



# Complexity in Endangered Species Management

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- Can we identify optimal water management strategies throughout the Middle Rio Grande River so that local economic and social needs are met without further endangering the resident Rio Grande silvery minnow and Southwest Willow Flycatcher?



# Complexity in Endangered Species Management

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- Can we identify appropriate strategies for reintroducing viable populations of scimitar-horned oryx across multiple countries throughout Sahelo-Saharan Africa, where habitat quality has been degraded through intensive agricultural activity?





# Complexity in Endangered Species Management

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- How do we reconstruct a functional network of small, isolated populations of African wild dogs across a human-dominated landscape?



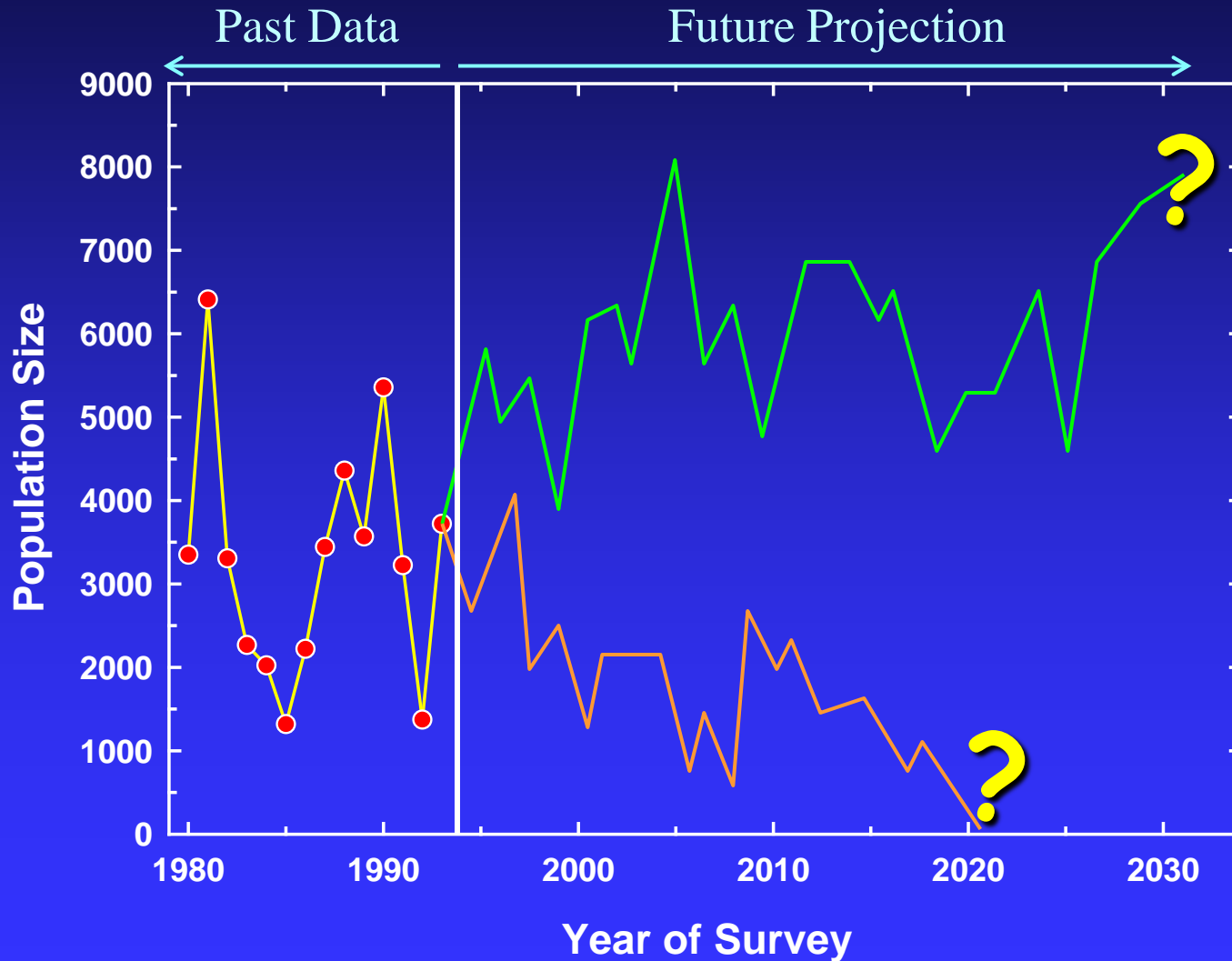
# Complexity in Endangered Species Management

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- How does sustained hunting pressure by local human populations impact long-term viability of North American polar bear populations in the face of increased climatic instability?



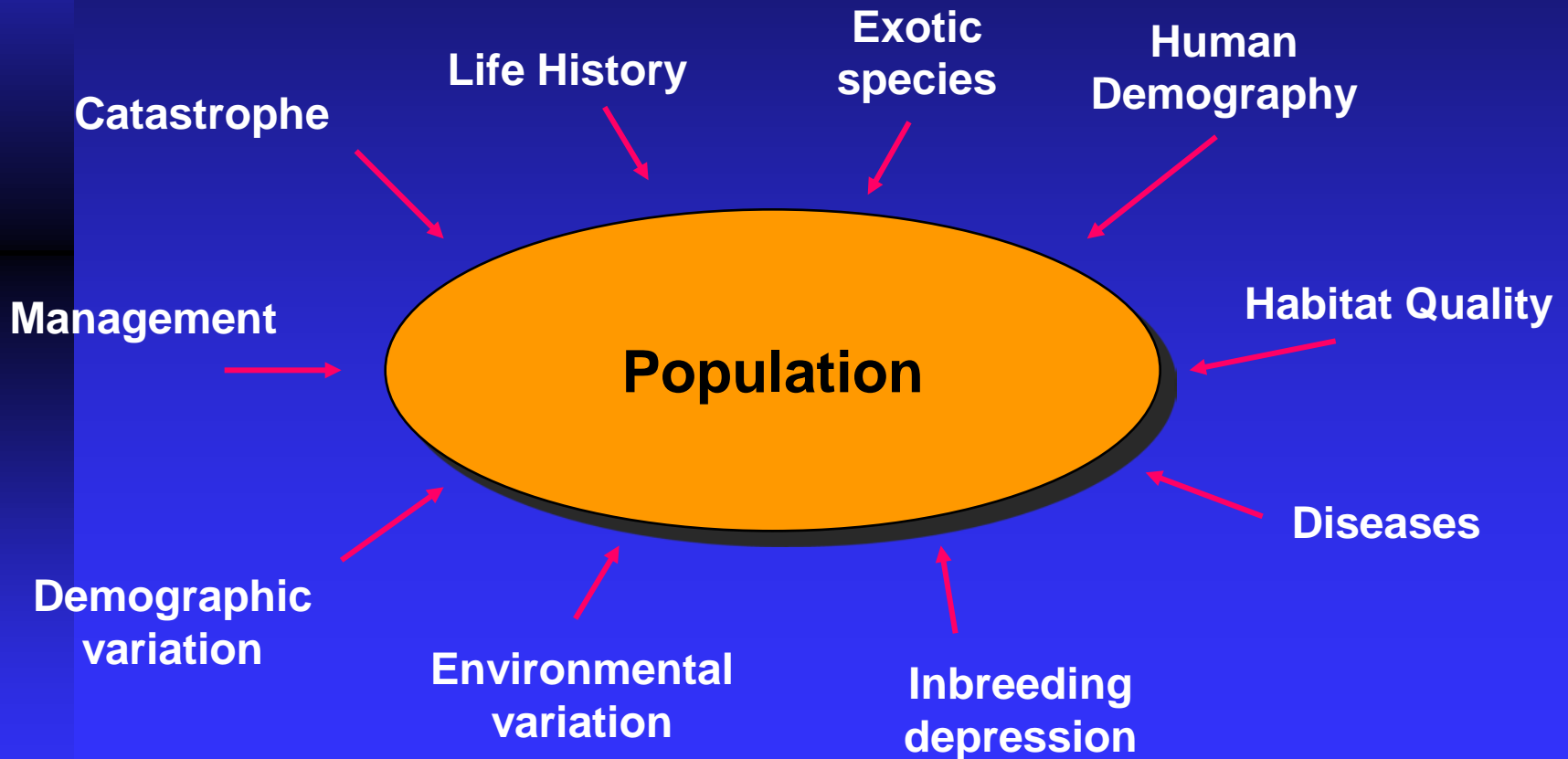
# What Might the Future Bring?



# Population Viability Analysis – PVA

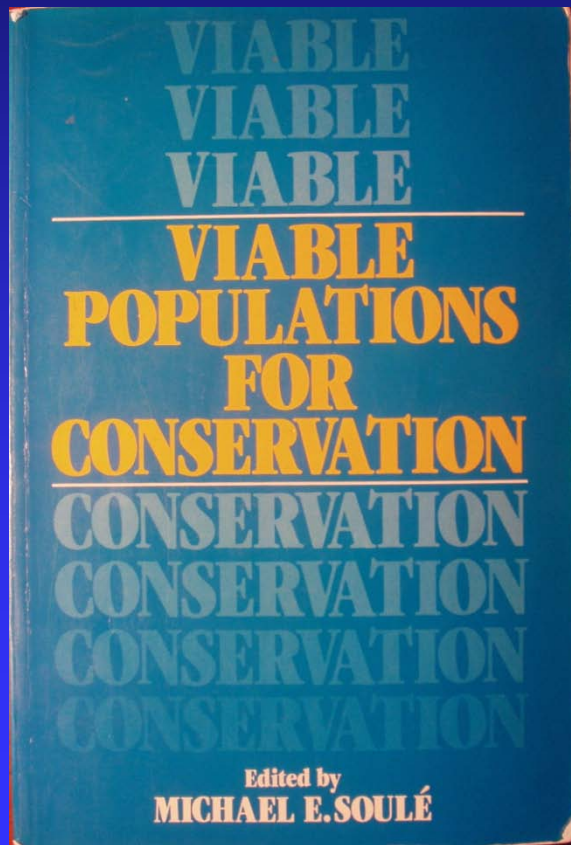
The Process of Evaluating the Interacting Factors Affecting Population Extinction Risk

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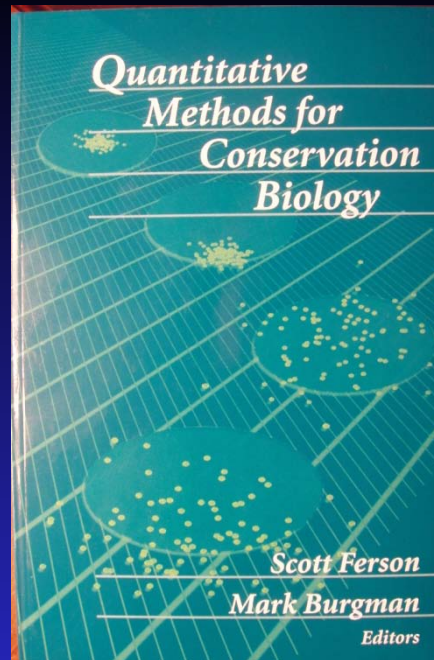




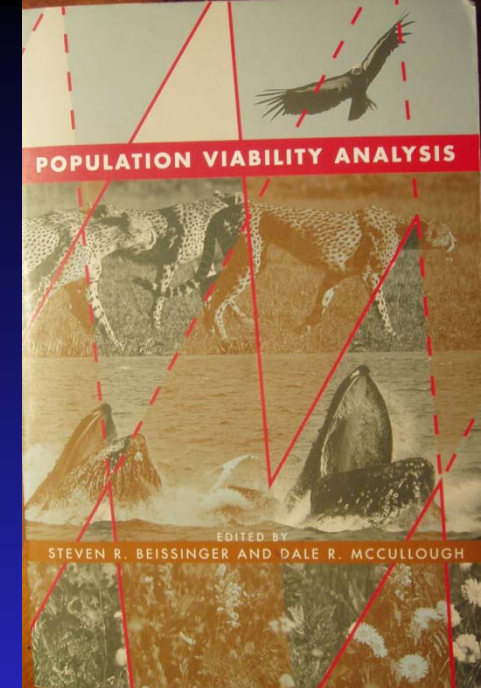
# The Science of PVA



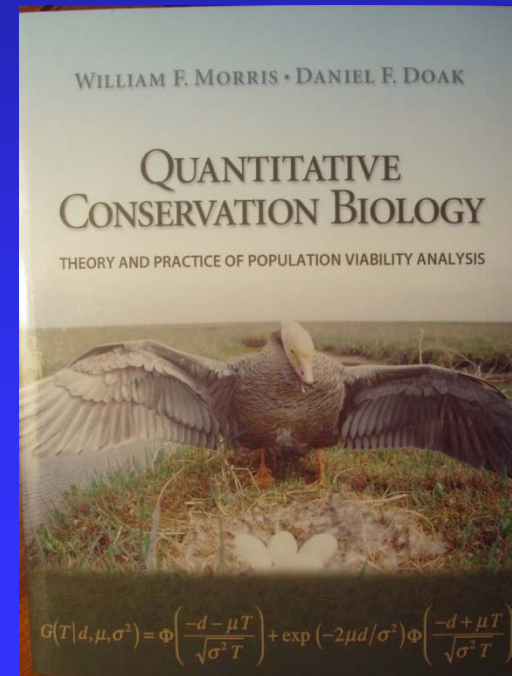
1987



2000



2002



2002



# An Analytical Approach to PVA

Mean Time to Extinction, MTE:

$$\text{MTE} = \sum_{x=1}^N \sum_{y=x}^K \frac{2}{y(yV_y - r_z)} \prod_{z=x}^{y-1} \frac{zV_z + r_z}{zV_z - r_z}$$

From:  
Goodman, 1987

*where*

$r$  = mean exponential growth rate

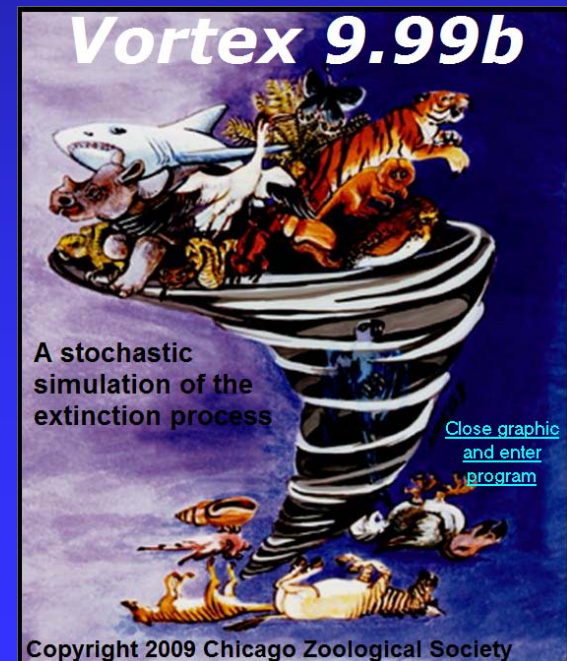
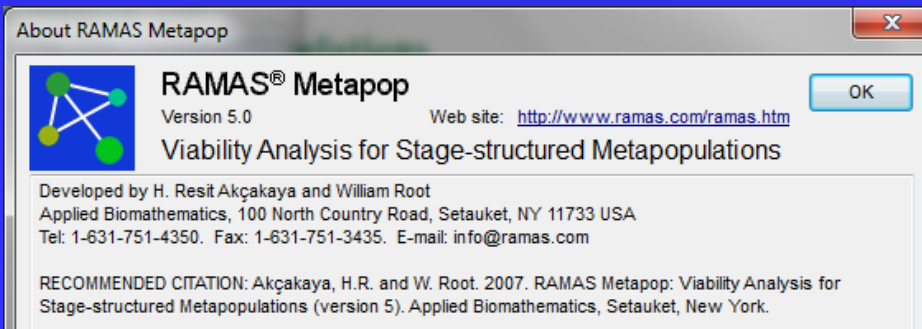
$V$  = variance in  $r$

$N$  = initial population size

$K$  = carrying capacity

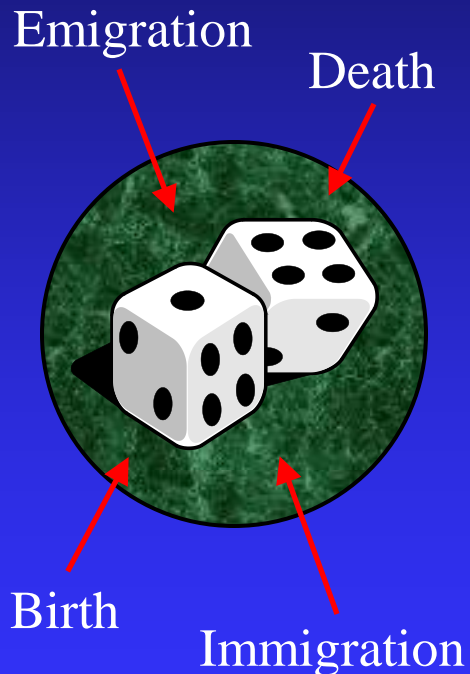
**But this approach remains simplistic** – little to no ability to tease apart the many factors that collectively determine and influence the population growth rate and its variability over time.

# A Complementary Alternative: Computer Simulation



# What is a Simulation Model?

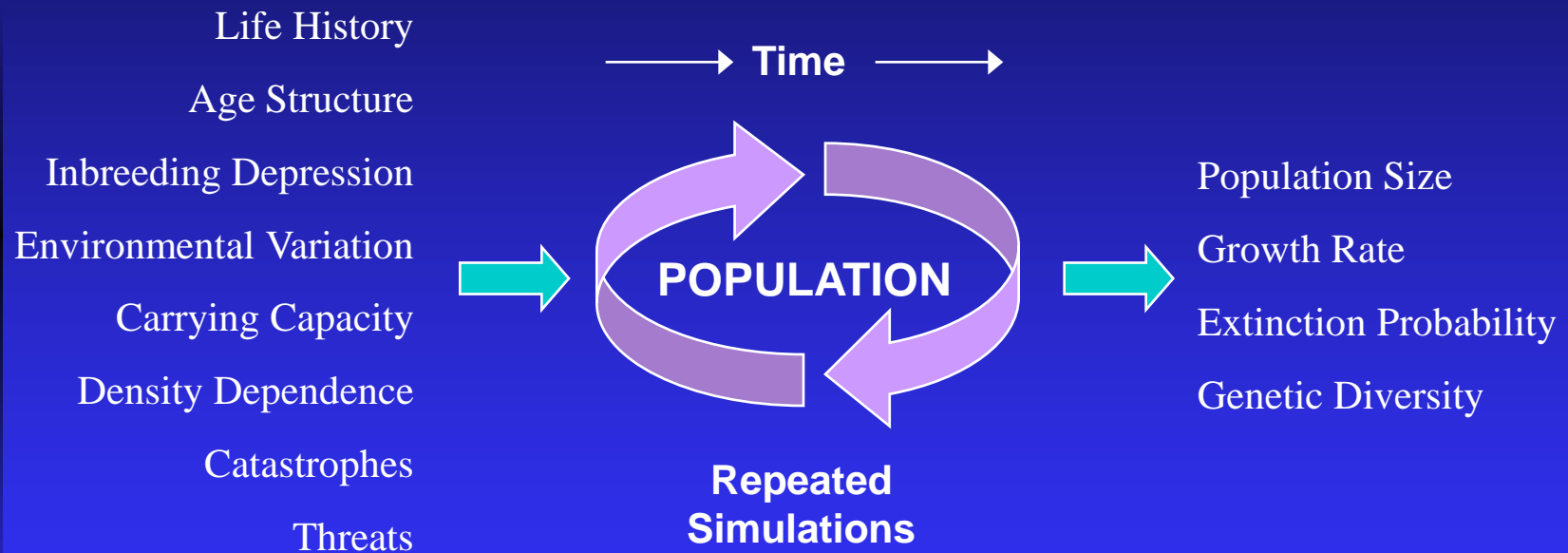
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- A simulation model is designed to follow, step by step, the essential elements of an animal population in the real world.
- A stochastic simulation incorporates the uncertainty and unpredictability of biological events in an attempt to recreate the natural world.

# The Mechanics of Population Dynamics Simulation Models

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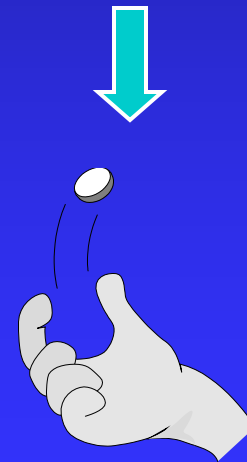




# Stochastic Simulation Models

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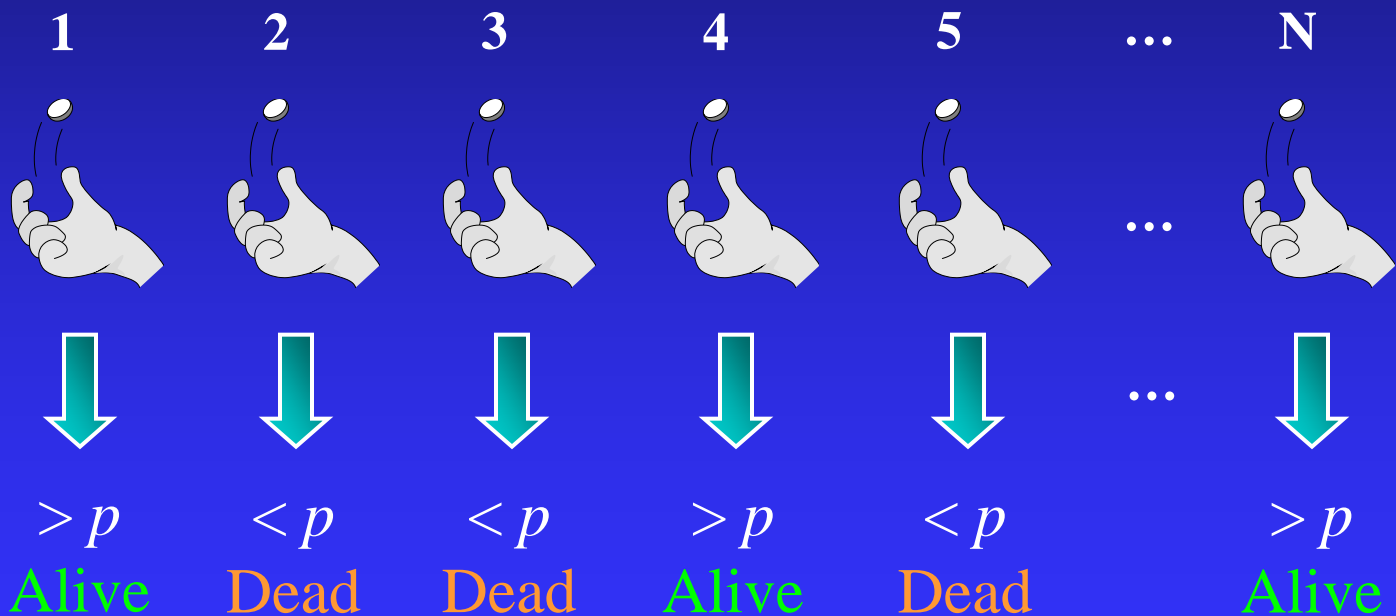
- Individual-based computer simulation uses a type of “coin-flipping” technique to determine the fate of individuals within populations at each time step (year, 6 months, day, etc.).
- Because of stochasticity in this process, different “runs” of the model will yield different results.



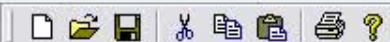
# Stochastic Simulation Models

## The Stochastic Nature of Mortality

Population size in year  $X = N_x$ ; probability of death =  $p$



Population size in year  $X + 1 = N_x - \text{Dead} = N_{X+1}$



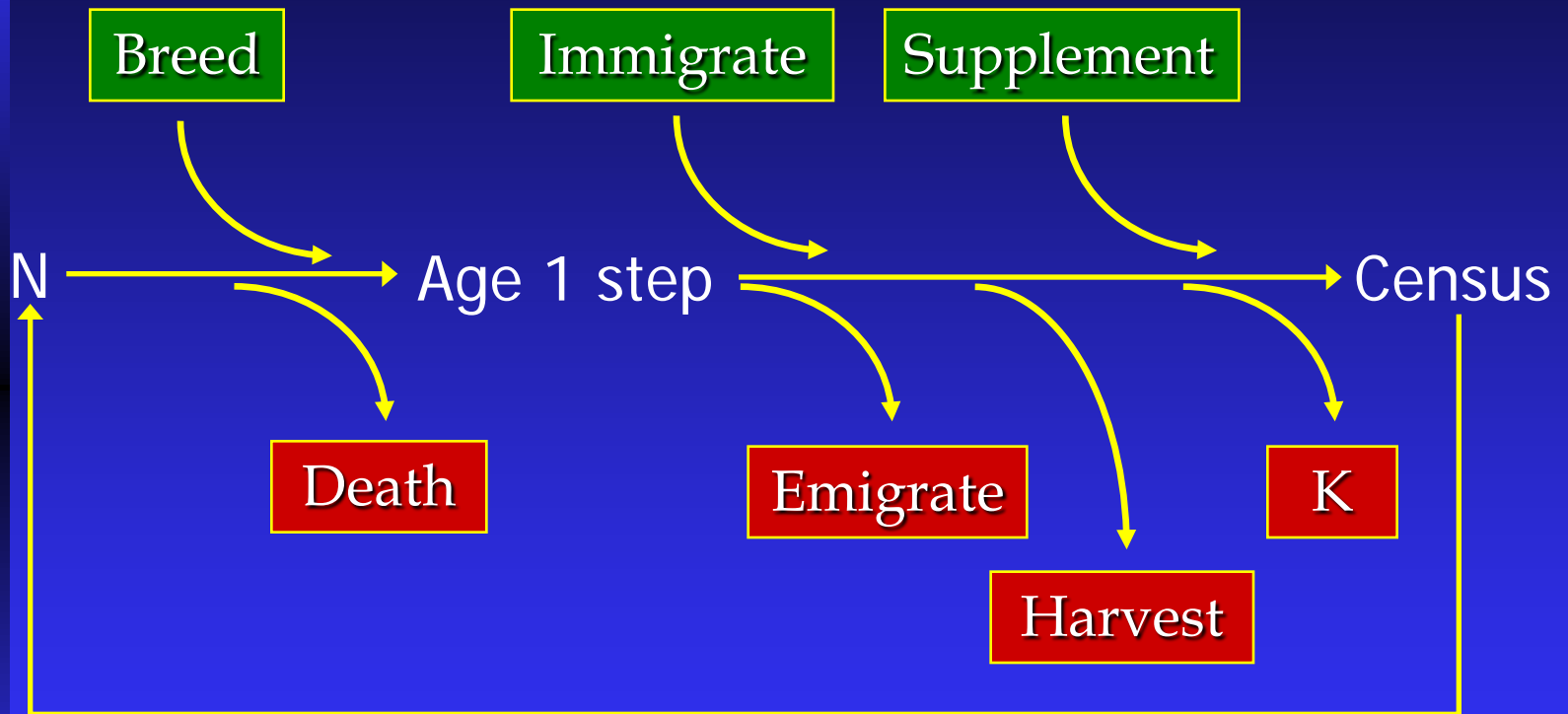
# Vortex 9.99b

A stochastic simulation of the extinction process

[Close graphic and enter program](#)

Copyright 2009 Chicago Zoological Society

# *Vortex* Simulation Model Timeline





# VORTEX Model Input Process

Vortex - Stochastic Simulation of the Extinction Process - [Northern Jaguar PVA\_New - C:\Phil's CBSG Data\Models\Vortex\Northern Jaguar PVA\New K Estimates\No]

File Vortex Window Help

Project Settings | Simulation Input | Text Output | Graphs and Tables | Project Report

Add Scenario Delete Scenario < Sonora Baseline\_000 > Reorder Sonora Baseline\_000 Sonora Baseline\_005 Sonora Baseline\_010 Sonora Baseline\_015 Sonora Baseline\_020 NJPAU Metapopulation\_000\_000 NJPAU Metapopul...

**Scenario Settings**

Scenario Name: Sonora Baseline\_000

Number of Iterations: 500

Number of Years: 100 Duration of each "year" in days: 365

Extinction Definition:  Only 1 Sex Remains  Total N < Critical Size 30000

Number of Populations: 1

Multiple scenario creation within a given modeling project

Stochastic simulation requires large number of iterations (repetitions)

“Table of Contents” style of quantitative model input

NOTES:

Vortex 9.99b

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# VORTEX Model Input Process

Vortex - Stochastic Simulation of the Extinction Process - [Northern Jaguar PVA\_New - C:\Phil's CBSG Data\Models\Vortex\Northern Jaguar PVA\New K Estimates\No]

File Vortex Window Help

Project Settings Simulation Input Text Output Graphs and Tables Project Report

Add Scenario Delete Scenario < NJPAU Metapopulation\_ > Reorder Sonora Baseline\_005 Sonora Baseline\_010 Sonora Baseline\_015 Sonora Baseline\_020 NJPAU Metapopulation\_000\_000 NJPAU Metapopulation\_000\_025 NJPAU

**Scenario Settings**  
Species Description  
Labels and State Vars.  
Dispersal  
Reproductive System  
Reproductive Rates  
Mortality Rates  
Catastrophes  
Mate Monopolization  
Initial Population Size  
Carrying Capacity  
Harvest  
Supplementation  
Genetic Management

Copy Input Values from  
Population 1  
This section  
to subsequent populations.

### Dispersal Among Populations

**Dispersing classes**  
Age Range: Youngest  Oldest   
Dispersing Sex(es)  Males  Females  
% Survival of Dispersers   
Dispersal Modifier Function (optional)

**Dispersal Rates**  
[Import Rate Matrix](#) [Apply Multiplier of](#)   
[Export Rate Matrix](#) [Fill Matrix with](#)

**Annual probabilities (as percents) of dispersal from source populations (rows) to recipient populations (columns)**

	Sinaloa	N Sinaloa	Sonora	N Sonora	US South I-10	US North I-10
Sinaloa	99.75	0.25	0.00	0.00	0.00	0.00
N Sinaloa	0.25	99.5	0.25	0.00	0.00	0.00
Sonora	0.00	0.25	99.475	0.25	0.025	0.00
N Sonora	0.00	0.00	0.25	99.55	0.20	0.00
US South I-10	0.00	0.00	0.025	0.20	99.65	0.125
US North I-10	0.00	0.00	0.00	0.00	0.125	99.875

**NOTES:**

Metapopulation Structure:  
Flexible specification of dispersal characteristics

Dispersal matrix among subpopulations within a metapopulation

Vortex 9.99b CAPS NUM INS Date/Time 9/19/2011 4:36 PM

# VORTEX Model Input Process

**Reproductive System**

Monogamous     Polygynous     Hermaphroditic  
 Long-term Monogamy     Long-term Polygyny

Age of First Offspring for Females: 3  
Age of First Offspring for Males: 3  
Maximum Age of Reproduction: 13  
Maximum Number of Broods per Year: 1  
Maximum Number of Progeny per Brood: 4  
Sex Ratio at Birth -- in % Males: 50

	Population 1
Density Dependent Reproduction	<input checked="" type="checkbox"/>
% Breeding at Low Density, P(0)	50
% Breeding at Carrying Capacity, P(K)	35
Allee Parameter, A	0
Steepness Parameter, B	16

View Function for: Population 1 [View](#)

**NOTES:**

Copy Input Values from:  
Population 1  
This section  
to subsequent populations.

Vortex 9.99b    CAPS   NUM   INS   Date/Time 9/19/2011 4:46 PM

Density dependence options for reproduction, with or without Allee effect (low reproductive output at low population densities)

**Mathematical Model**

# VORTEX Model Input Process

Vortex - Stochastic Simulation of the Extinction Process - [Northern Jaguar PVA\_New - C:\Phil's CBSG Data\Models\Vortex\Northern Jaguar PVA\New K Estimates\No]

File Vortex Window Help

Project Settings Simulation Input Text Output Graphs and Tables Project Report

Add Scenario Delete Scenario < Sonora Baseline\_020 > Reorder Sonora Baseline\_005 Sonora Baseline\_010 Sonora Baseline\_015 Sonora Baseline\_020 NJPAU Metapopulation\_000\_000 NJPAU Metapopulation\_000\_025 NJPAL >>

**Scenario Settings**  
Species Description  
Labels and State Vars.  
Dispersal  
Reproductive System  
Reproductive Rates  
**Mortality Rates**  
Catastrophes  
Mate Monopolization  
Initial Population Size  
Carrying Capacity  
Harvest  
Supplementation  
Genetic Management

**Mortality Rates**

**Mortality of Females as %**

	Population 1
Mortality From Age 0 to 1	20.5
SD in 0 to 1 Mortality Due to EV	6
Mortality From Age 1 to 2	16
SD in 1 to 2 Mortality Due to EV	4
Mortality From Age 2 to 3	20.5
SD in 2 to 3 Mortality Due to EV	5
Annual Mortality After Age 3	=10+((A>=5)*5.5)+((A>=7)*5.5)+((A>=10)*5.5)
SD in Mortality After Age 3	3

**Mortality of Males as %**

	Population 1
Mortality From Age 0 to 1	23
SD in 0 to 1 Mortality Due to EV	6
Mortality From Age 1 to 2	17
SD in 1 to 2 Mortality Due to EV	7
Mortality From Age 2 to 3	30
SD in 2 to 3 Mortality Due to EV	9
Annual Mortality After Age 3	25
SD in Mortality After Age 3	5

Copy Input Values from  
Population 1  
This section  
to subsequent populations.

**Age-specific mortality rates**

**Function editor**

Function >  $10+((A>=5)*5.5)+((A>=7)*5.5)+((A>=10)*5.5)$

Function Preview

30.0  
25.0  
20.0  
15.0  
10.0  
5.0  
.0

.0 5.0 10.0 15.0 20.0

Show Polish Notation Update Graph

Help OK Cancel

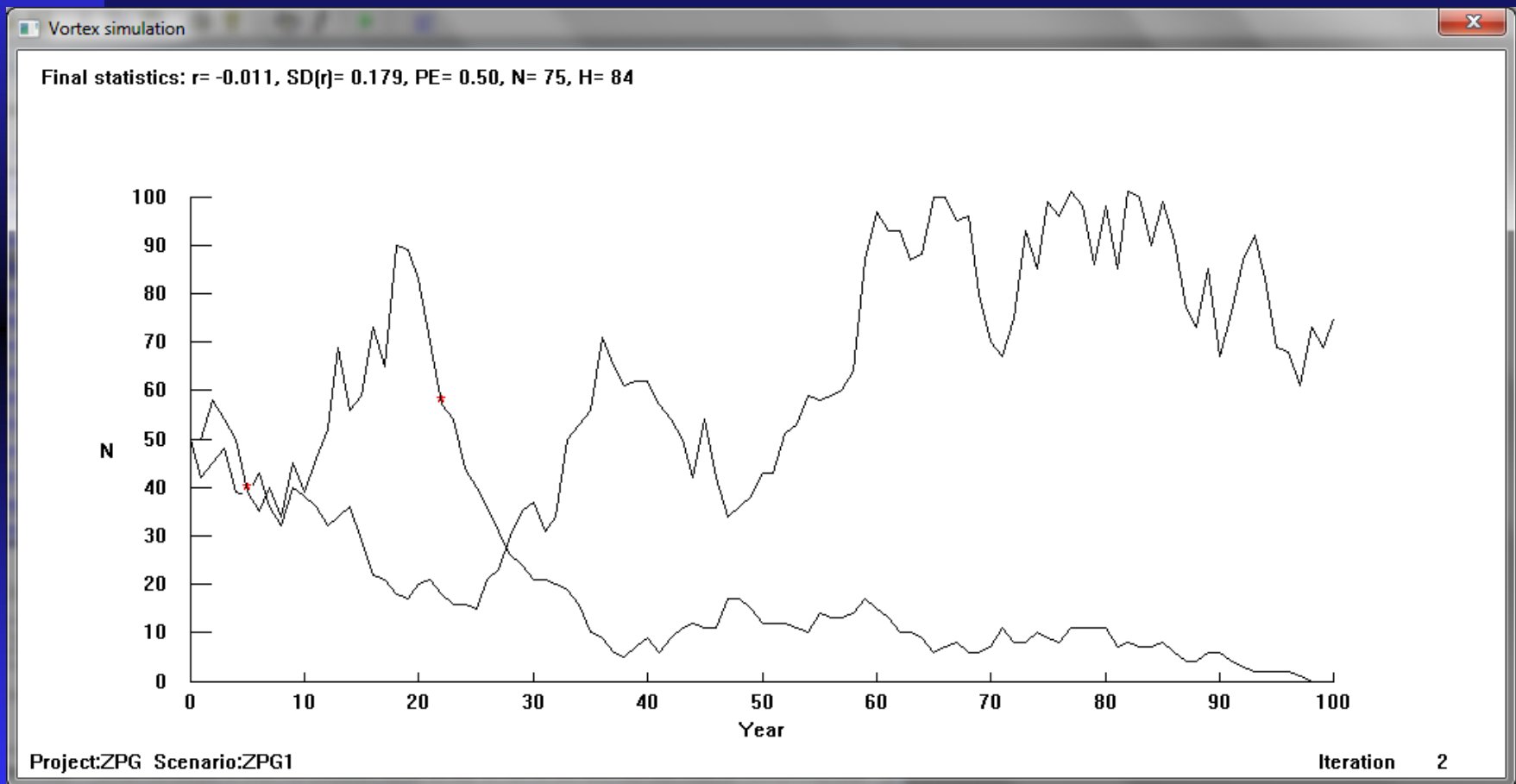
Enter annual mortality as a percent

Vortex 9.99b

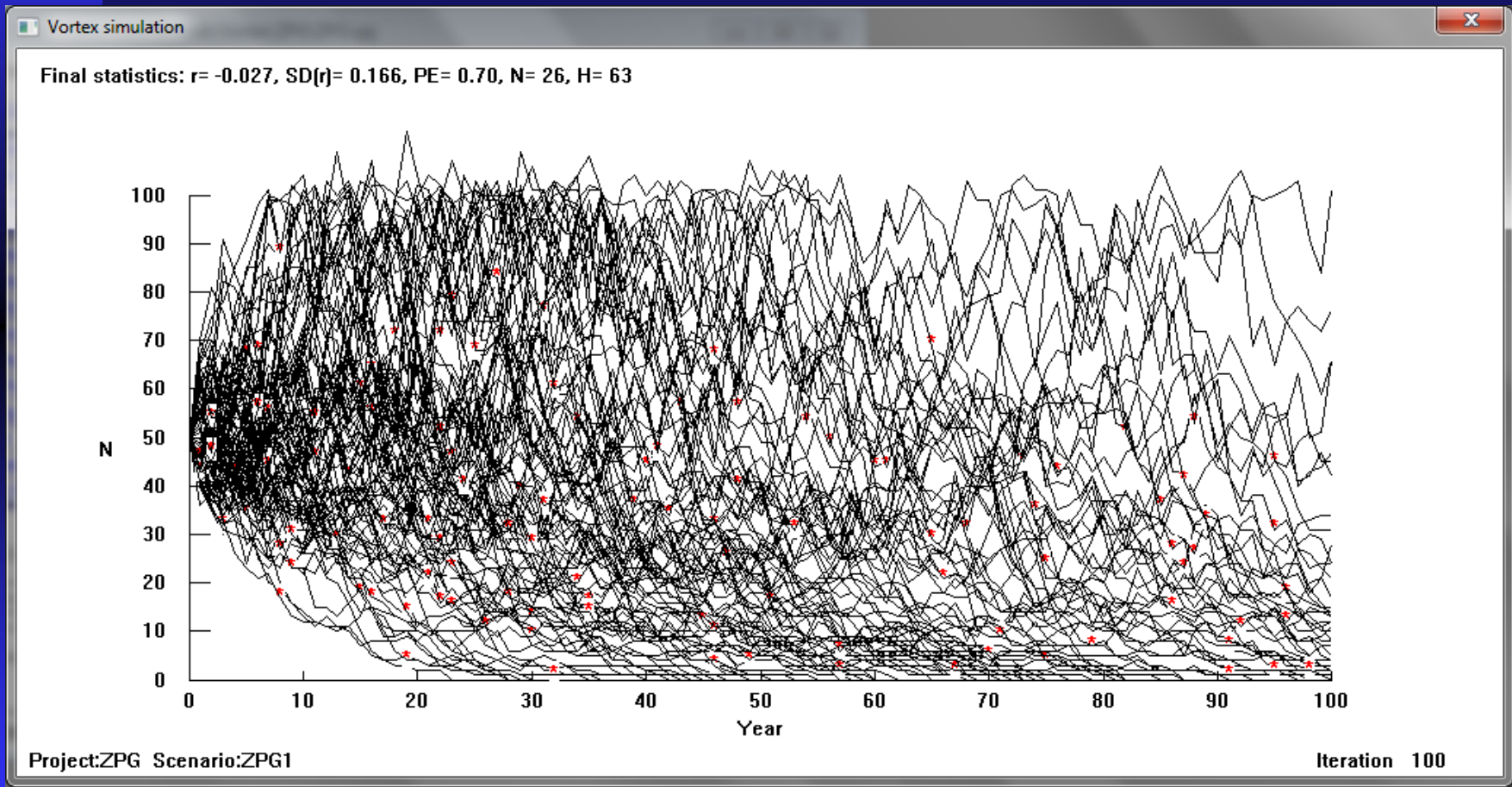
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# VORTEX Model Output

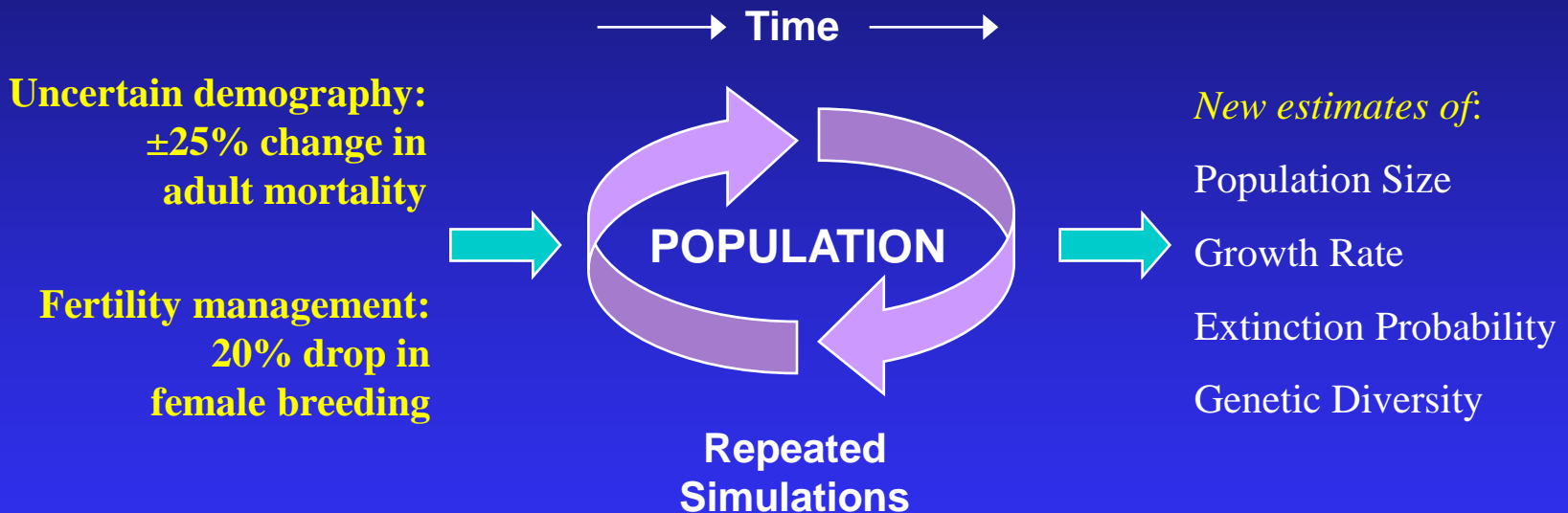


# VORTEX Model Output



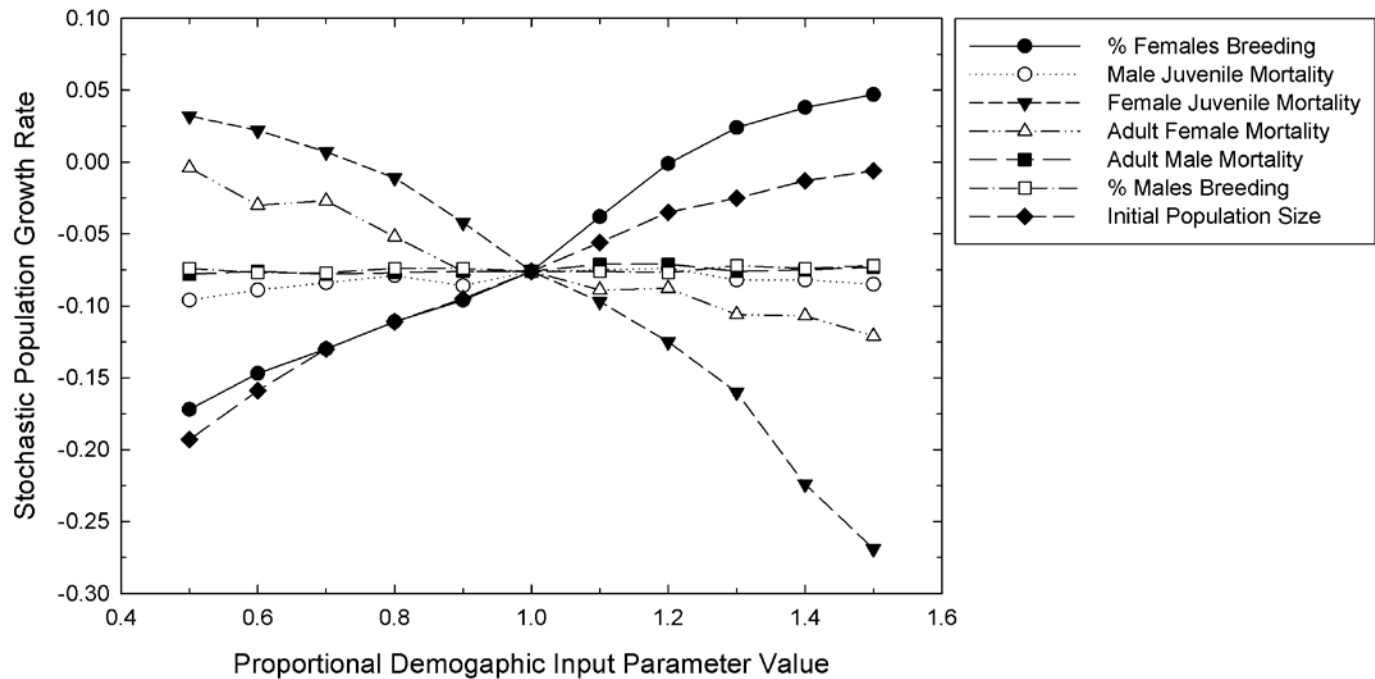
# Sensitivity Analysis: "What if...?"

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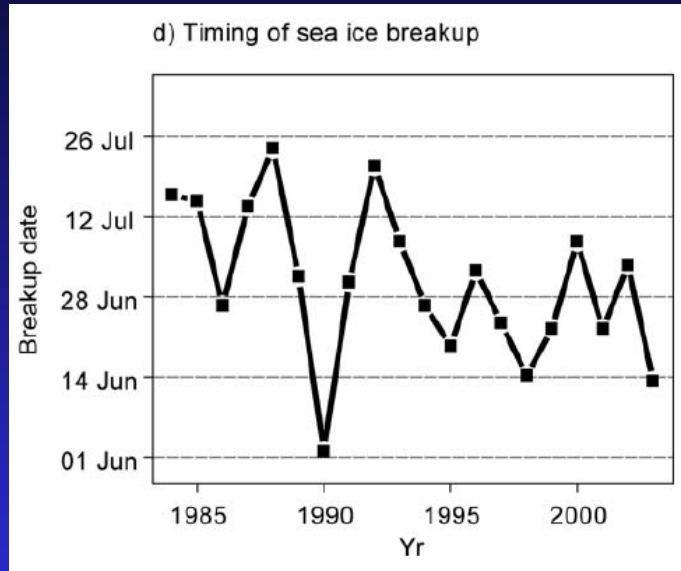
# Demographic Sensitivity Analysis

Western Hudson Bay Polar Bears  
Demographic Sensitivity Analysis





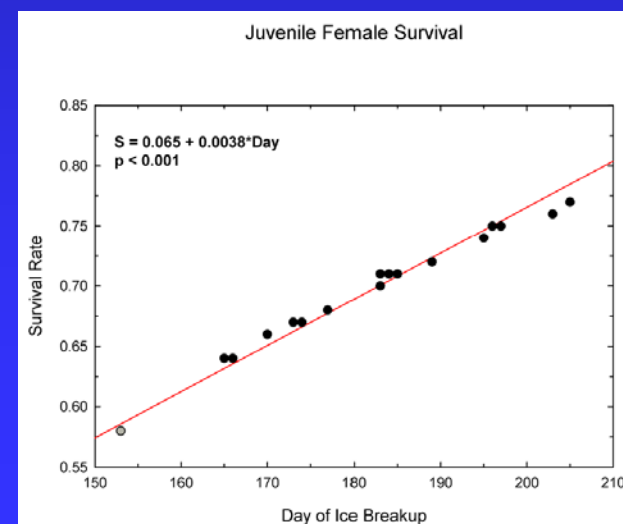
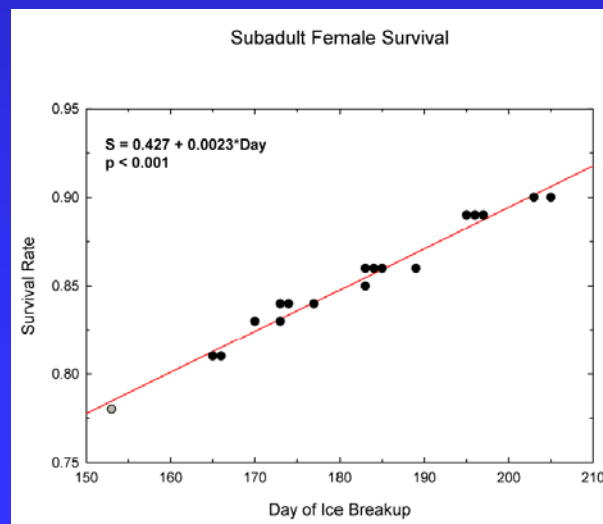
# Modeling impacts of climate change: Polar Bears of Western Hudson Bay



Regehr et al. 2007



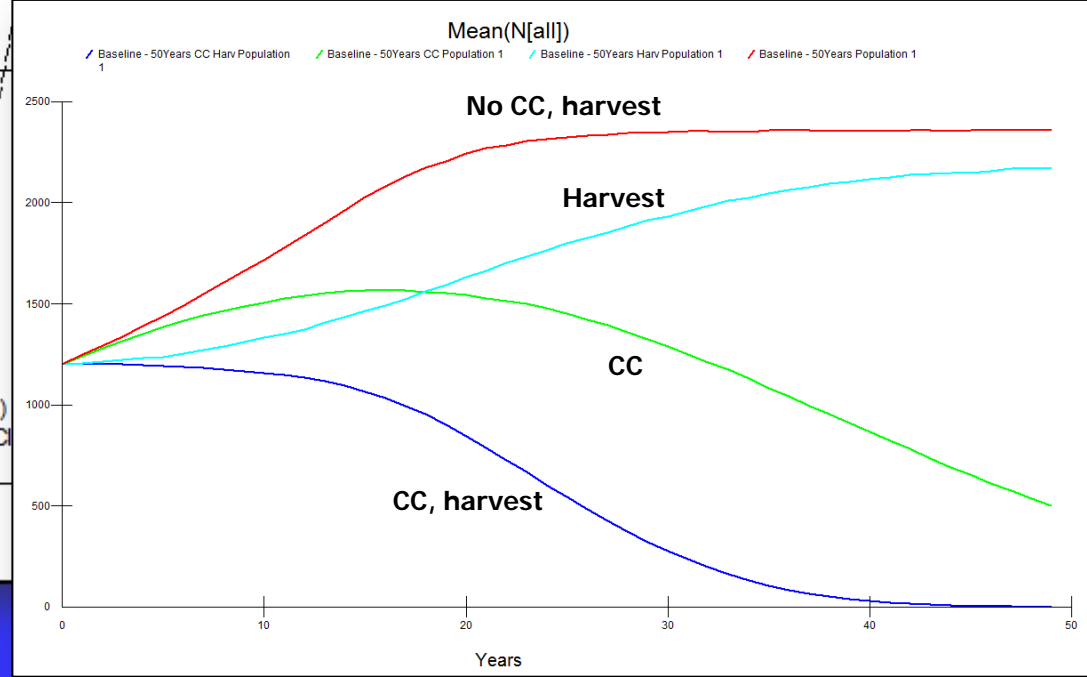
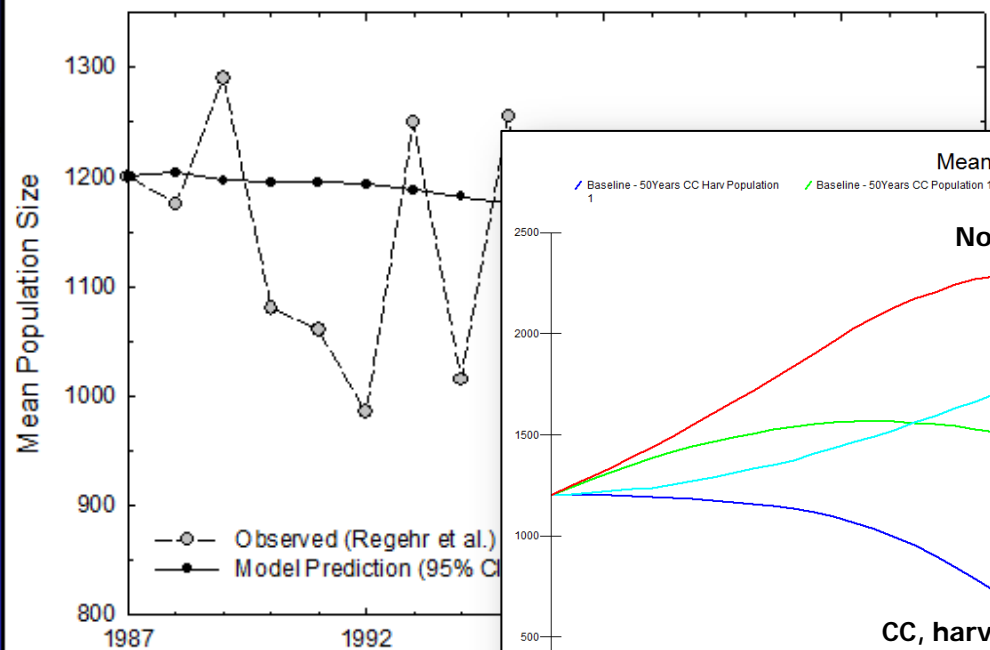
## Statistical Model



# Modeling impacts of climate change: Polar Bears of Western Hudson Bay



Polar Bears of Western Hudson Bay:  
Retrospective Population Analysis



# Tool Development for Disease Risk Assessment and Management

## *OUTBREAK*

An individual-based simulation of  
wildlife disease epidemiology



# OUTBREAK

The screenshot shows the 'OUTBREAK' software interface with three main panels:

- Disease Parameters:** Contains a compartmental model diagram with states P (Pre-Susceptible), S (Susceptible), E (Exposed), I (Infectious), R (Recovered), and D (Deceased). Below the diagram are input fields for the 'I (Infectious)' state: 'What proportion of individuals will remain infectious indefinitely?' (0.0) and 'What is the minimum amount of time in days an individual will remain infectious?' (30).
- Demographic Parameters:** A table for entering demographic parameters. The table is as follows:

Parameter	Value
Mortality Each Year:	
0 - 1	.2
Subadult	.2
Adult male	.17
Adult female	.15
Fecundity Each Year:	
Prop. breeding	.5
#litters / yr	1
Litter size	2
- Indirect Effects of Disease on Mortality and Reproduction:** A table showing the effects of disease on mortality and reproduction across different life stages and compartments. The table is as follows:

	P/S	E	I	R/V
Mortality:				
0 - 1	.2	.2	.2	.2
Subadult	.2	.2	.2	.2
Adult male	.17	.17	.17	.17
Adult female	.15	.15	.15	.15
Fecundity:				
Prop. breeding	.5	.5	.5	.5
#litters / yr	1	1	1	1
Litter size	2	2	2	2

Standard SEIR model structure

Basic description of population demographics

Option for indirect disease effects

### Simulation End Results

Summary data - means across all iterations

Population summary information

#### End Counts

Category	Count
A	3
S	55
E	3
I	16
R	5

Pop. Counts

■ P ■ S ■ E ■ I ■ R

#### Disease Prevalence

Population dynamics - double click on either of the graphs for more extensive graphing options

#### Disease Dynamics

#### Demographic Dynamics

OK

Demographic Parameters

Disease Parameters

Indirect Effects

Vaccination

Culture

Set up

W

P

C

C

P (F

P

V

V

V



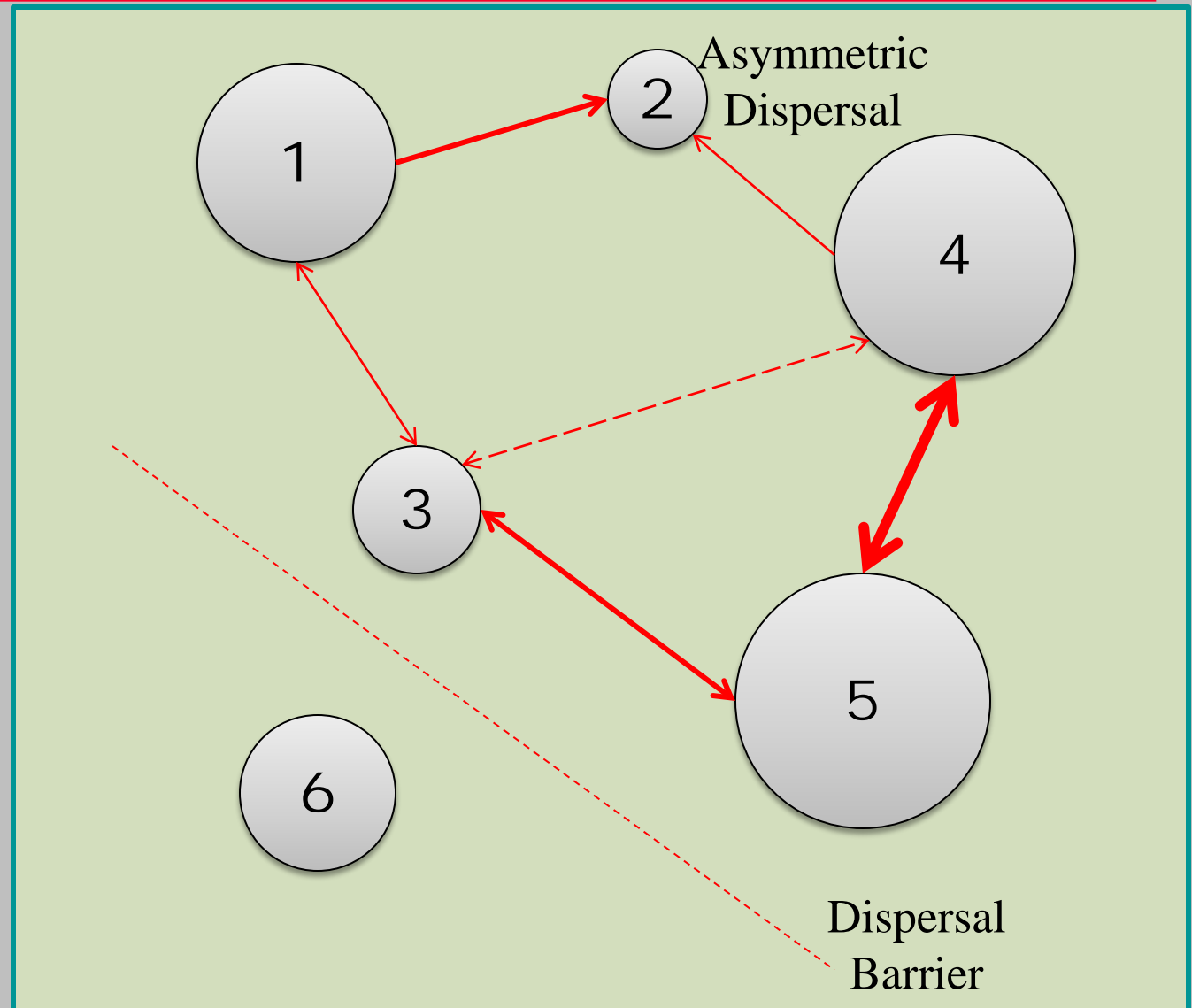
# Issues to Consider in Free-Roaming Cat Population Management Analysis

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- How important is an explicit consideration of the spatial dynamics of FRC population demography for management design?
  - Need for metapopulation analysis
- How do pathogens and disease play a role in the design of FRC population management protocols?
  - Susceptibility as a function of reproductive state
  - Reservoir for disease introduction / transmission to other species
- Can we expect more complex alterations to FRC population demography that could result from sterilization protocols?
  - Increased lifespan – Assateague Island horses
- What are the implications of population management protocols on associated species inhabiting the same landscape?
  - “Feral” – “Native” wildlife interface

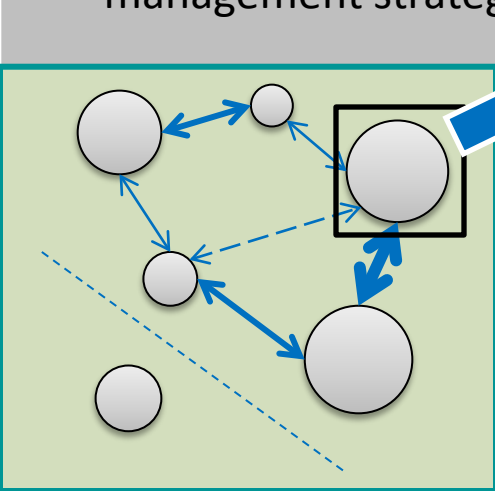
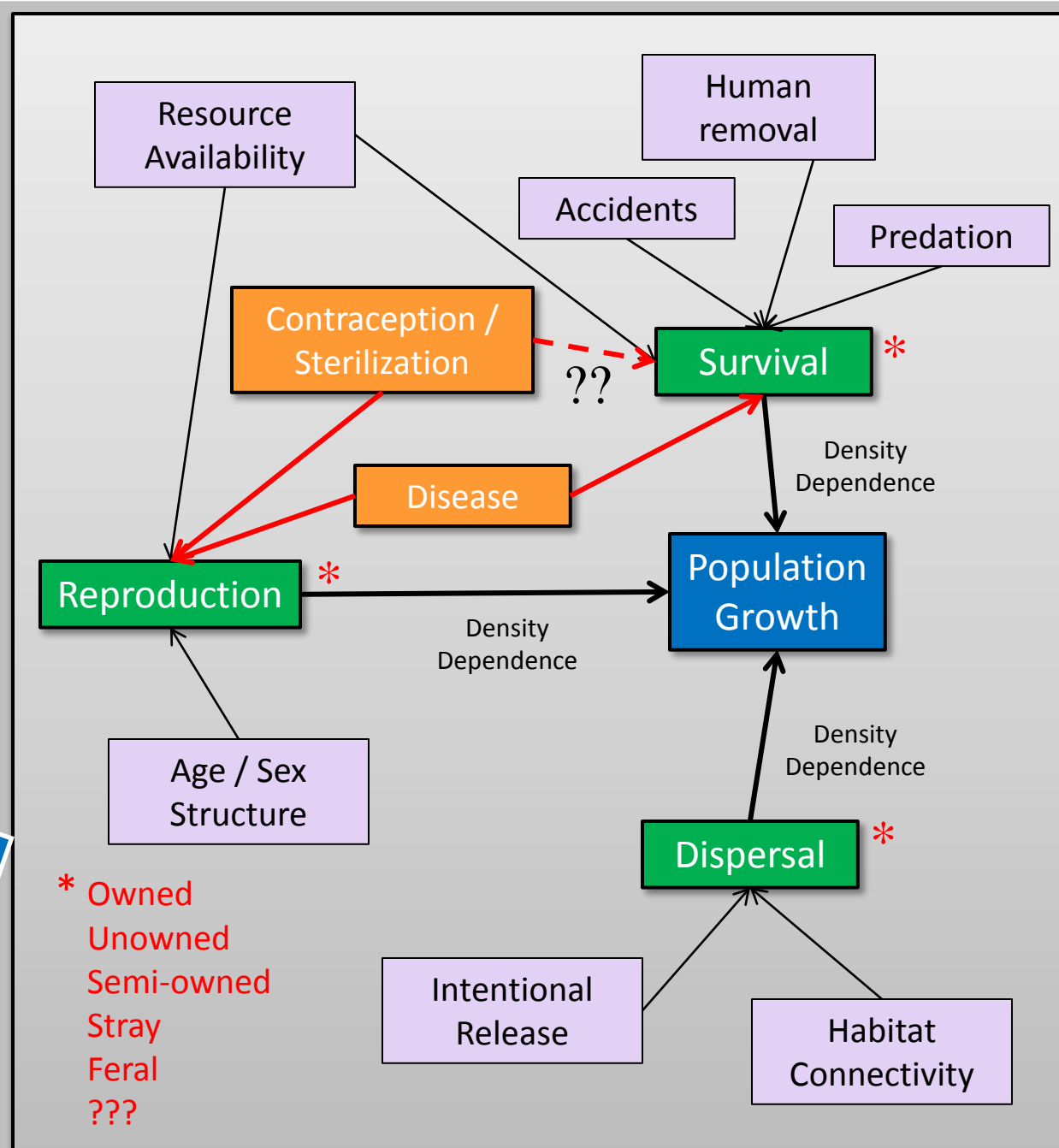
# Potential Metapopulation Structure for Demographic Analysis

- Complex dispersal patterns – functions of density, distance, etc.
- Asymmetric dispersal may lead to “source-sink” dynamics across system
- If metapopulation structure exists, does reproductive management require attention to this structure?



# Proposed Structure of Subpopulation System for Demographic Analysis

- Unique demographic characterization for each subpopulation where appropriate
- Does reproductive management influence survival rates (longevity)?
- How do other rate modifiers influence success of reproductive management strategies?



# Biocomplexity Research Initiative for Species Conservation

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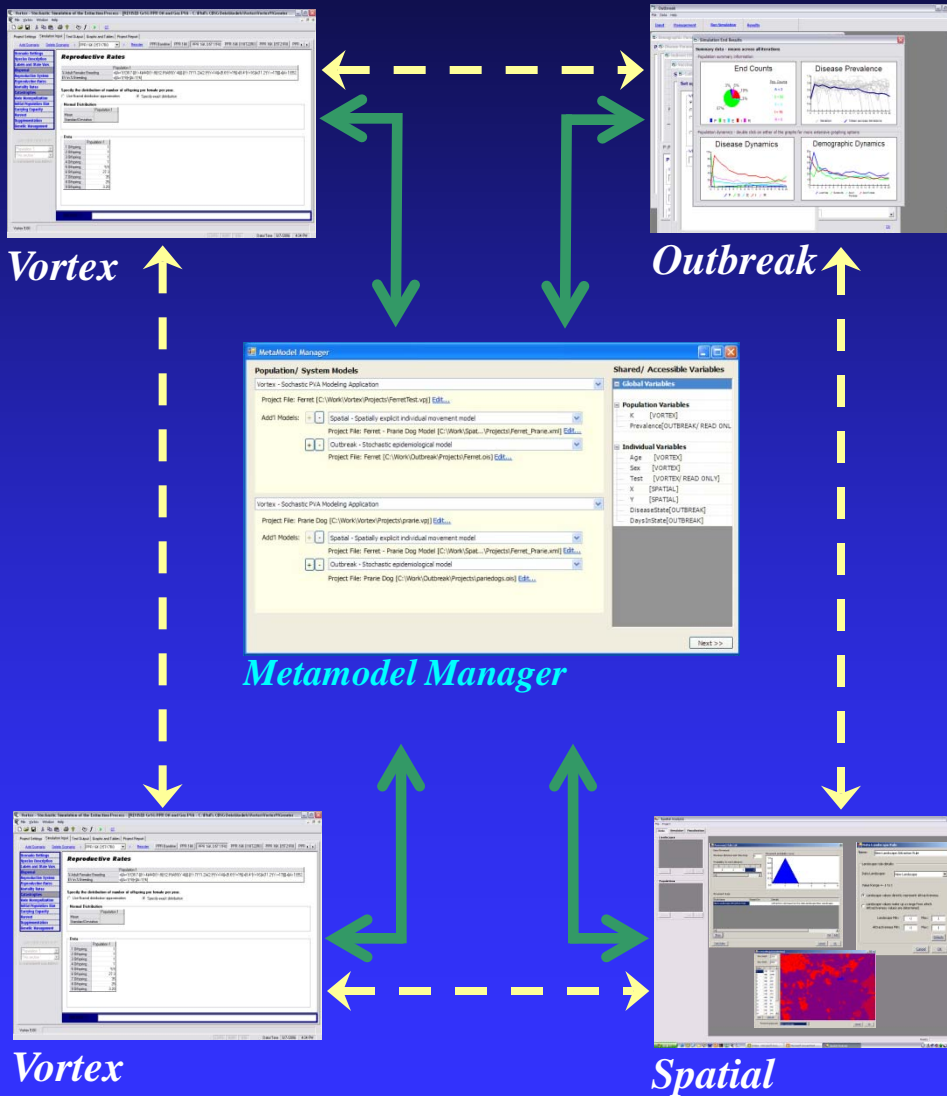
Primary research focus:

- Developing **social mechanisms for engaging stakeholders** from a broad diversity of disciplines and perspectives
- Creating **new tools for using information from these stakeholders** more effectively in evaluating the risk of wildlife population extinction:

Metamodeling



# Metamodeling for Species Risk Assessments

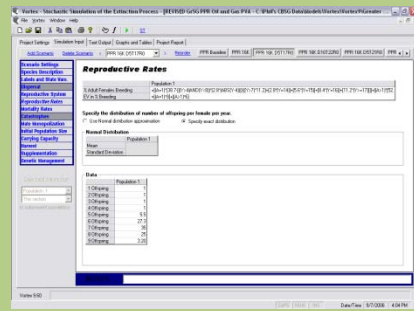


Using a central communication hub as a mediator, called the “MetaModel Manager”, we can physically link traditional PVA programs like *Vortex* with other modeling tools such as GIS software, epidemiology simulation programs (*Outbreak*), animal movement models (*Spatial*) and other appropriate models.

**Revolutionary approach to effective implementation of PVA methodologies**



# Two-Species PVA: Black-Footed Ferrets and Black-Tailed Prairie Dogs

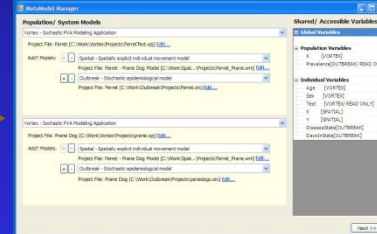


*Vortex*<sub>(BFF)</sub>

- Mortality of all age-classes directly tied to prairie dog abundance (prey availability)

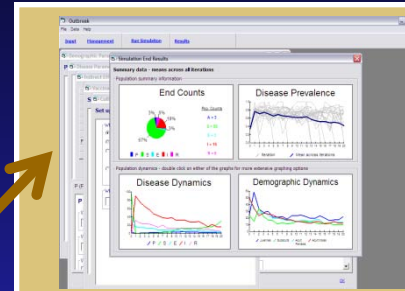


Number of adult BFF



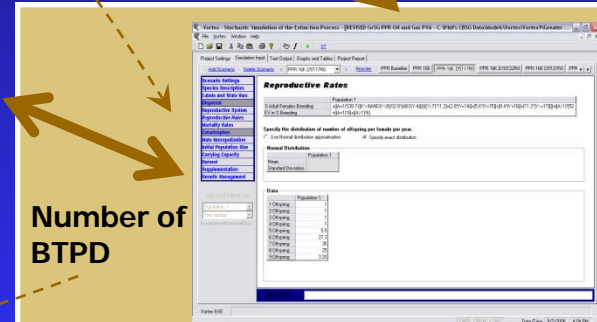
*MMM*

Number of infected animals



*Outbreak*

Sylvatic plague epidemiology



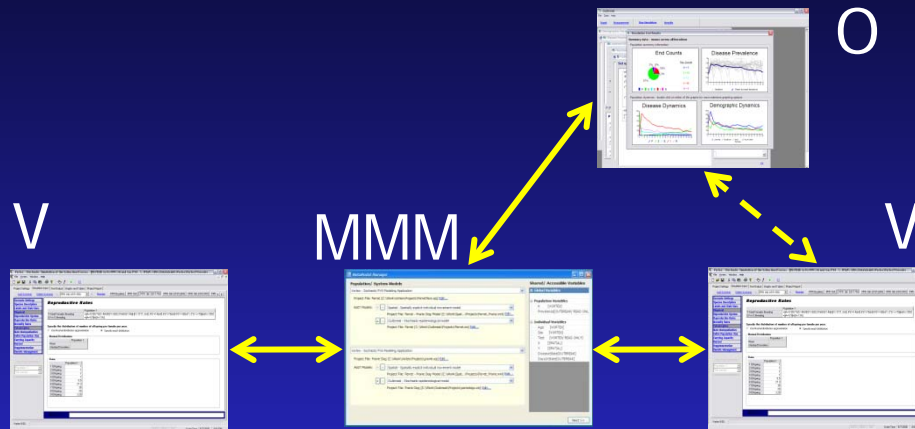
Number of BTPD

*Vortex*<sub>(BTPD)</sub>

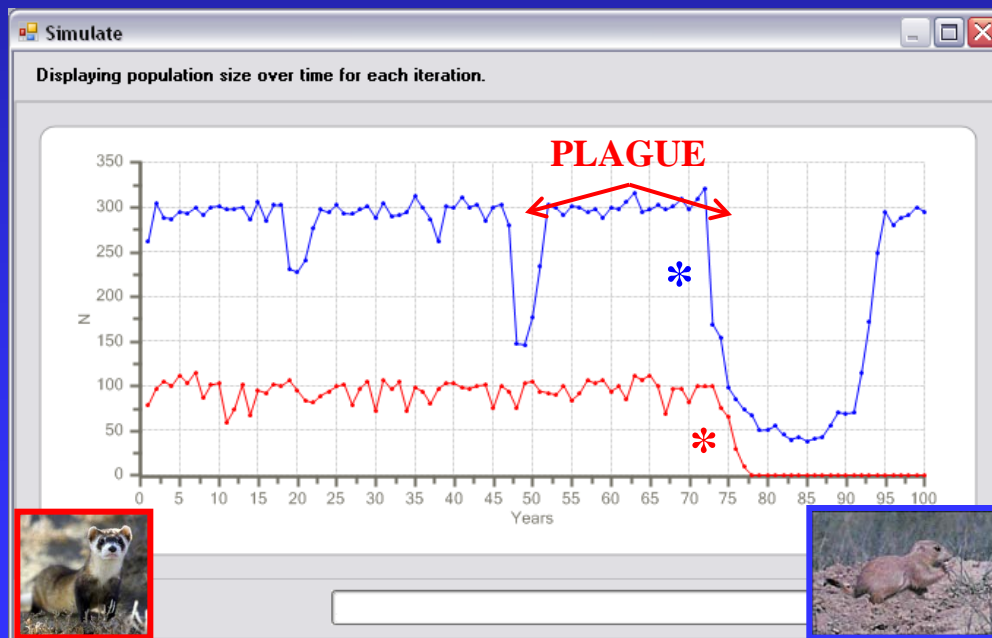
- No reproduction among infected individuals
- First-year mortality a function of adult ferret abundance



# Two-Species Metamodel with Disease: Black-Footed Ferrets and Black-Tailed Prairie Dogs



*Vortex – Vortex –  
Outbreak  
linkage through MMM*



*Disease outbreak  
in prairie dogs →  
extinction of  
ferret population*

# Simulation Modeling of FRC Dynamics: Strengths

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- Highly explicit – usually need to deconstruct larger system into components for effective analysis.
- System complexity makes derivation of analytical solutions very difficult, or can only be achieved by making simplifying assumptions that might be omitting important factors
- Can develop a projection for a specific case, incorporating all that we know about that situation, rather than identifying expected general trends for a generic case
- Valuable for processes that have a lot of uncertainty. Other models often can be used to calculate expected variation in results, but the generation of that variation in a simulation can make it easier to understand.

# Simulation Modeling of FRC Dynamics: Weaknesses

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- System complexity can often lead to difficulty in creating a realistic description of the many factors and their interactions
- Often computationally intensive, especially in the case of individual-based modeling environment – often precludes analysis of larger population sizes ( $N > 50,000?$ )
- Propagation of parameter uncertainty makes accurate predictive capacity very low

**Using a variety of model types is often the most informative, especially in that results can then be compared to gain the strengths and recognize the weaknesses of each approach**