Endogenous Lifecycle Models for Chemical Risk Assessment

Matthew Etterson & Gerald Ankley

US Environmental Protection Agency
Office of Research and Development
Center For Computational Toxicology and Exposure
Great Lakes Toxicology and Ecology Division
Duluth, MN, USA

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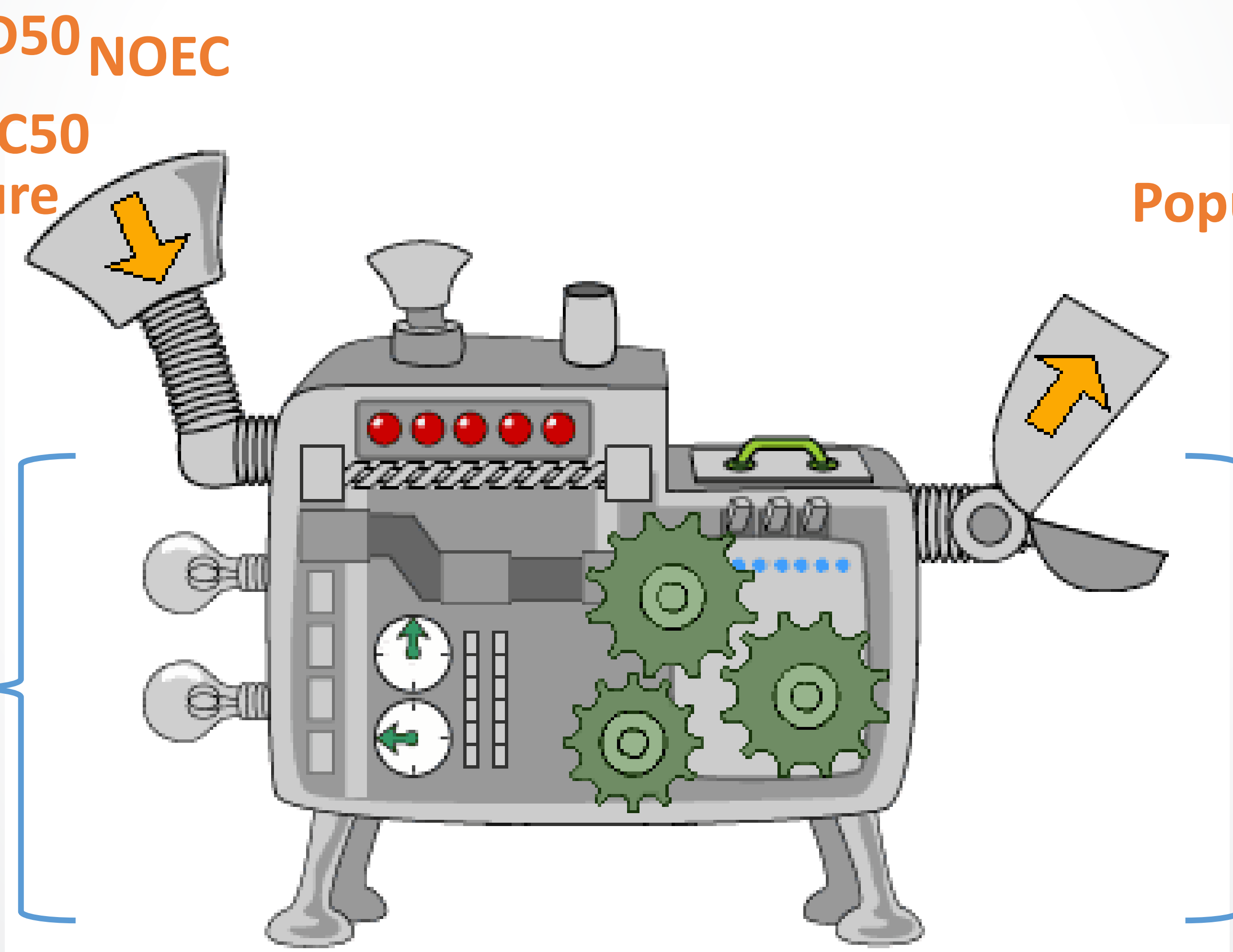
Population models add value to ecotoxicological data

- Integrate separate effects on survival, growth, and reproduction
- Help to identify sensitive life-history stages
- Seamless integration of AOP
- Support environmental protection goals
- Allow exploration of interaction between environment and chemical stressors

So, why do we need another ecological modeling concept?

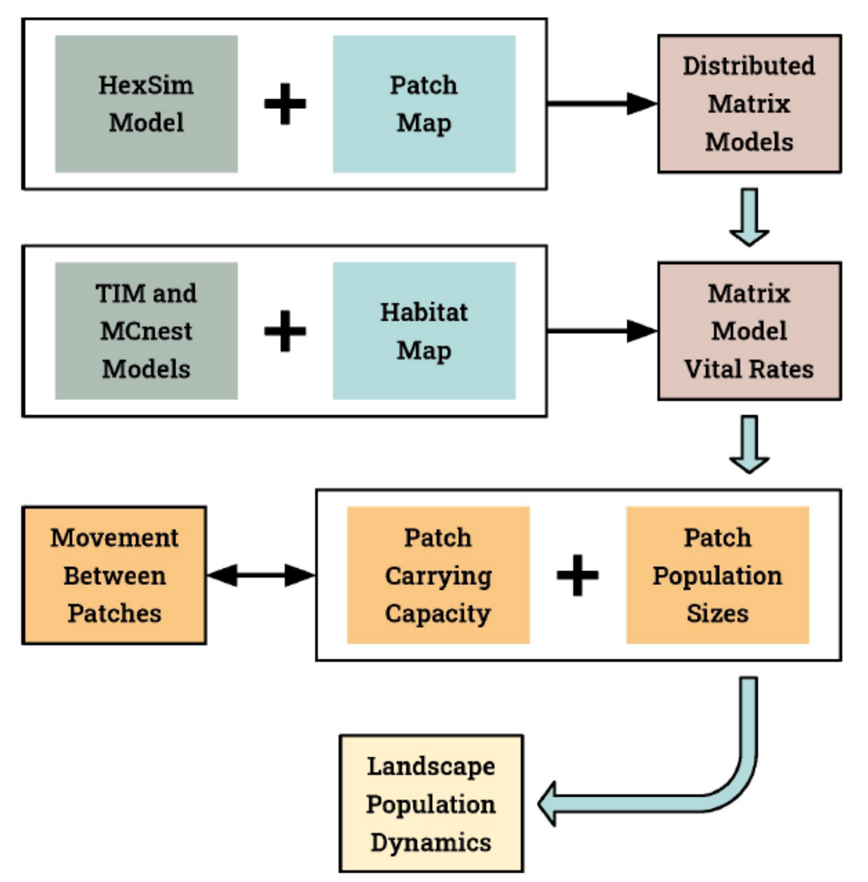
Leap between screening-level assessments and population models is huge

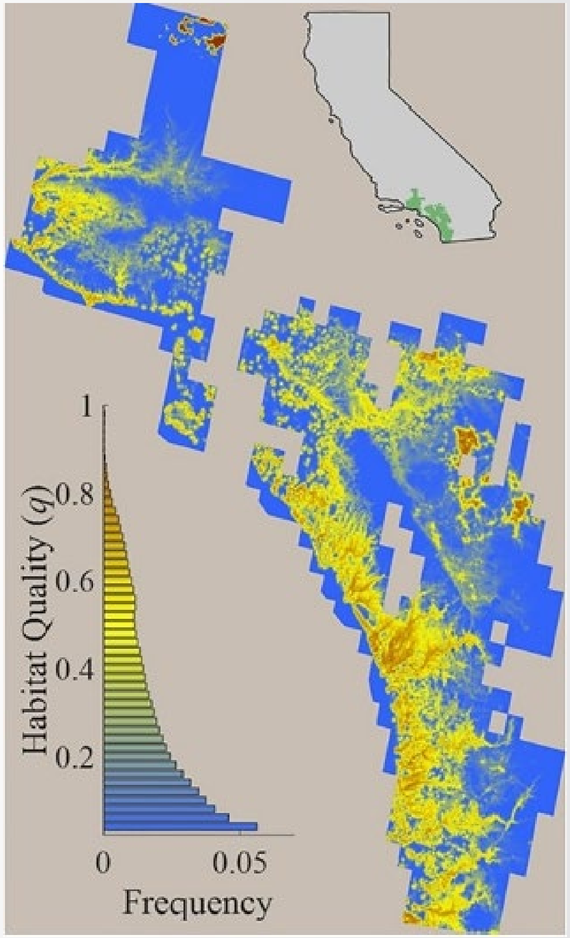


Endogenous systems
Lifecycle
Reproductive cycle
Hormone signaling
Immune systems
Organ function
Metabolism & other cellular processes
Gene regulation
Homeostatic mechanisms

Exogenous factors
Population size
Population structure
Habitat quality
Density dependence
Environ. stochasticity
Behavioral interactions
Competition
Predation
Resource limitation
Landscape structure

Exogenous factors are difficult to parameterize and often poorly understood

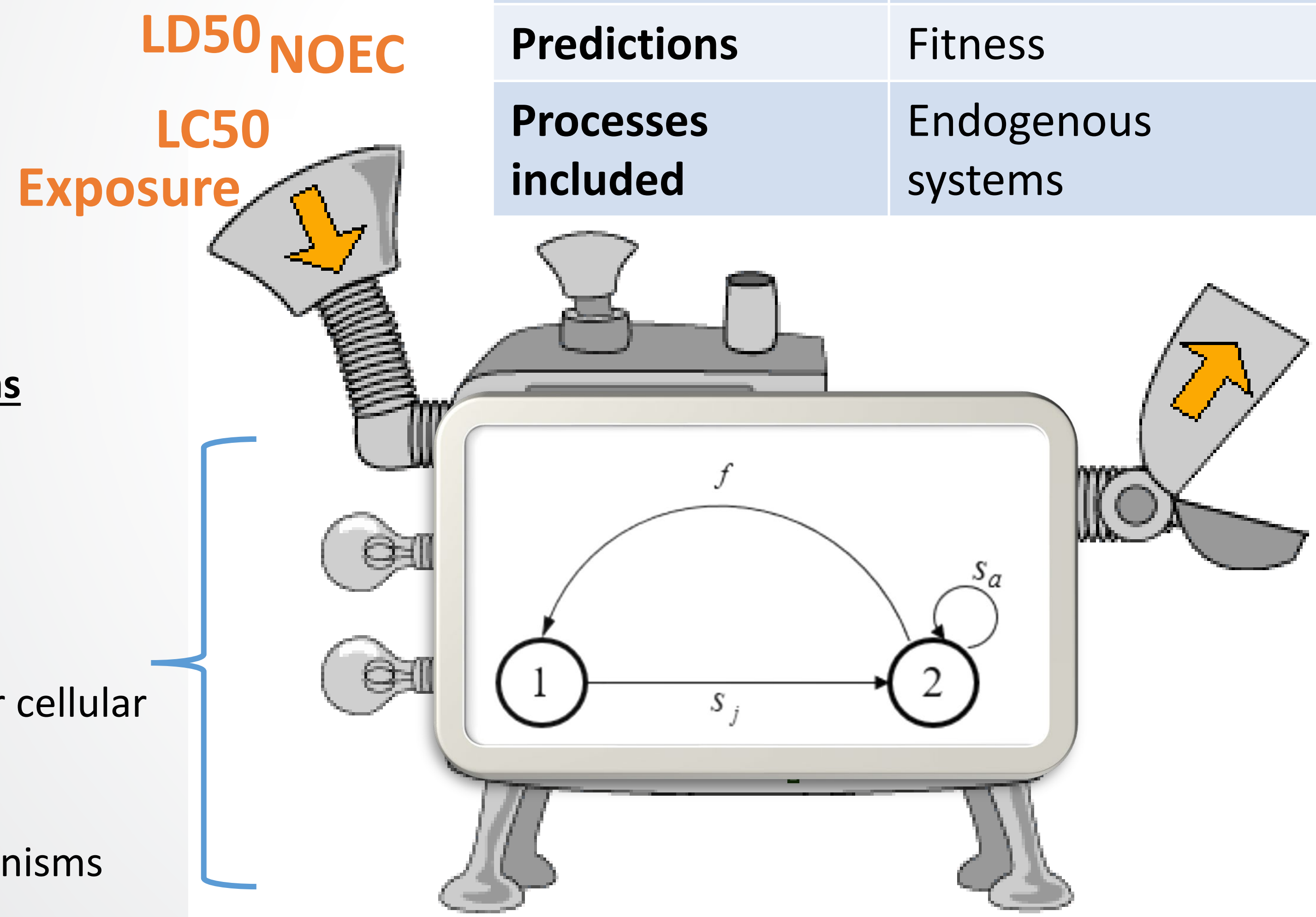




Etterson et al. 2021. A spatially explicit model for estimating risks of pesticide exposure to bird populations. PLOS One

Endogenous Lifecycle Models (ELMs)

	ELM	Population model
Subject	Lifecycle	Collection of individuals
Predictions	Fitness	ΔN, Extinction Probability
Processes included	Endogenous systems	Endogenous systems & Exogenous systems



Endogenous systems

- Lifecycle
- Reproductive cycle
- Hormone signaling
- Immune systems
- Organ function
- Metabolism & other cellular processes
- Gene regulation
- Homeostatic mechanisms

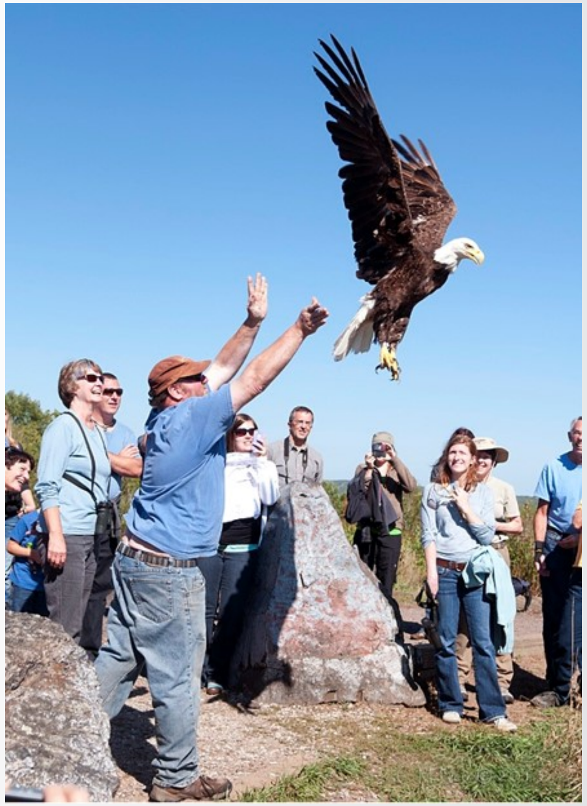
~~**Exogenous factors**~~

- ~~Population size~~
- ~~Population structure~~
- ~~Habitat quality~~
- ~~Density dependence~~
- ~~Environ. stochasticity~~
- ~~Behavioral interactions~~
- ~~Competition~~
- ~~Predation~~
- ~~Resource limitation~~
- ~~Landscape maps~~

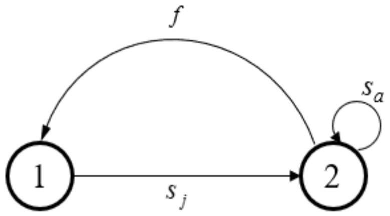
OK, maybe…let's see some examples

Parameter definitions:

- s_j = survival from fledging to 1st year
- s_a = survival after 1st year
- f = annual fecundity (offspring/year)
- p = breeding propensity

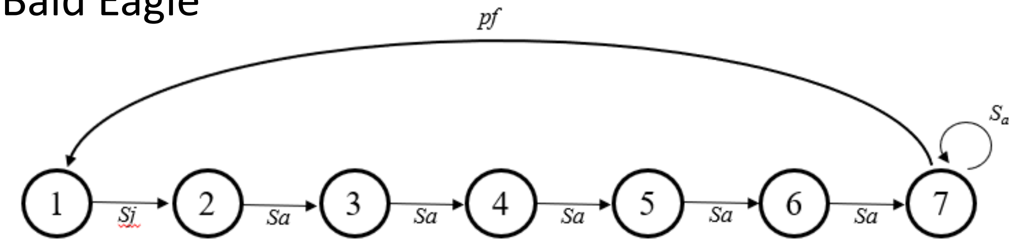


Tree Swallow



Lifecycle adapted from Pulliam 1988. American Naturalist

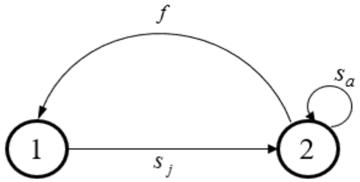
Bald Eagle



Lifecycle from Young 1968. Ecology

The lifecycle graph and model are isoinformatic

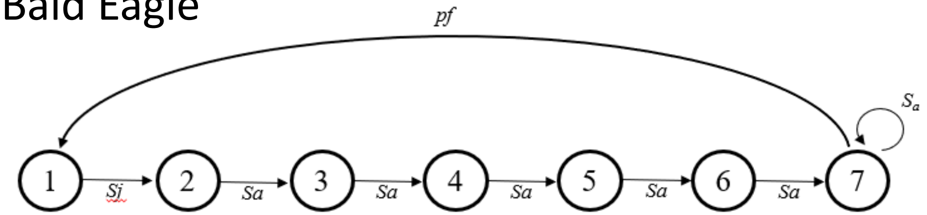
Tree Swallow



Lifecycle adapted from Pulliam 1988. American Naturalist

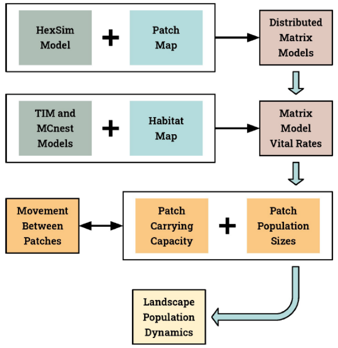
$$M = \begin{bmatrix} f s_j & f s_j \\ s_a & s_a \end{bmatrix}$$

Bald Eagle



Lifecycle from Young 1968. Ecology

$$M = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & pf \\ s_j & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & s_a & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & s_a & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & s_a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & s_a & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & s_a & s_a \end{bmatrix}$$



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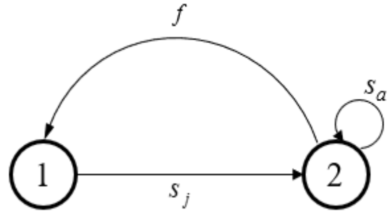
Stakeholders can reach consensus on the lifecycle graph without reference to the mathematics

Fitness predictions

Tree Swallow



$$M = \begin{bmatrix} f s_j & f s_j \\ s_a & s_a \end{bmatrix}$$

Fitness predictions:

- Intrinsic fitness (λ_f) = expected annual production of genetic descendants (including self)

$$\lambda_f = s_a + f s_j$$

- Lifetime reproductive success (LRS) = expected lifetime production of offspring

$$LRS = f \frac{s_j}{1 - s_a}$$

Identification of sensitive life stages

Process	Parameter	λ_f Sensitivity	LRS Sensitivity
Juvenile Survival	s_j	$\frac{\partial \lambda_f}{\partial s_j} = f$	$\frac{\partial LRS}{\partial s_j} = \frac{f}{1 - s_a}$
Adult Survival	s_a	$\frac{\partial \lambda_f}{\partial s_a} = 1$	$\frac{\partial LRS}{\partial s_a} = \frac{s_j f}{(1 - s_a)^2}$
Fecundity	f	$\frac{\partial \lambda_f}{\partial f} = s_j$	$\frac{\partial LRS}{\partial f} = \frac{s_j}{(1 - s_a)}$

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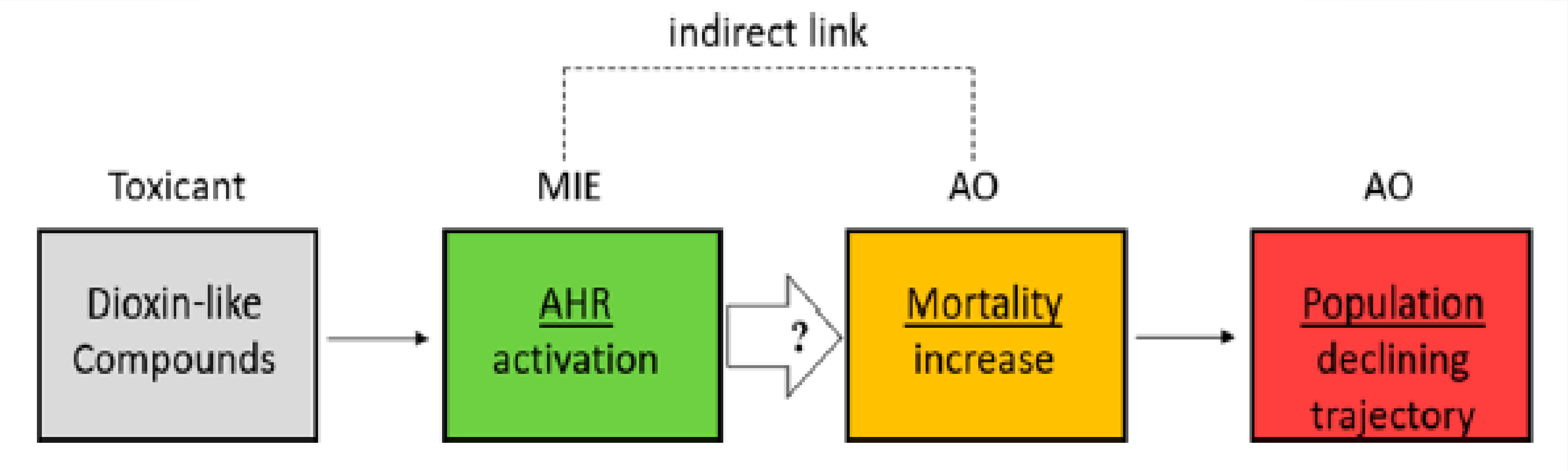
Integration with adverse outcome pathways

- AOPs describe perturbations to endogenous biological systems



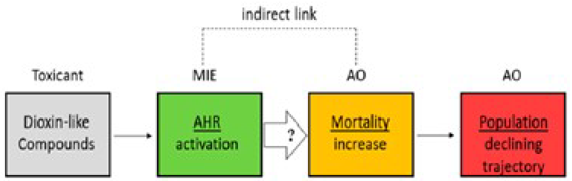
AOP from Doering et al. 2018. ES&T

ELM = a series of directed graphs

	AOP	Endogenous System	ELM

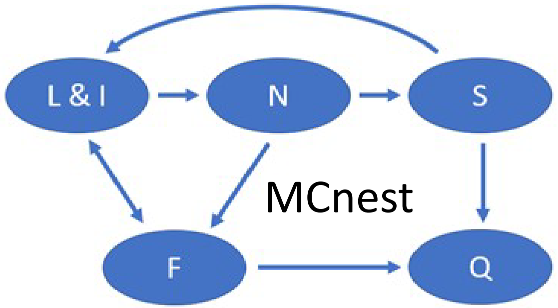
Conceptual Model

AOP

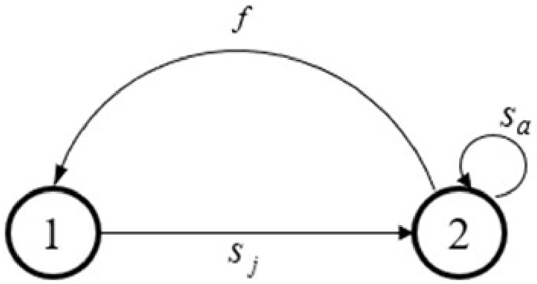


AOP from Doering et al. 2018. ES&T

Endogenous System



ELM



Model & Parameters

LDx	m_x	b_x
0	0.6764	3.33
10	0.7471	3.063
50	0.7123	2.775
100	0.7599	2.365

$$log_{10}(LDx) = log_{10}(DLC) - b_x + m_x log_{10}(EC50)$$

$$\begin{array}{c} \\ L\&I \\ N \\ S \\ F \\ Q \end{array} \begin{array}{c} \begin{array}{ccccc} L\&I & N & S & F & Q \end{array} \\ \begin{bmatrix} 0 & s_i^{d_i} & 0 & 1 - s_i^{d_i} & 0 \\ 0 & 0 & s_n^{d_n} & 1 - s_n^{d_n} & 0 \\ 1 - q_s & 0 & 0 & 0 & q_s \\ 1 - q_f & 0 & 0 & 0 & q_f \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}$$

Adapted from Etterson et al. 2009. Ecological Applications

$$\begin{bmatrix} f s_j & f s_j \\ s_a & s_a \end{bmatrix}$$

Predictions

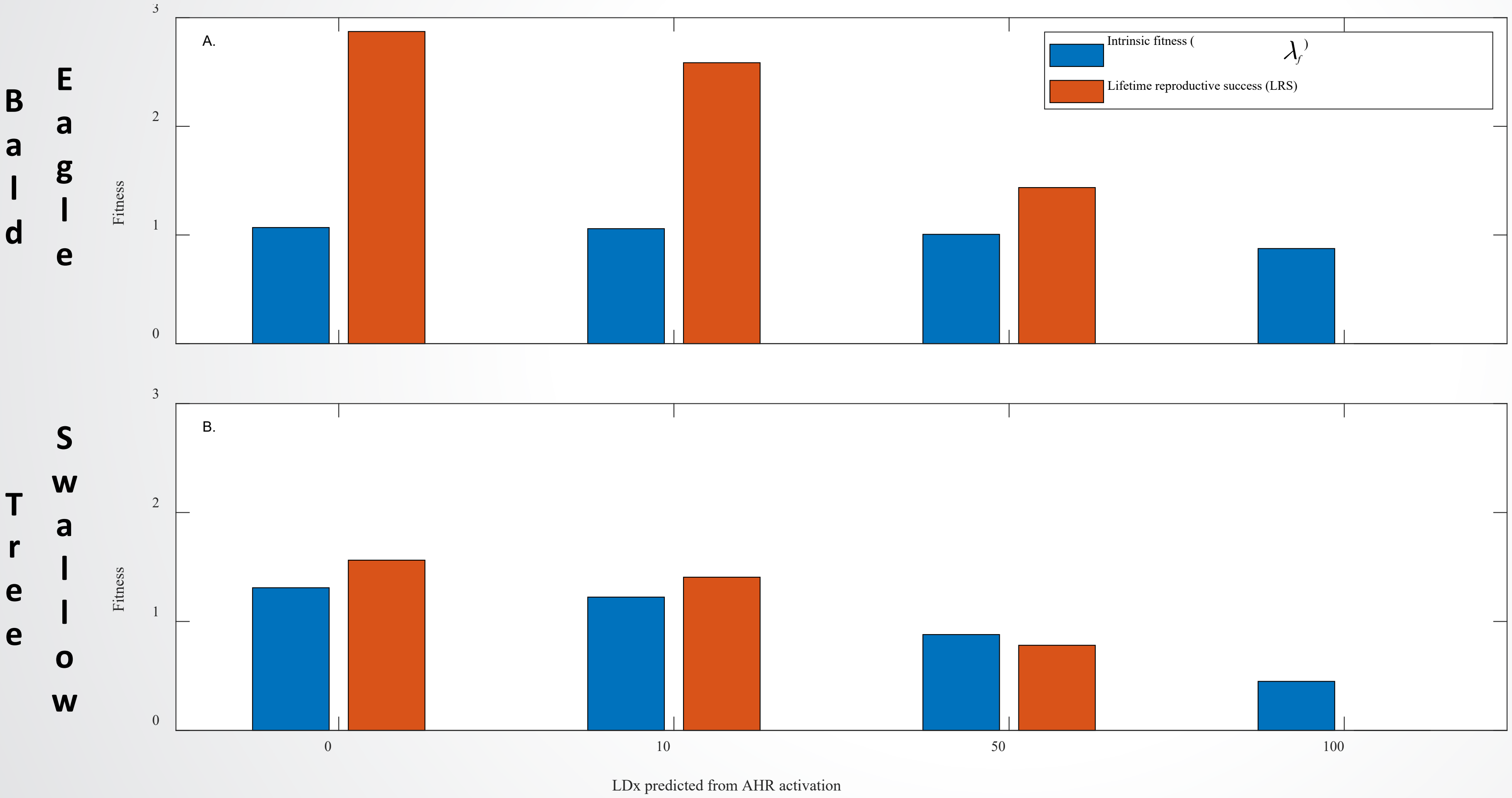
Embryo survival(DLC) = 1-x/100

$$f = \left(1 - \frac{x}{100}\right) c \frac{s_i^{d_i} s_n^{d_n}}{q_f + s_i^{d_i} s_n^{d_n}(q_s - q_f)}$$

$$LRS = f \frac{s_j}{1 - s_a}$$

$$\lambda_f = s_a + f s_j$$

Response depends on lifecycle



EPA

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- ✓Help identify sensitive life-history stages
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- Ø ~~Allow exploration of interaction between environment and chemical stressors~~

For more information…

- See forthcoming manuscript in Environmental Science & Technology
- Email us: etterson.matthew@epa.gov