. 2003 (Table 10, mean of instars 20 – 23) | 1.0                        |
| 18 – 19    | 0.08     | Carmichael et al. 2003 (Table 10, instar 24)               | 1.0                        |
| 20         | 0        | All dead - assumption                                      | 1.0                        |

S values randomly drawn from a beta distribution with mean equal to above values and assumed c.v. = 0.15

# LEGEND



Areas occupied by spawning females



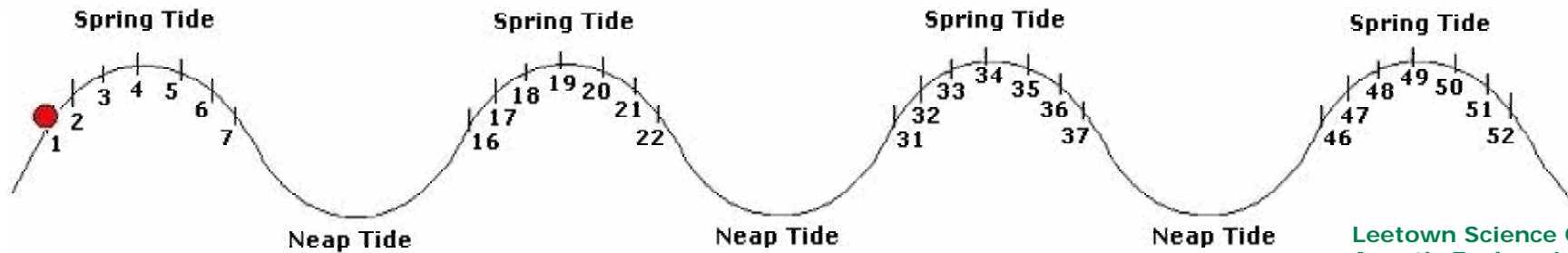
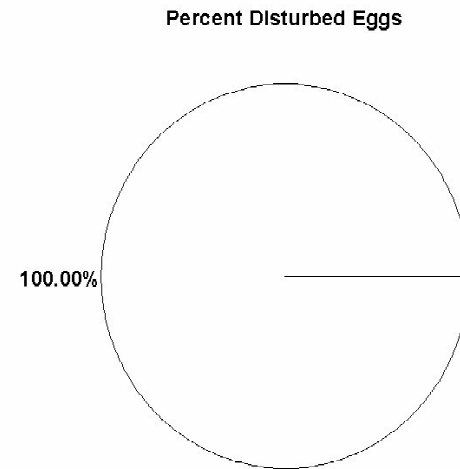
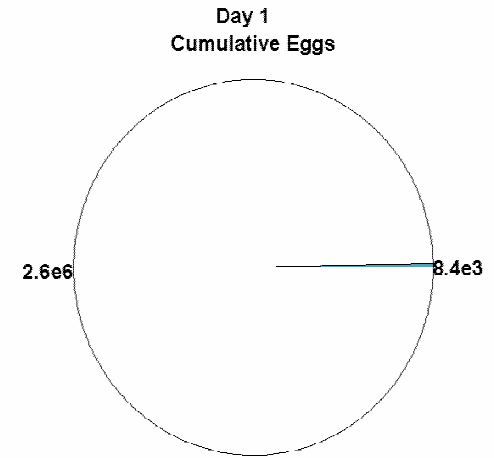
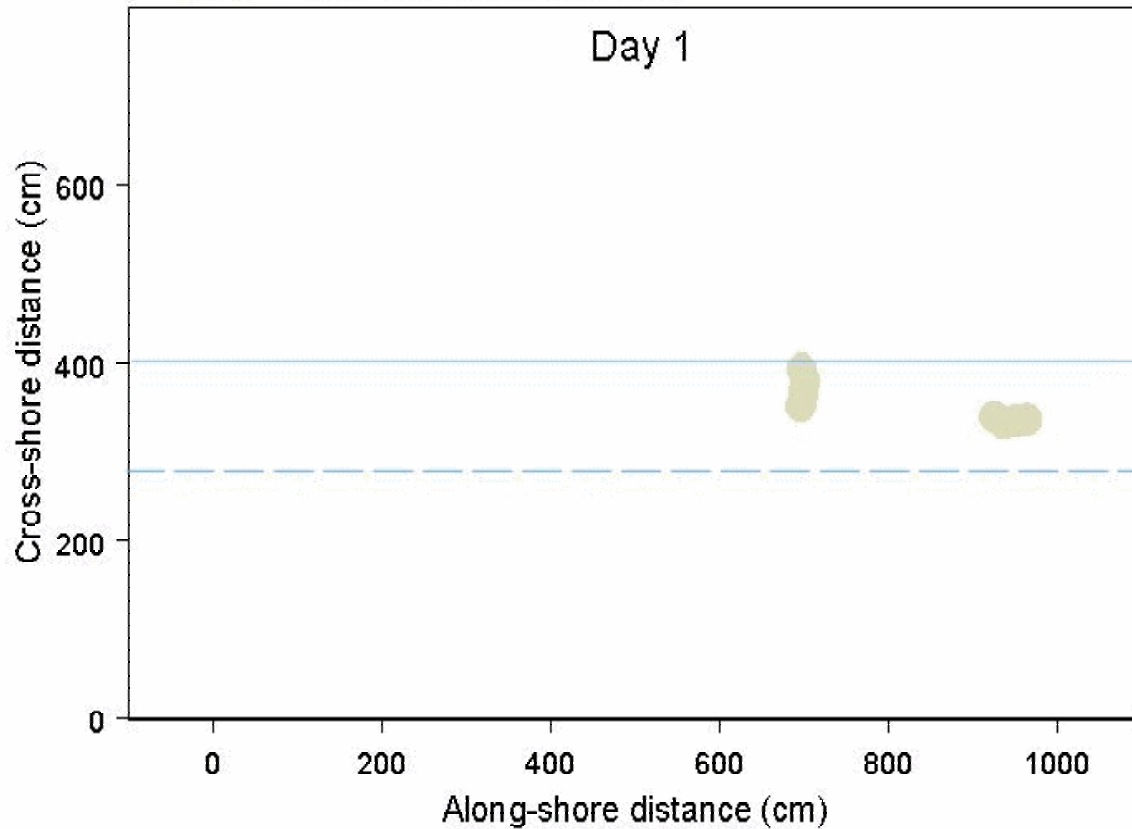
High-high Tide



Eggs clutches disturbed by 1 or more spawning females



Low-high Tide



Egg mortality: density dependent function of spawning female abundance

Based on modeling of Smith (2007)

As female spawner abundance increased –

Nest disturbance increased

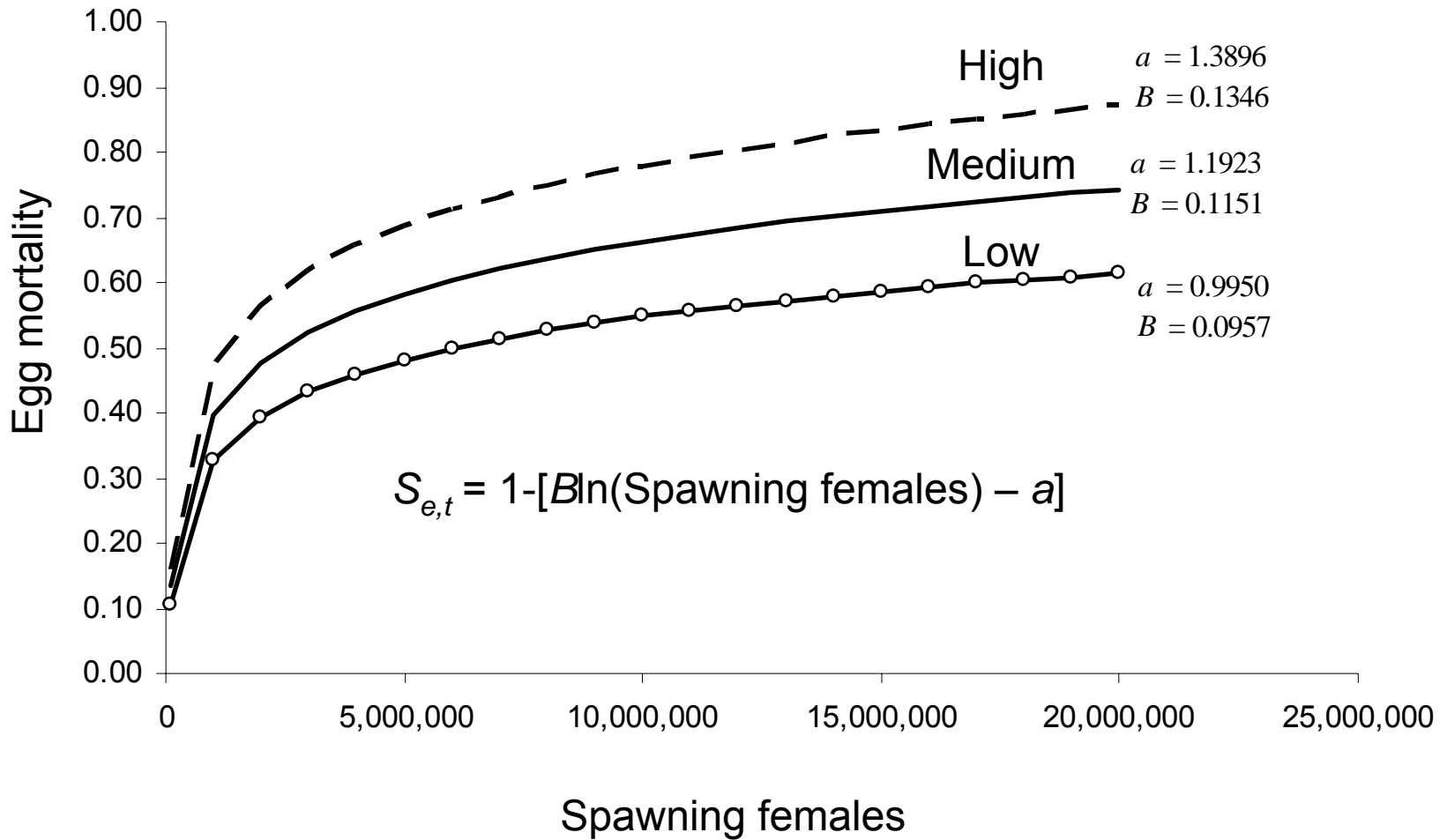
Spawning moved lower on the beach

Eggs laid in lower 15% of beach did not develop

Eggs in upper 85% of beach –

3 assumed rates of mortality given nest disturbance (50, 65, and 80%)

Egg mortality: density dependent function of spawning female abundance





Surface eggs: density dependent function of spawning female abundance

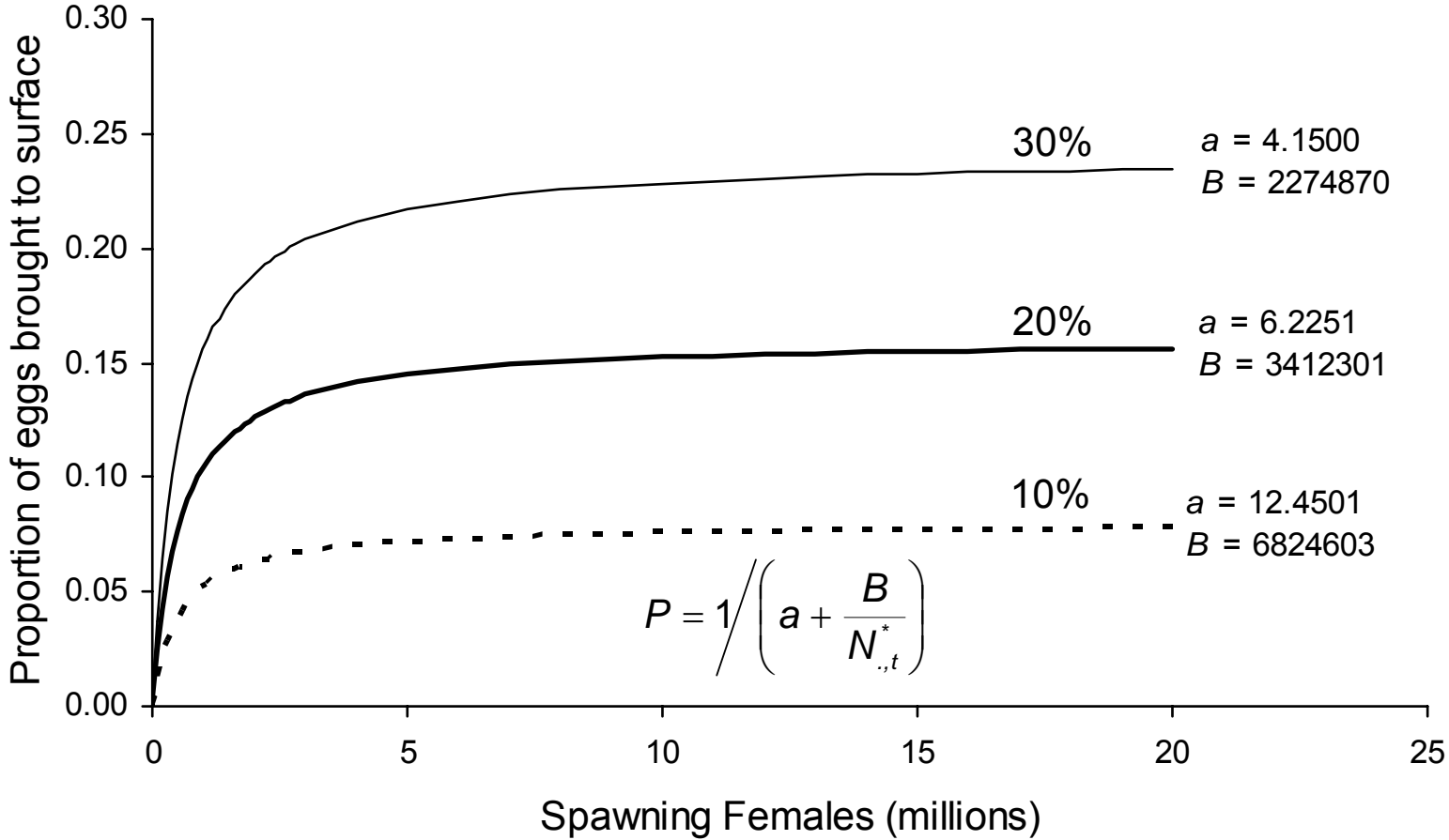
Based on modeling of Smith (2007)

As female spawner abundance increased –

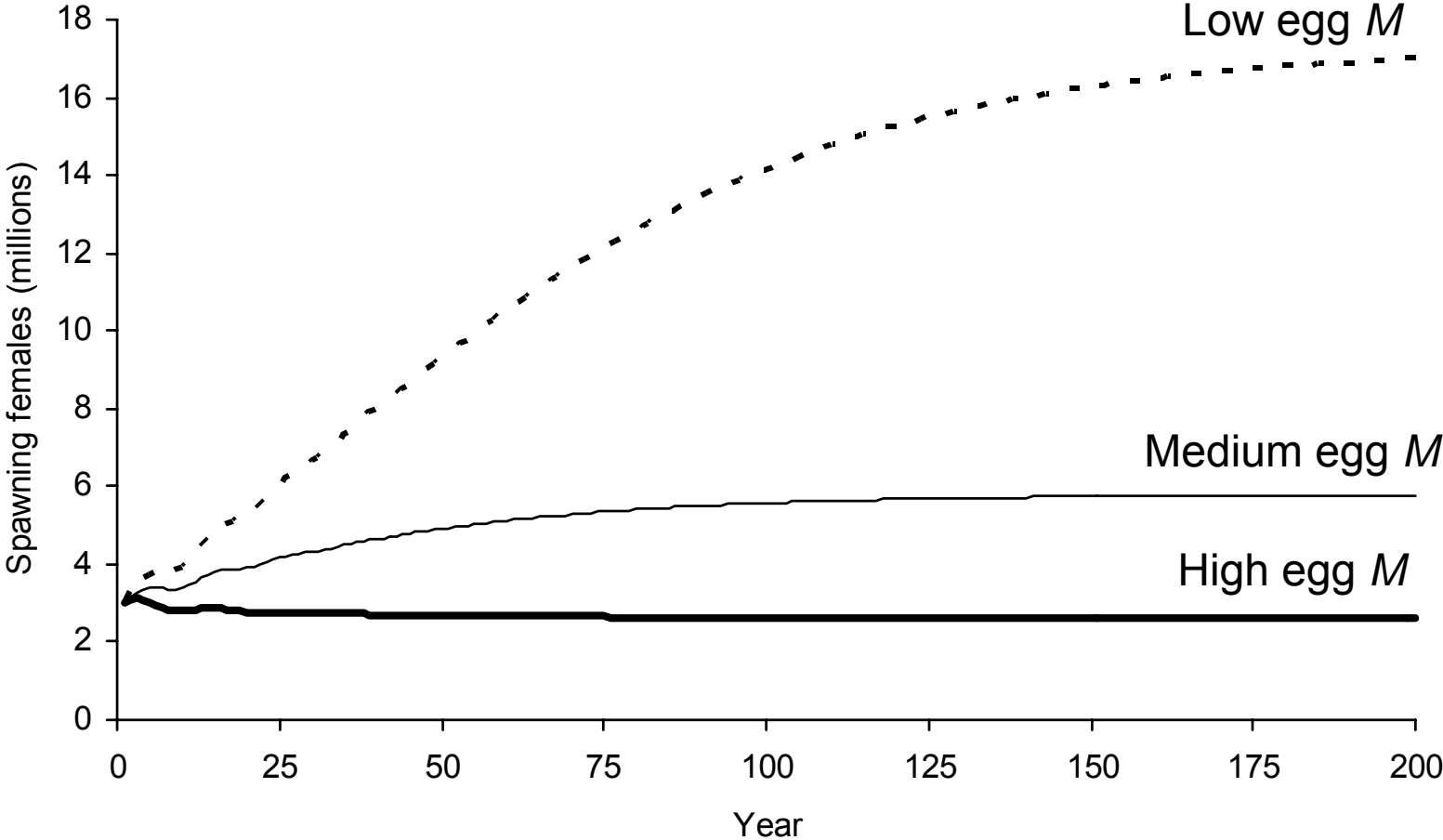
Nest disturbance increased

Assumed 3 rates of exhumation – 10, 20, & 30% of eggs brought to surface given nest disturbance

Surface eggs: density dependent function of spawning female abundance

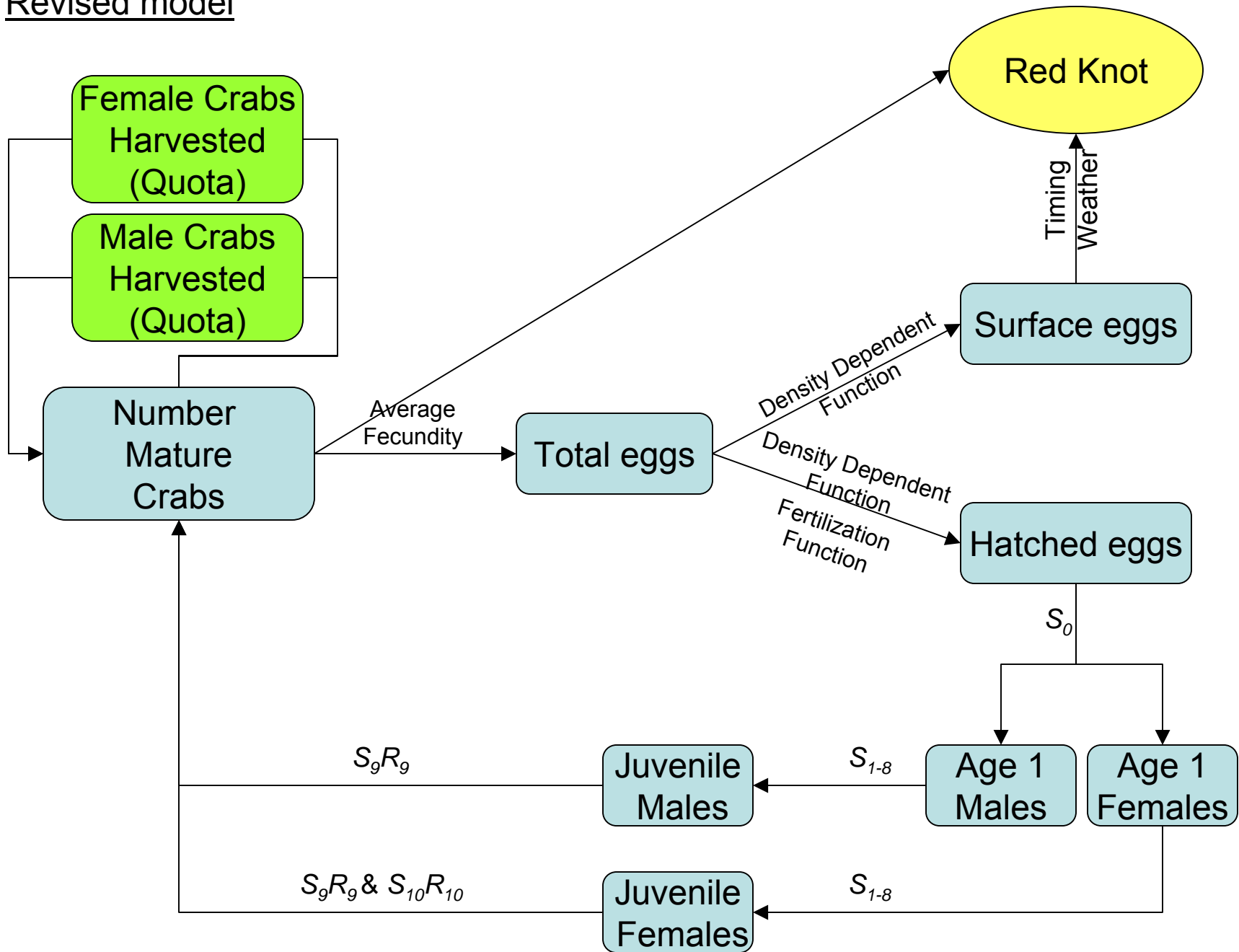


Projection from deterministic model



## Changes to Age-Structured Model

Revised model



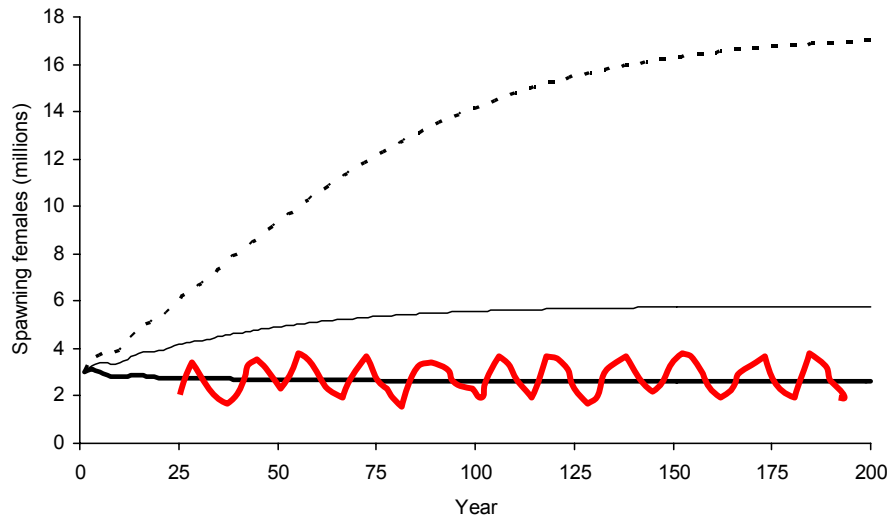
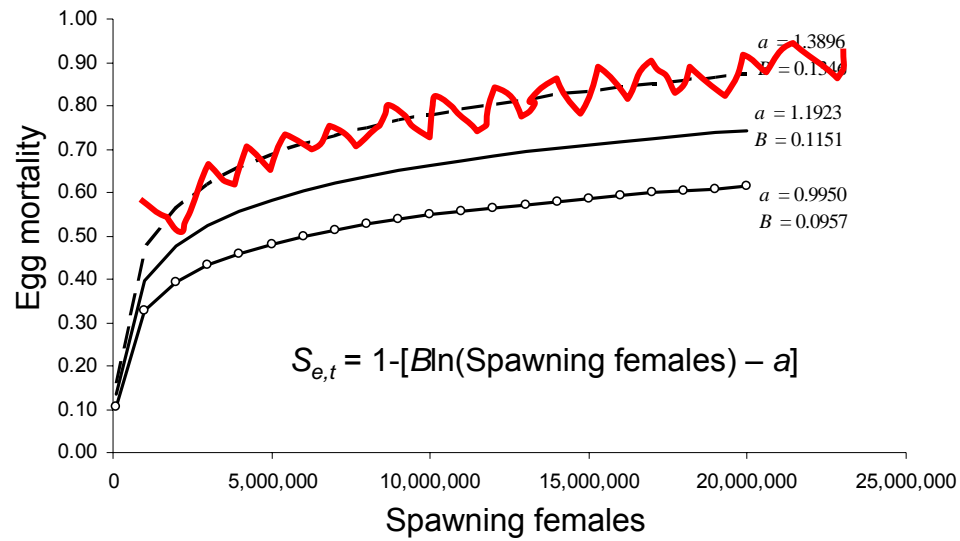
## Addition of Males

| <b>Age</b> | <b>Female recruitment</b> | <b>Male recruitment</b> |
|------------|---------------------------|-------------------------|
| 0 – 1      | 0.0                       | 0.0                     |
| 1 – 8      | 0.0                       | 0.0                     |
| 9          | 0.25                      | 0.4                     |
| 10         | 0.50                      | 1.0                     |
| 11 – 20    | 1.0                       | 1.0                     |

Recruitment to spawning stock AND fishery

Assume age-specific survivals are the same as females

Drop “High” egg mortality scenario – does not allow population growth even in the absence of harvest



## Alternative Survivorship Schedules

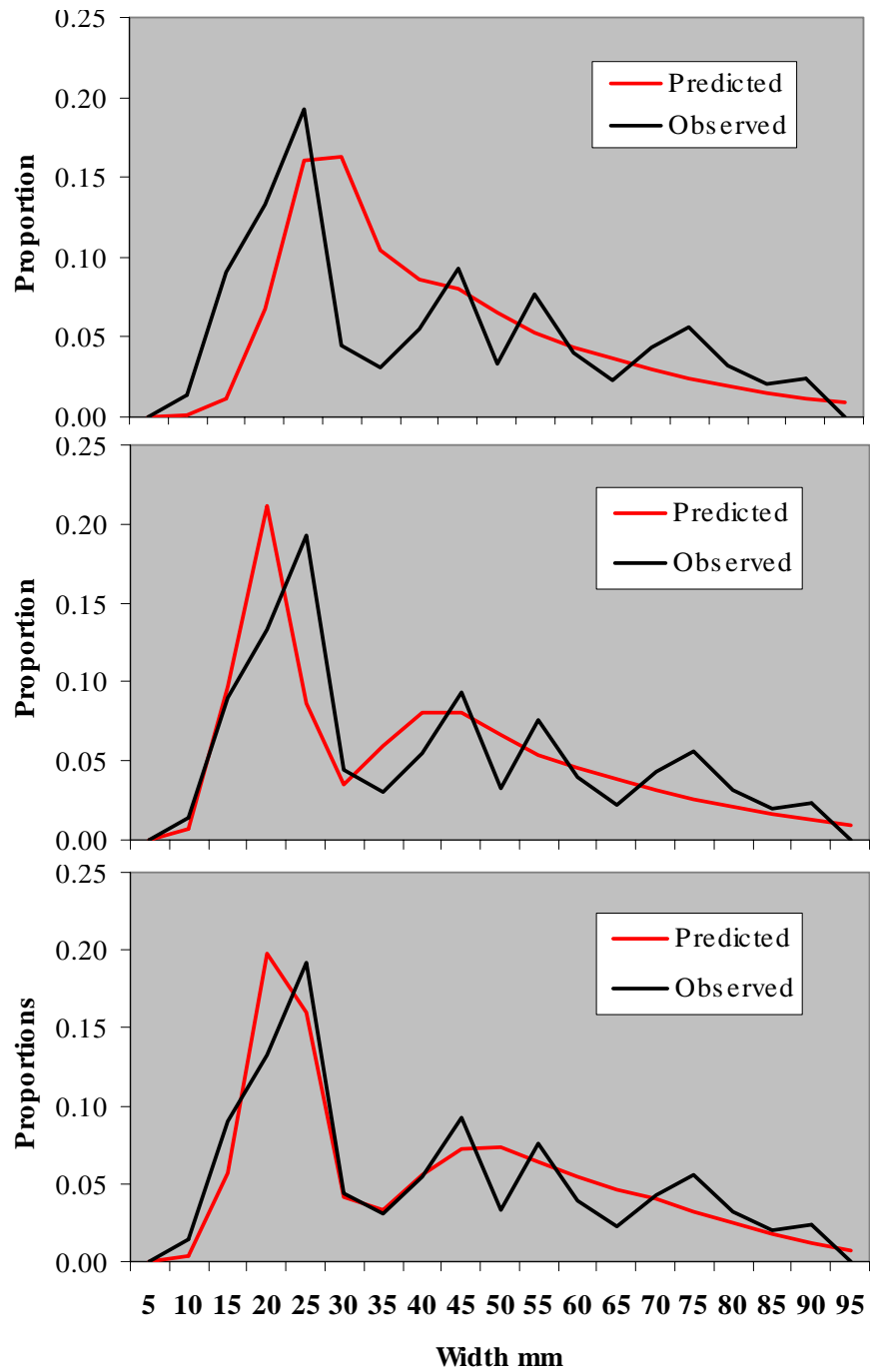
Sweka et al. 2007 – values from literature and assumed c.v.

|            | <i>Sweka et al. 2007</i> |             |
|------------|--------------------------|-------------|
| <b>Age</b> | <b>S</b>                 | <b>C.V.</b> |
| 0          | 0.00003                  | 0.15        |
| 1 – 8      | 0.9738                   | 0.15        |
| 9 – 10     | 0.7994                   | 0.15        |
| 11 – 17    | 0.6250                   | 0.15        |
| 18 – 19    | 0.08                     | 0.15        |
| 20         | 0                        | 0.15        |

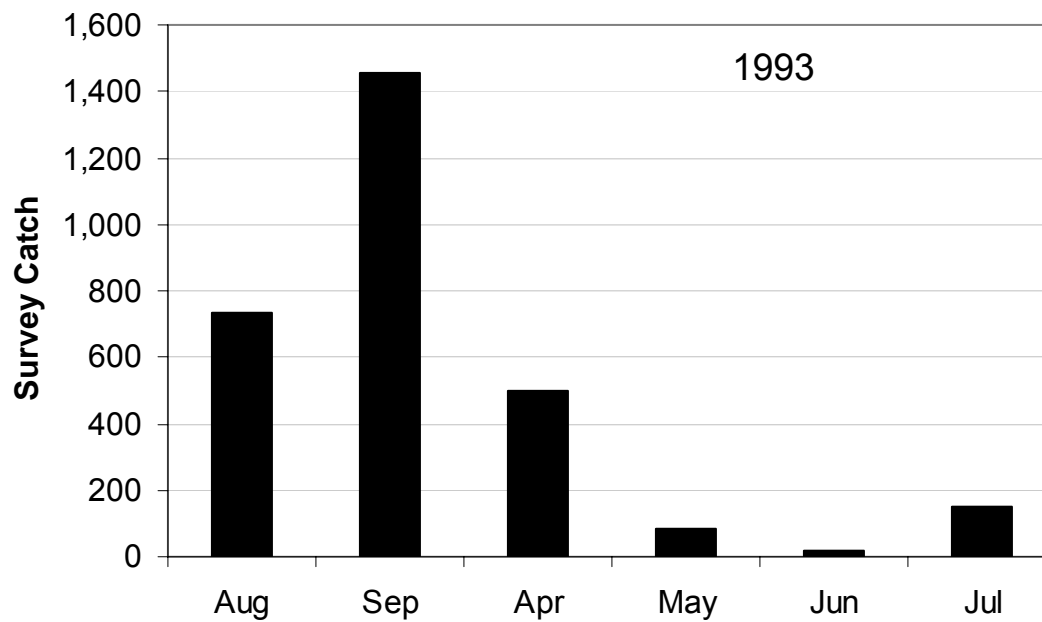
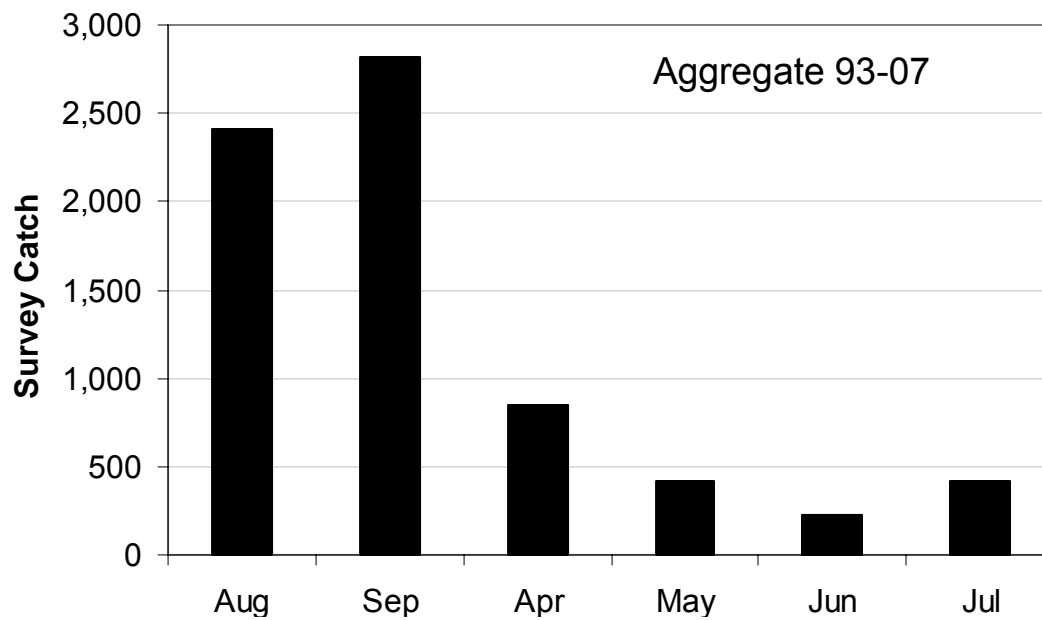
Rich Wong – Estimates of Z and c.v. from Delaware Trawl Survey



# Mortality Rate Estimation



# Young-of-the-Year Survival



## Alternative Survivorship Schedules



Sweka et al. 2007 – values from literature and assumed c.v.

Rich Wong – Estimates of  $Z$  and c.v. from Delaware Trawl Survey

|         | <i>Sweka et al. 2007</i> |      |  | Rich Wong (DE Trawl Survey) |      |      |                |
|---------|--------------------------|------|--|-----------------------------|------|------|----------------|
| Age     | $S$                      | C.V. |  | Age                         | $Z$  | $S$  | range $S$      |
| 0       | 0.00003                  | 0.15 |  | 0 only                      | 3.60 | 0.03 | 0.00009 – 0.21 |
|         |                          |      |  | 0 – 6                       | 0.86 | 0.42 | 0.14 – 0.76    |
|         |                          |      |  |                             |      |      |                |
| 1 – 8   | 0.9738                   | 0.15 |  | 1 – 6                       | 0.32 | 0.73 | 0.72 – 0.76    |
| 9 – 10  | 0.7994                   | 0.15 |  |                             |      |      |                |
| 11 – 17 | 0.6250                   | 0.15 |  |                             |      |      |                |
| 18 – 19 | 0.08                     | 0.15 |  |                             |      |      |                |
| 20      | 0                        | 0.15 |  |                             |      |      |                |

## Competing models or a blending of models

Sensitivity analysis – age 0  $S$  most sensitive parameter in model, slight increases result in very rapid population growth followed by a crash due to “overshooting” egg mortality curves



## Handling sex ratios in the model (?)

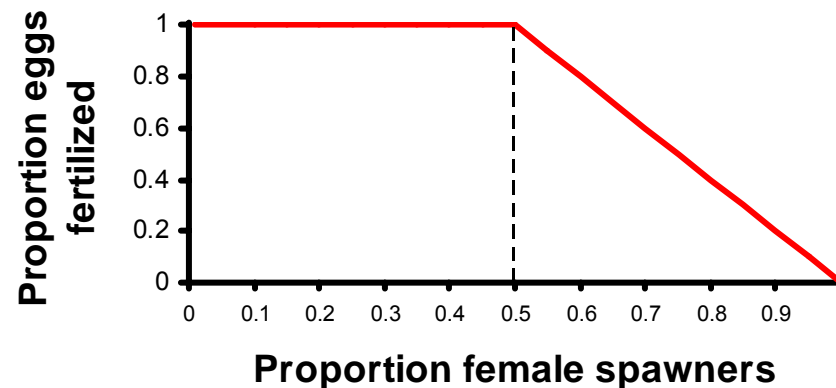
Male only harvest is one management alternative

At what point will harvest of males begin to influence spawning success?

Currently in model:

If proportion mature females  $\leq 0.5$ , then all eggs are fertilized

Else, proportion of eggs fertilized =  $1 - (\text{prop. Female} - \text{prop. Male})$



Jane Brockman's lab – conducting studies to link operational sex ratios to fertilization rates; We have contacted her for an update

Any other suggestions????

## Alternative HSC modeling approaches



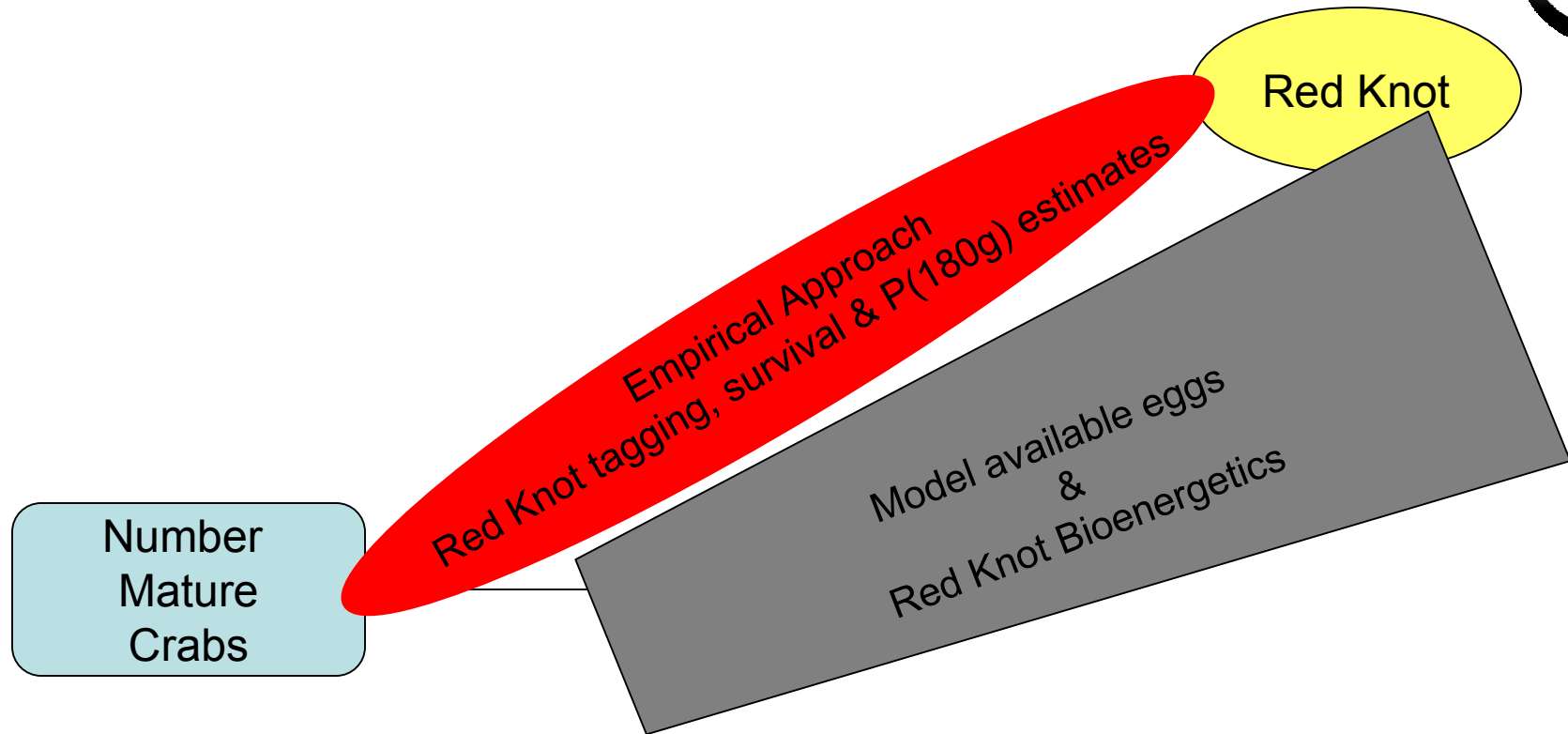
Currently using age-structured model

Also consider for estimation/projection:

Catch-survey models

Surplus production models

# Modeling the Link between HSC egg production and Red Knots (?)



Currently favoring the **Empirical Approach**

Direct link to HSC abundance

Much uncertainty in egg availability modeling

# Linking Red Knot and Horseshoe Crab populations



By Conor P. McGowan, James D. Nichols,  
David R. Smith and the Delaware Bay  
Horseshoe Crab - Red Knot ARM work  
Group

# The Objective Function

Maximize allowable harvest of horseshoe crabs with the constraint that 90% of early arriving red knots reach 180 gms by May 28th. [Comment: The objective statement links HSC and REKN populations by isolating the influence of horseshoe crabs, through their eggs, on red knot weight gain during stop over.]

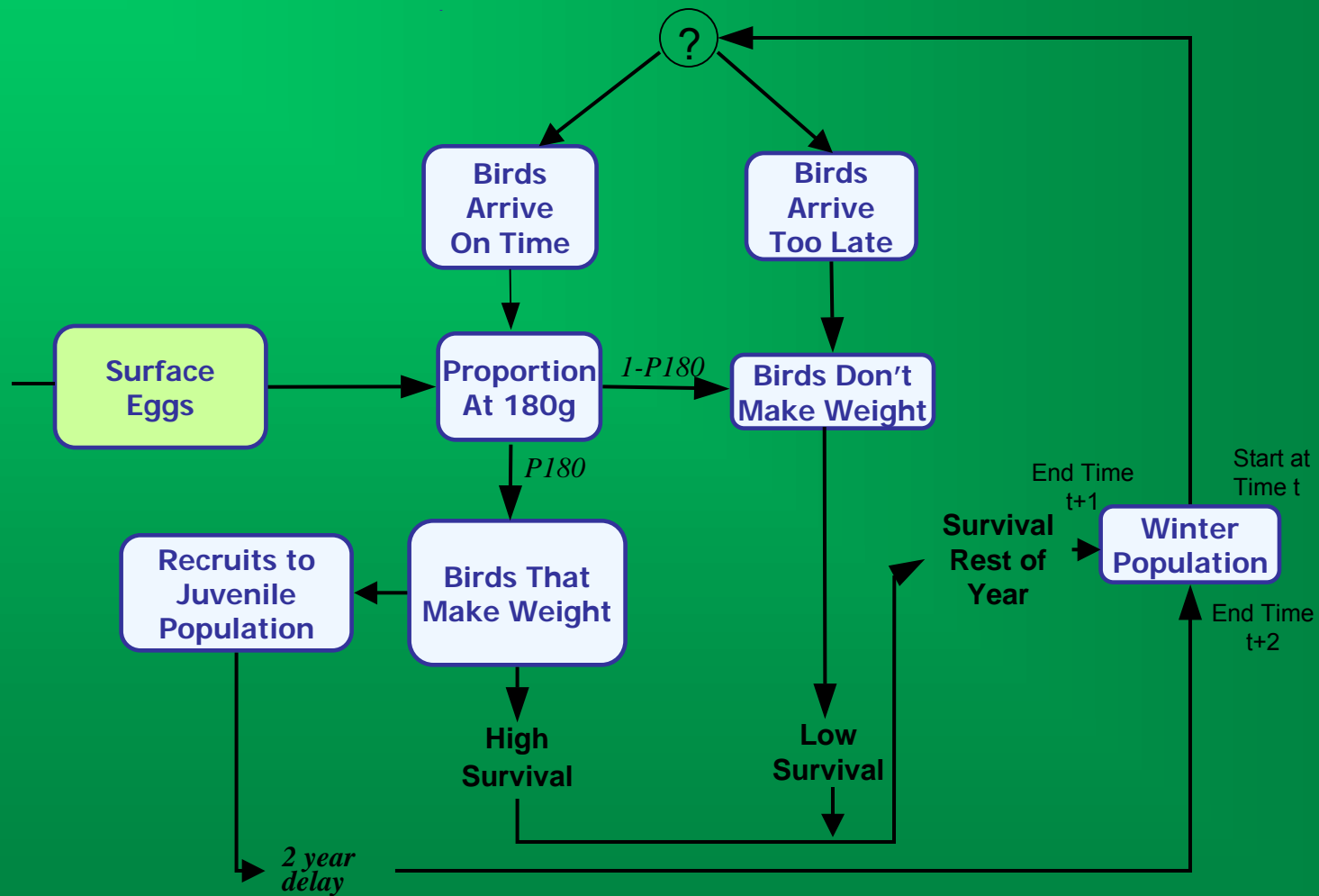
$$\max \sum_{t=1}^{\infty} u_t H_t$$

$u$  = utility of harvesting horseshoe crabs, which is a function of whether there are sufficient eggs for red knots

$H$  = number of horseshoe crabs harvested



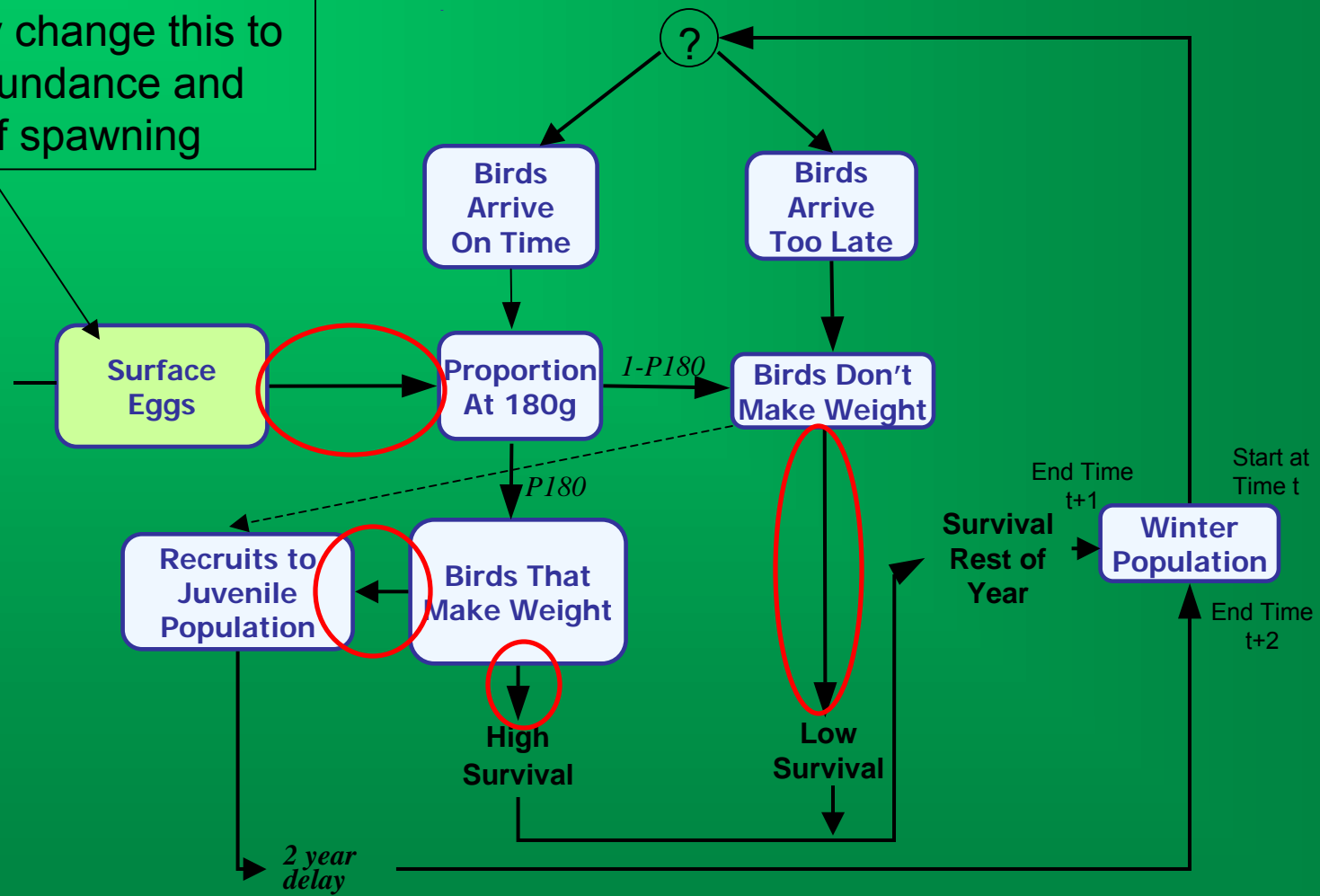
# Red Knot



# Red Knot



We may change this to HSC abundance and timing of spawning



# Red Knot Population Matrix

$$\begin{array}{|c|c|c|} \hline 0 & 0 & F \\ \hline S_i & 0 & 0 \\ \hline 0 & S_f & S_a \\ \hline \end{array} \times \begin{array}{|c|} \hline N_{i,t} \\ \hline N_{f,t} \\ \hline N_{a,t} \\ \hline \end{array} = \begin{array}{|c|} \hline N_{i,t+1} \\ \hline N_{f,t+1} \\ \hline N_{a,t+1} \\ \hline \end{array}$$

# Red Knot Population Matrix

$$\begin{array}{|c|c|c|} \hline 0 & 0 & F \\ \hline S_i & 0 & 0 \\ \hline 0 & S_f & S_a \\ \hline \end{array} \times \begin{array}{|c|} \hline N_{i,t} \\ \hline N_{f,t} \\ \hline N_{a,t} \\ \hline \end{array} = \begin{array}{|c|} \hline N_{i,t+1} \\ \hline N_{f,t+1} \\ \hline N_{a,t+1} \\ \hline \end{array}$$

# Red Knot Adult survival and Horseshoe Crab abundance

- Theory and evidence indicates that annual adult survival of REKN is dependent on mass at the time of departure from the Delaware Bay.
- Horseshoe crab eggs are the primary food resource in the Delaware Bay during migration.
- Logically, HSC abundance determines HSC-egg availability for migrating Red Knots

Multi-state Open Robust Design  
Mark-Recapture/resight Survival  
Analysis for Red Knots in the  
Delaware Bay

# Goals of the analysis

- Estimate annual survival of red knots contingent upon weight or mass at the end of the Delaware Bay stop-over period.
- Estimate weight at end of Del Bay stopover period (based on estimated weights on arrival and weight class transition probabilities during stopover period)
- Estimate the relationship between mass class transition probabilities and horseshoe crab abundance
  - Adult female abundance, Egg abundance

# Mark-Recapture with multiple states

- Typical capture history for mark-recapture
  - 10100110110
- In multi-state analysis there is some state assigned to the individuals in the study
  - State could be an assigned: mass class or habitat patch
  - A0A00BB0CC0
    - A, B and C denote differ states that the animal was in at the times of capture
- Covariate analyses can be incorporated



# Applying this approach to Red Knots

- We have extensive mark-recapture/resight data
- We can assign individuals to a weight class at time of capture
- Use the few (>200 1998 - 2008) within season re-traps together with resighting data to estimate transition rates from one weight class to the next
- Use HSC population metrics as covariates of the transition rates
  - Benthic trawl surveys combined with spawning survey (to capture both abundance and timing of spawning)

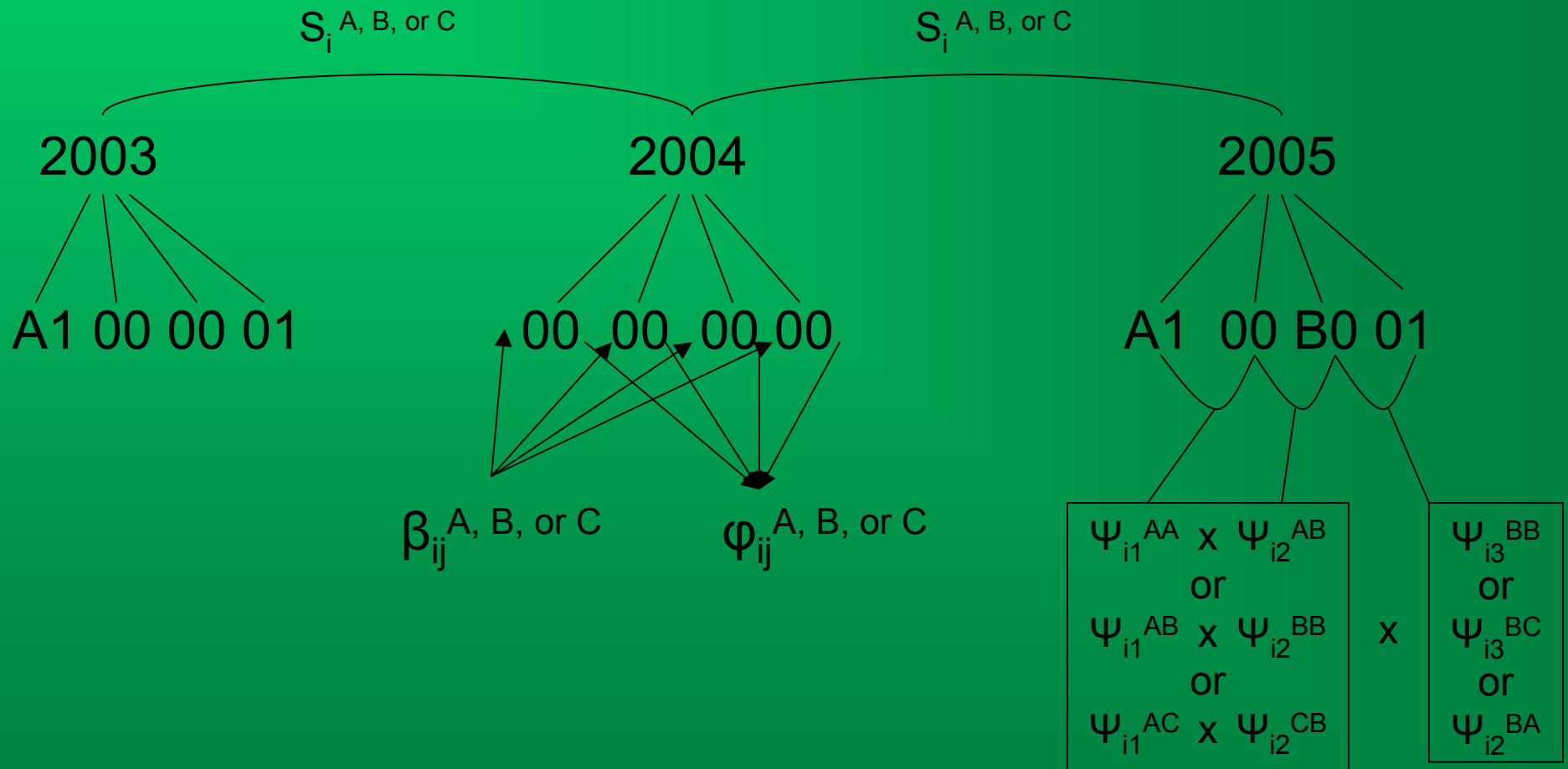
# Sampling Framework

- Multiple sampling “windows” over multiple years.
- Something like: four 8-day periods within a season from 2003 to 2008
- Three weight classes:
  - A = less than 135 grams
  - B = between 135 and 180 grams
  - C = greater than 180 grams

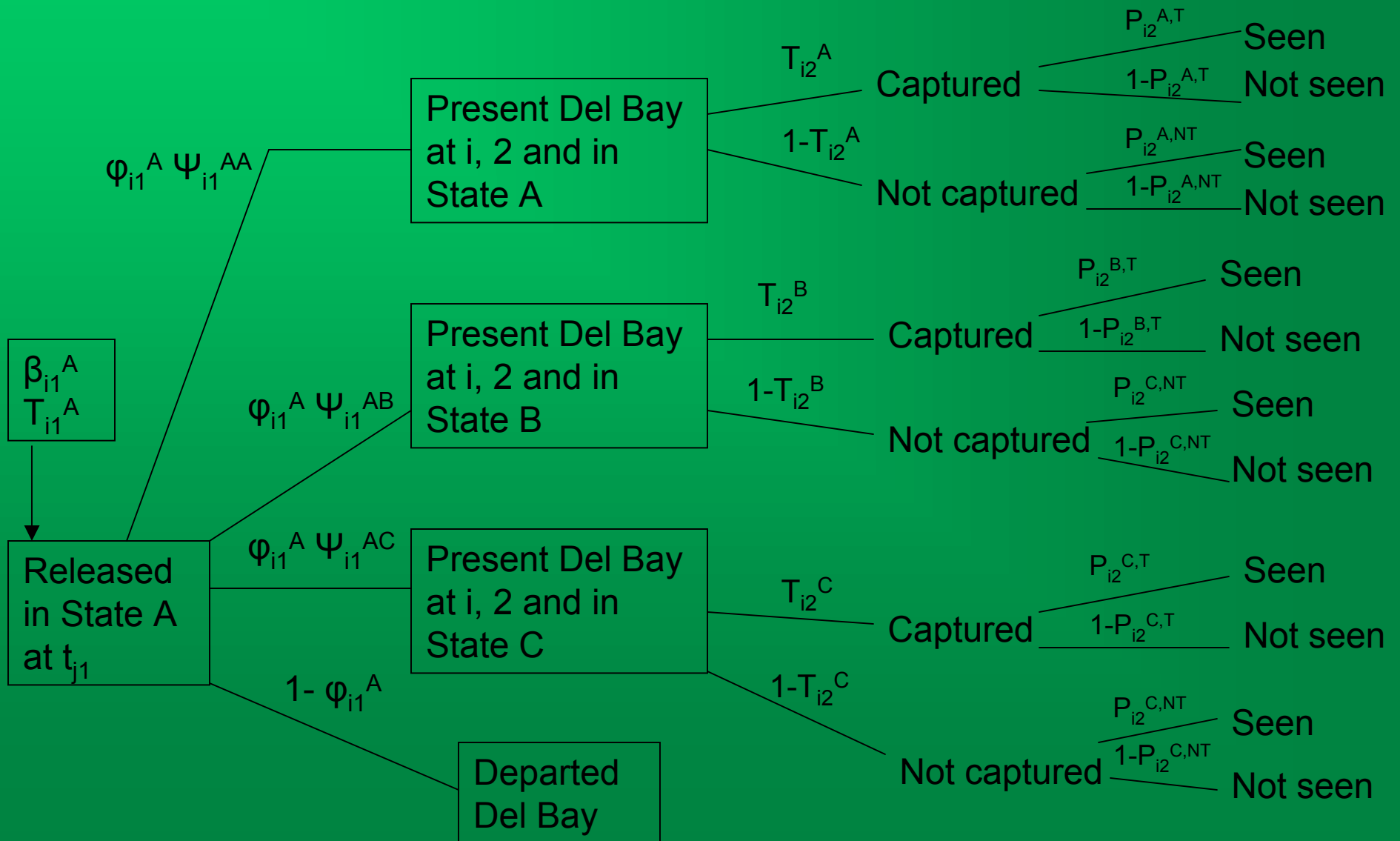
# More Frameworking

- We also have seen but not captured and not seen
  - 1 = seen but not captured
  - 0 = not seen
- Capture histories would look something like this:
  - A1 00 01 01, 01 00 B0 01, A1 01 00 C1

# Biologically important estimation



# Within year transition for one time step



# Parameter estimation

- Survival will be modeled as a function of state at time of departure.
  - $S_i^A, S_i^B, S_i^C$
- We will also estimate state dependent arrival, departure, transition, capture and resighting probabilities
  - $\beta_{ij}^{A, B, C}, \varphi_{ij}^{A, B, C}, \Psi_{ij}^{YX}, T_{ij}^{A, B, C}, p_{ij}^{A, B, C}$ 
    - $YX$  represent the numerous possibilities for transistions (eg: AA, AB, CA, BC,...)

# Tying Red Knots to Horseshoe Crab population metrics



- The multi-state survival and transition analysis can be run with covariates
- We will use benthic trawl survey and spawning survey data as covariates.
  - Captures HSC Abundance, and timing of peak spawning, both keys to REKN mass gain

# Red Knot Population Matrix

$$\begin{array}{|c|c|c|} \hline 0 & 0 & F \\ \hline S_i & 0 & 0 \\ \hline 0 & S_f & S_a \\ \hline \end{array} \times \begin{array}{|c|} \hline N_{i,t} \\ \hline N_{f,t} \\ \hline N_{a,t} \\ \hline \end{array} = \begin{array}{|c|} \hline N_{i,t+1} \\ \hline N_{f,t+1} \\ \hline N_{a,t+1} \\ \hline \end{array}$$



# Red Knot Fecundity and Horseshoe Crab Abundance

- Theory and evidence indicates that mass gain during migration will affect Red Knots ability to breed.
- Horseshoe crab eggs are the primary food resource in the Delaware Bay during migration.
- Logically, HSC abundance determines HSC-egg availability for migrating Red Knots

# How do we quantify that relationship?

- There is little or no data relating fecundity to mass at time of departure from Delaware Bay.
- High uncertainty in Juvenile to adult ratios from wintering flocks in Tierra Del Fuego.
- Possibly explore Delaware Bay recruitment
  - $\text{Recruitment} = \text{Actual \# new captures} - \text{expected \# of new captures}$

# Estimating recruitment

- Niles et al. in press suggest that:

$$N_{i+2}/N_i = ((N_i * S_i * S_{i+1}) + A_{i+2})/N_i = (S_i * S_{i+1}) + R_{i+2}$$

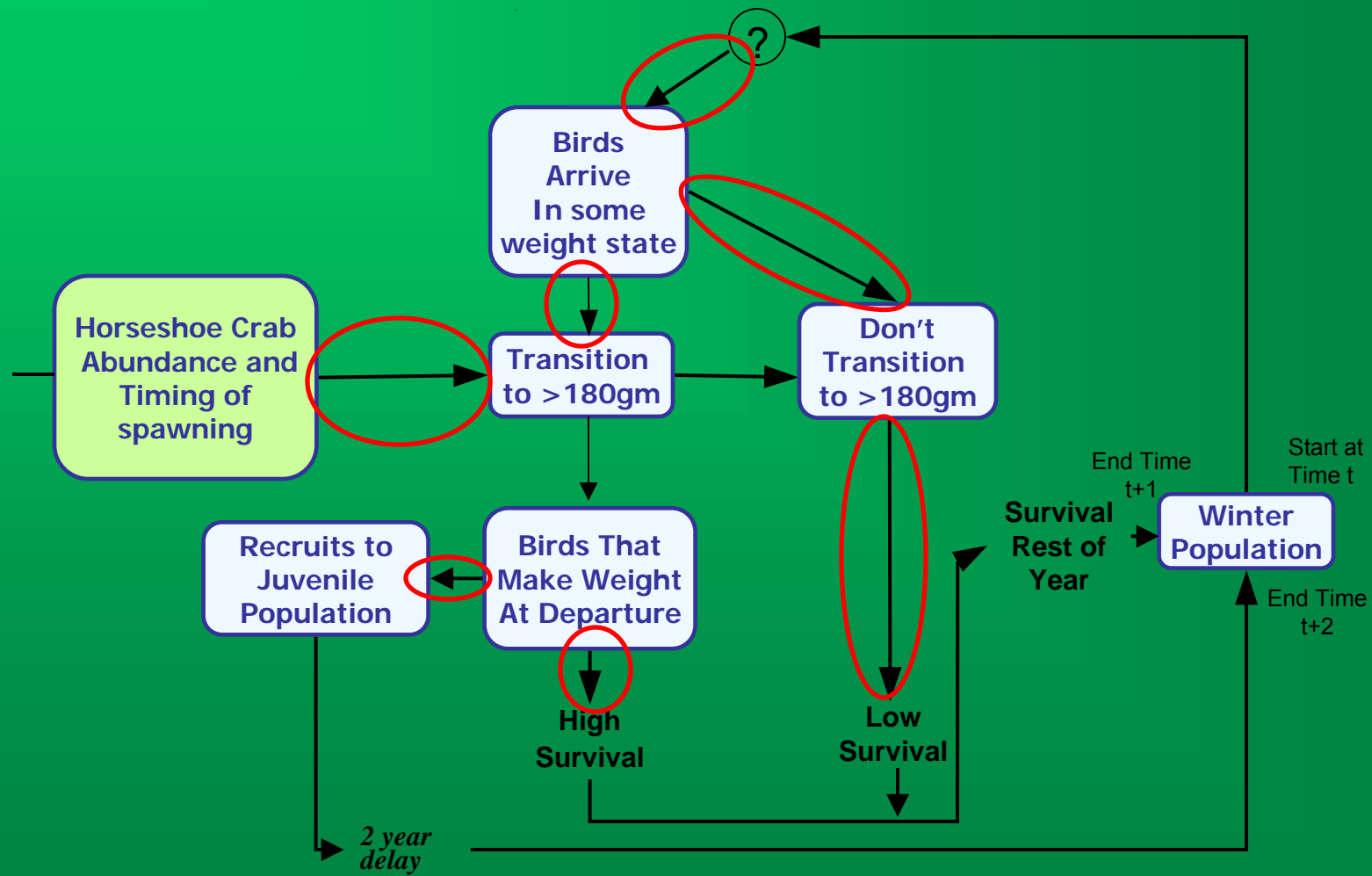
- $N$  is population size,  $S$  is annual adult survival,  $A$  is newly added individuals, and  $R$  is annual recruitment.
- Which reduces to

$$R_{i+2} = (N_{i+2}/N_i) - (S_i * S_{i+1})$$

# Decision Sensitivity to Fecundity/Recruitment



# Red Knot



# The Red Knot Population model

# Red Knot Population Matrix

$$\begin{array}{|c|c|c|} \hline 0 & 0 & F \\ \hline S_i & 0 & 0 \\ \hline 0 & S_f & S_a \\ \hline \end{array} \times \begin{array}{|c|} \hline N_{i,t} \\ \hline N_{f,t} \\ \hline N_{a,t} \\ \hline \end{array} = \begin{array}{|c|} \hline N_{i,t+1} \\ \hline N_{f,t+1} \\ \hline N_{a,t+1} \\ \hline \end{array}$$

# Model structure and some details: Modeling P180

- P180 is a population level summary statistic that may be obsolete with the Multi-state survival analysis
- Alternatively: Use the state dependent arrival, transition, departure and survival probabilities
  - Incorporated into the population model as stochastic variables



# Model structure and some details: Modeling Annual Survival

- Modeling state based survival:

$$N_{t+1}^{\text{REKN}} = (N_t^{\text{REKN}} \times \sum^j \phi_{ij}^{\text{C}} \times S_i^{\text{C}}) + (N_t^{\text{REKN}} \times \sum^j \phi_{ij}^{\text{B}} \times S_i^{\text{B}}) + (N_t^{\text{REKN}} \times \sum^j (1 - \phi_{ij}^{\text{B}} + \phi_{ij}^{\text{C}}) \times S_i^{\text{A}}) + \text{Recruits}$$

# Model structure and some details: Modeling fecundity or recruitment

- Modeling state based Fecundity

$$F_t^{\text{REKN}} = \left( (N_t^{\text{REKN}} \times \sum^j \varphi_{ij}^{\text{C}} \times F_i^{\text{C}}) + (N_t^{\text{REKN}} \times \sum^j \varphi_{ij}^{\text{B}} \times F_i^{\text{B}}) + (N_t^{\text{REKN}} \times \sum^j (1 - \varphi_{ij}^{\text{B}} + \varphi_{ij}^{\text{C}}) \times F_i^{\text{A}}) \right) / N_t^{\text{REKN}}$$

# Summary

- Identified a mass dependant survival analysis for Red Knots.
- Proposed approach for testing the effect of fecundity on the decision analysis
- Specific population model structure will depend on Data and results from survival analyses

# The Objective Function

Maximize allowable harvest of horseshoe crabs with the constraint that 90% of early arriving red knots reach 180 gms by May 28th. [Comment: The objective statement links HSC and REKN populations by isolating the influence of horseshoe crabs, through their eggs, on red knot weight gain during stop over.]

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

$u$  = utility of harvesting horseshoe crabs, which is a function of whether there are sufficient eggs for red knots

$H$  = number of horseshoe crabs harvested

# Questions?



# Model structure and some details:

Modeling the State based population parameters

- $$P180_i \approx \sum^j (\beta_{ij}^A \times (\Psi_{ij}^{AB} \times \Psi_{ij}^{BC}) \times \Psi_{ij}^{AC}) + (\beta_{ij}^B \times \Psi_{ij}^{BC}) + (\beta_{ij}^C \times \Psi_{ij}^{CC}) - (\beta_{ij}^A \times \Psi_{ij}^{AA}) - (\beta_{ij}^B \times \Psi_{ij}^{BA} \times \Psi_{ij}^{BB}) - (\beta_{ij}^C \times \Psi_{ij}^{CA} \times \Psi_{ij}^{CB})$$
- The exact complexity is dependent on data
- OR... ~~P180~~ ...and instead use state based departure probabilities:  $\sum^j \varphi_{ij}^A$ ,  $\sum^j \varphi_{ij}^B$ ,  $\sum^j \varphi_{ij}^C$