Evaluating potential responses of salmon populations exposed to acetylcholinesterase inhibiting insecticides

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Objective:

Provide an overview of population models used in NMFS' biological opinions on the effects of acetylcholinesterase- inhibiting insecticides.

Overview

Introduction

Conceptual framework

Life history and species

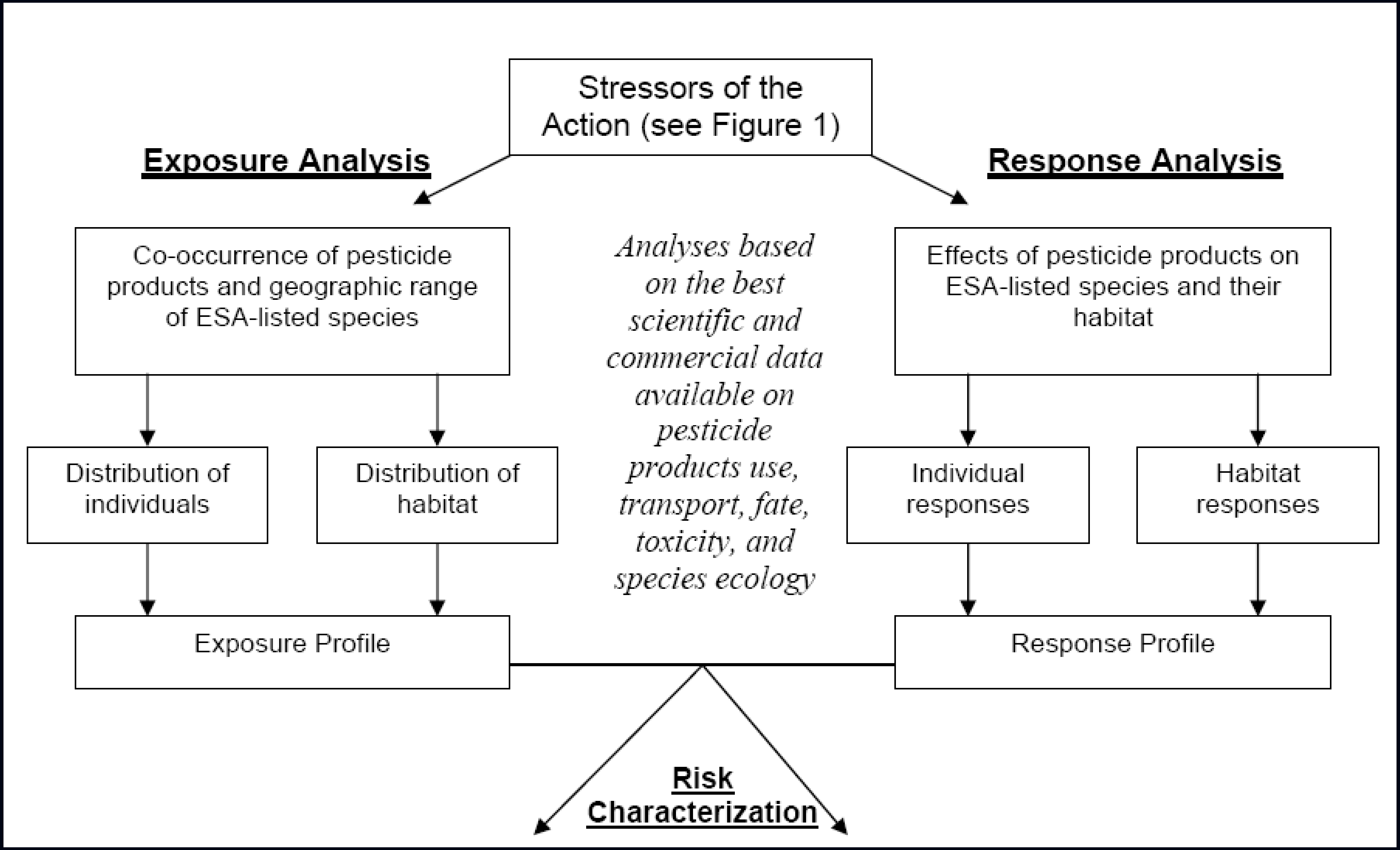
Model 1. Survival of subyearling salmon: acute lethality

Model 2. Growth of sub-yearling salmon: direct and indirect effects

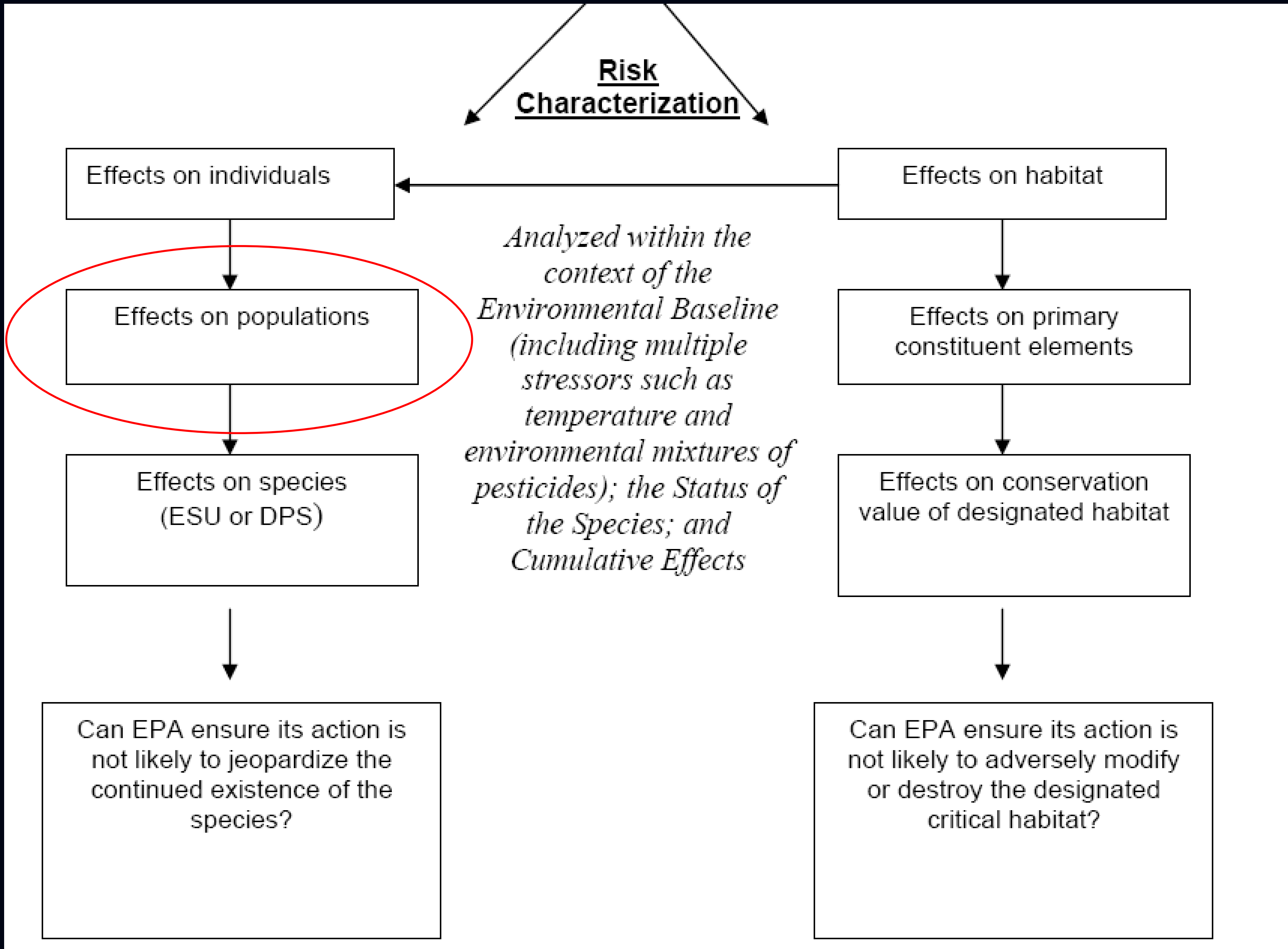
Applications within opinions

Discussion

Framework for Assessing Effects

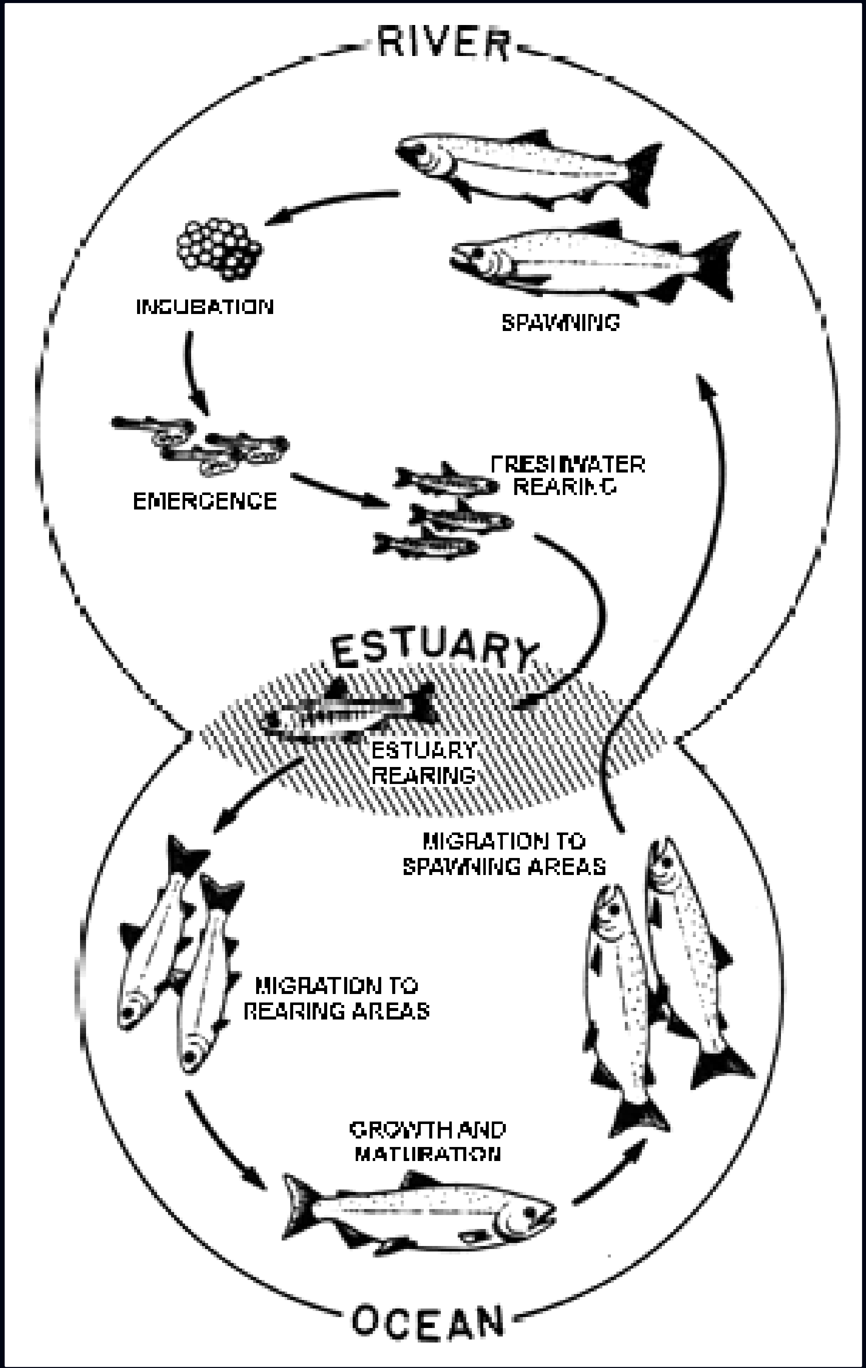


Framework for Assessing Effects (continued)



Salmonid Lifecycle

Key Lifestage and Model Parameter:
Subyearling survival

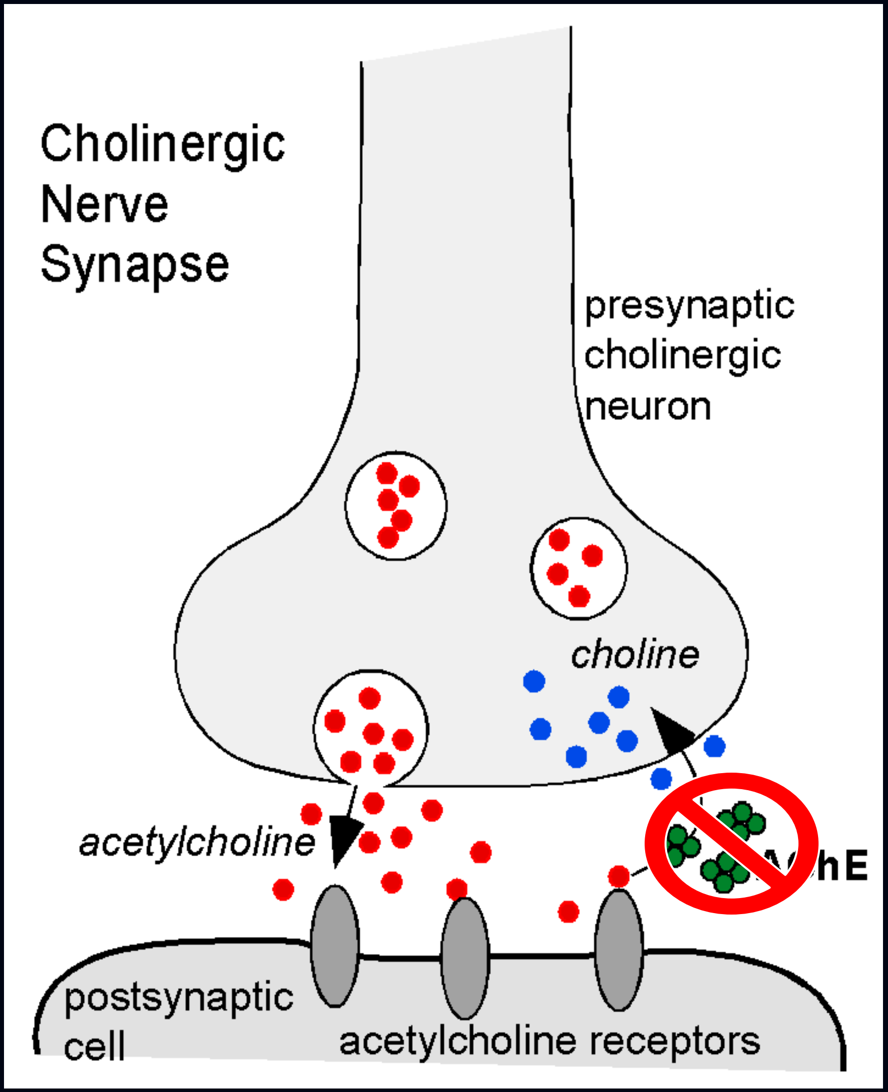


What do these insecticides do?

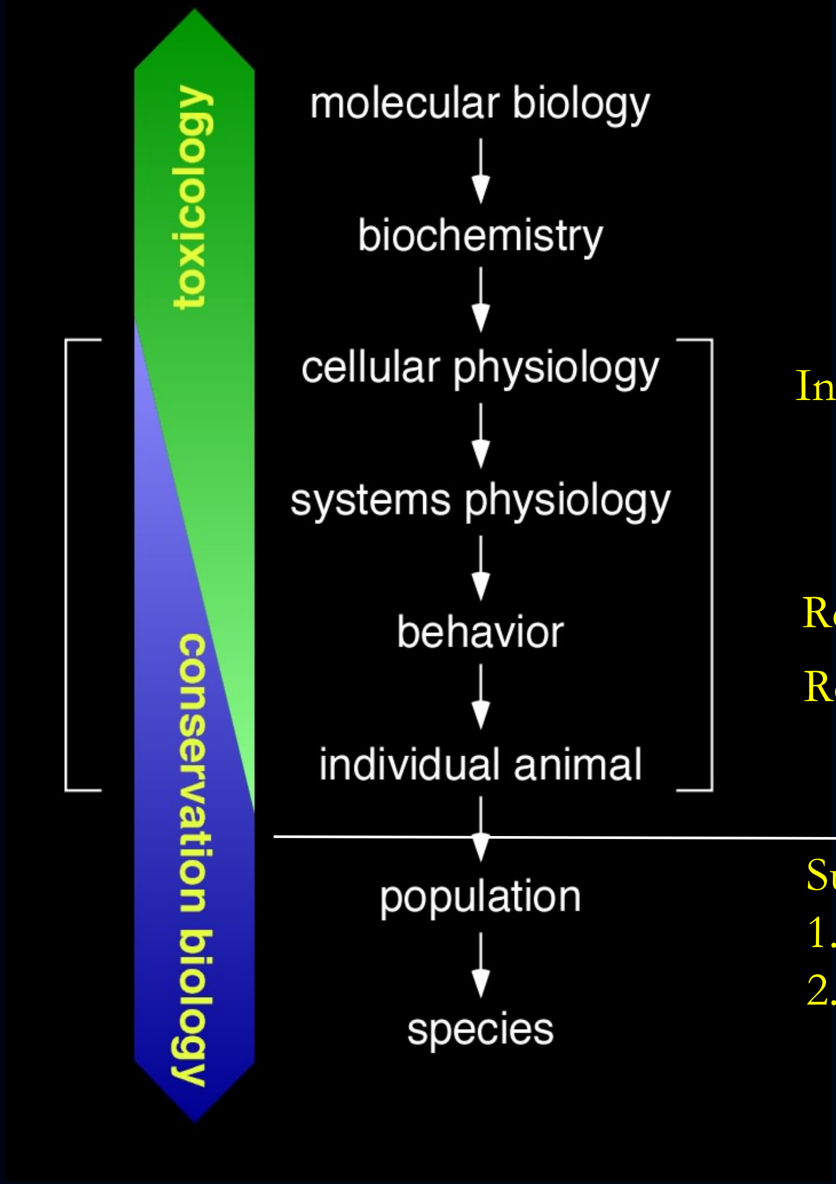
NEUROTOXICANTS

<u>Mode of action:</u>

- disrupt neurotransmission
- inhibit an enzyme, acetylcholinesterase (AChE), by binding to it
- Nerve cells continue to fire



Linking data across biological scales using models



Inhibition of AChE

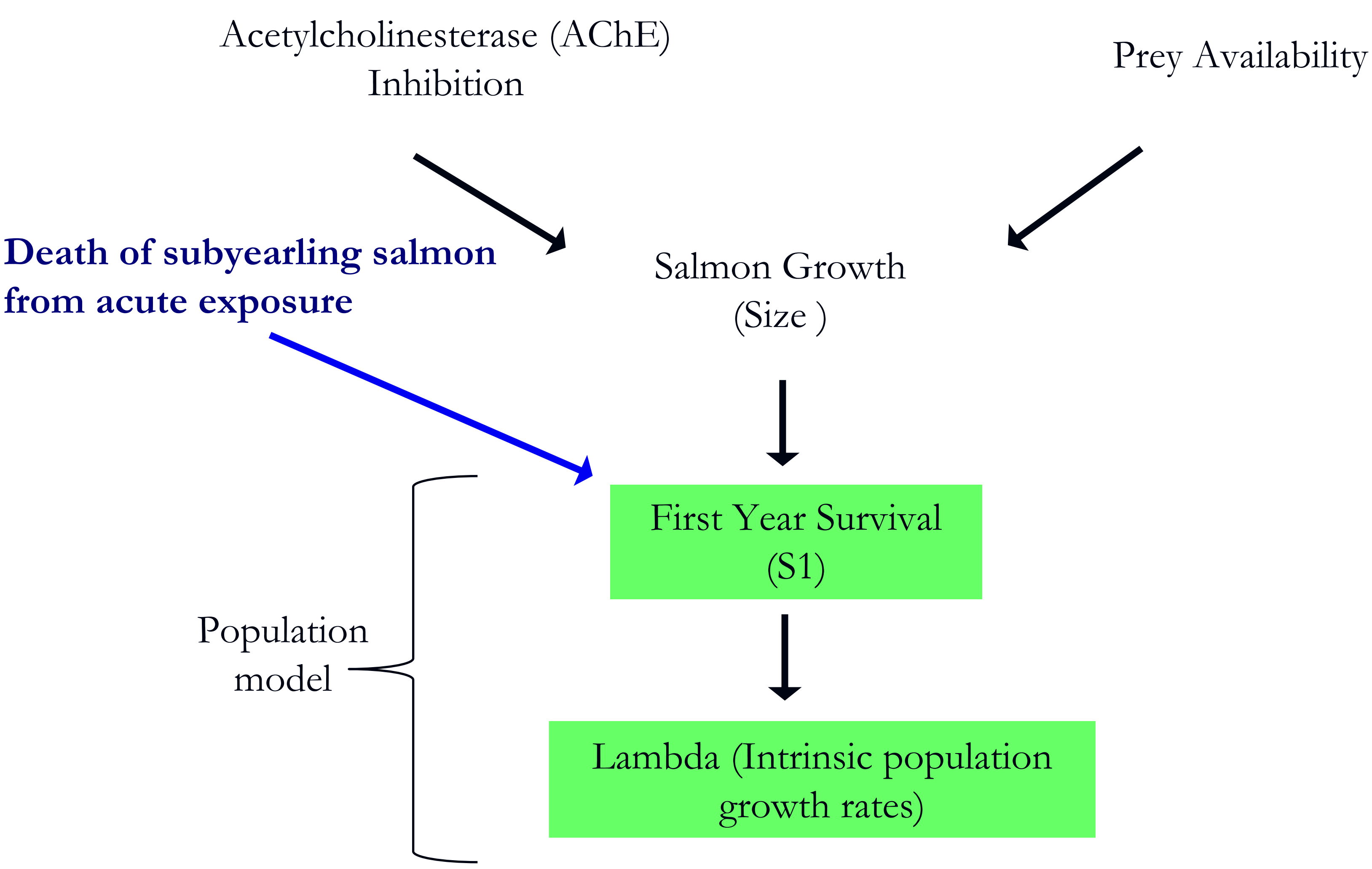
Reduced prey survival

Reduced feeding success

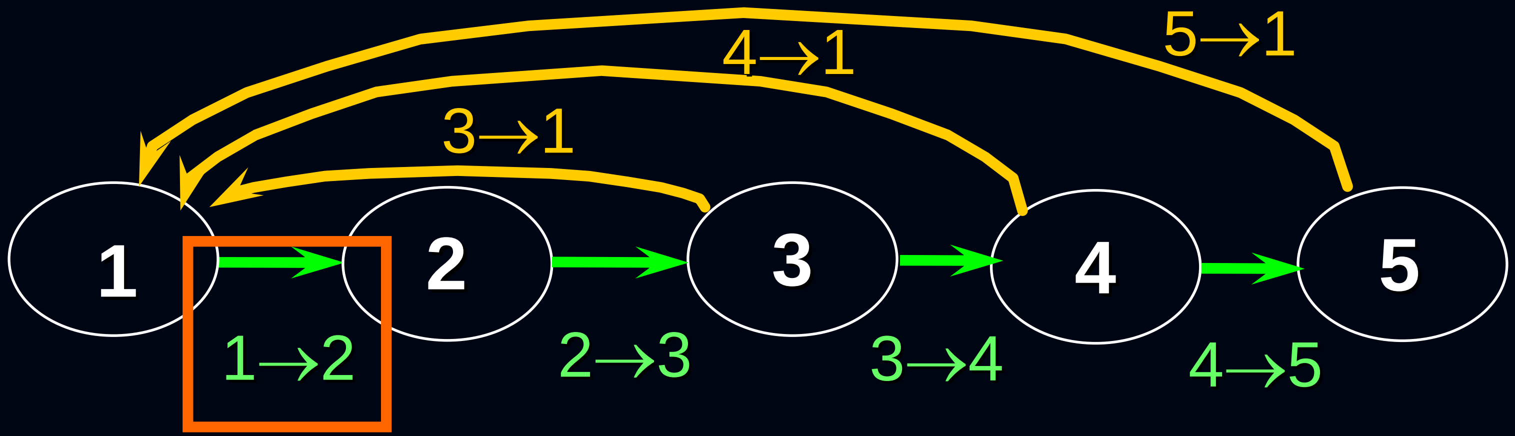
Survival of subyearlings:

1. Acute lethality
2. Reduced growth (size)

Two Models:


Acetylcholinesterase (AChE) Inhibition
Prey Availability
Death of subyearling salmon from acute exposure
Salmon Growth (Size)
First Year Survival (S1)
Population model
Lambda (Intrinsic population growth rates)

Chinook Salmon Life-History



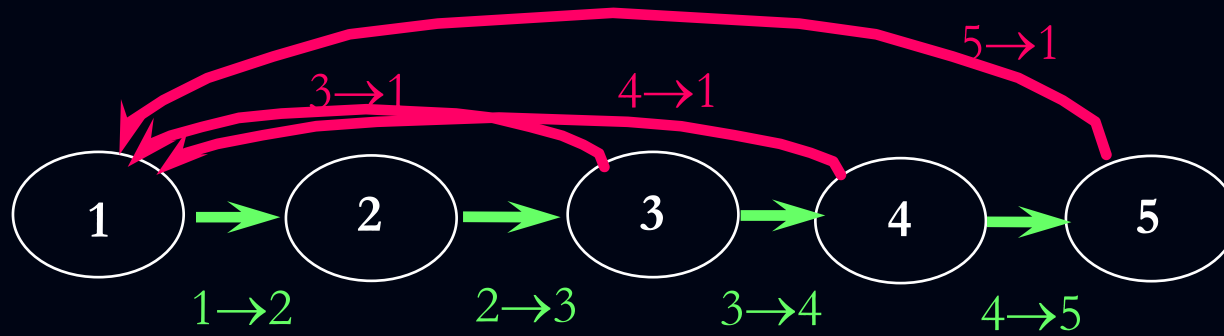
- Stream and ocean-type life-history
- Maximum Age 5 years
- Earliest female Reproduction Age 3
- Density Independent vital rates
- Slight changes in survival and reproduction could alter lambda and age distribution
- Impacts to first year survival produce the largest change in lambda

WDFW

Transition matrix for life-history graph of Chinook salmon

Chinook Salmon

O. tshawytscha

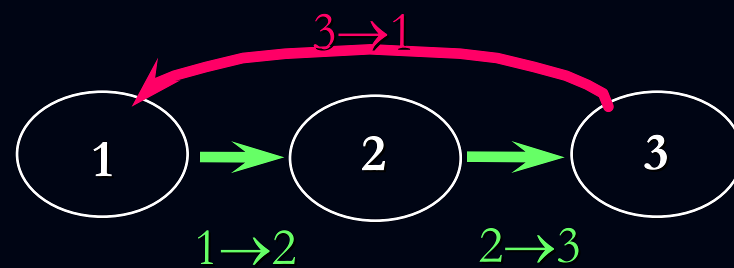


$$A = \begin{bmatrix} 0 & 0 & R3=a_{13} & R4=a_{14} & R5=a_{15} \\ S1=a_{21} & 0 & 0 & 0 & 0 \\ 0 & S2=a_{32} & 0 & 0 & 0 \\ 0 & 0 & S3=a_{43} & 0 & 0 \\ 0 & 0 & 0 & S4=a_{54} & 0 \end{bmatrix}$$

Life-History Modeling

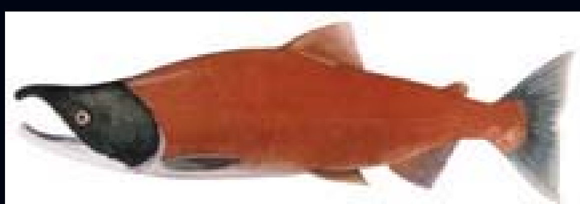
Coho Salmon

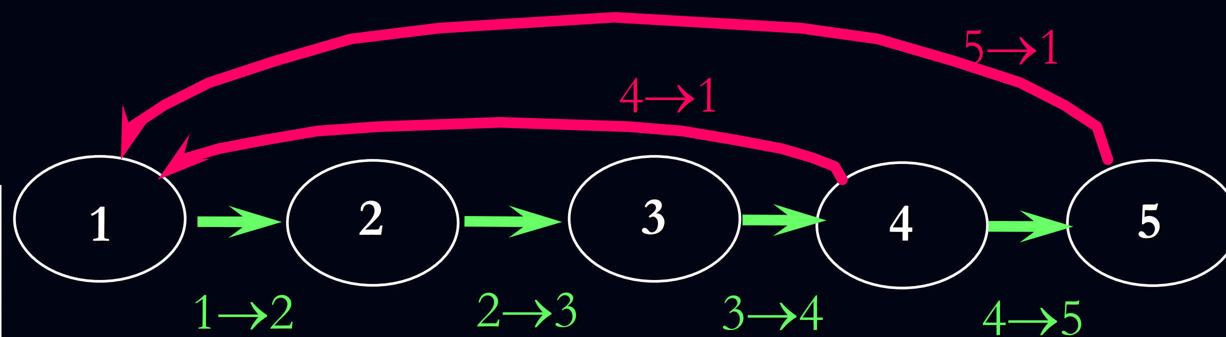
Oncorhynchus kisutch



Sockeye Salmon

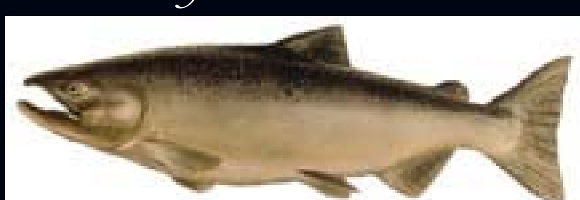
O. nerka

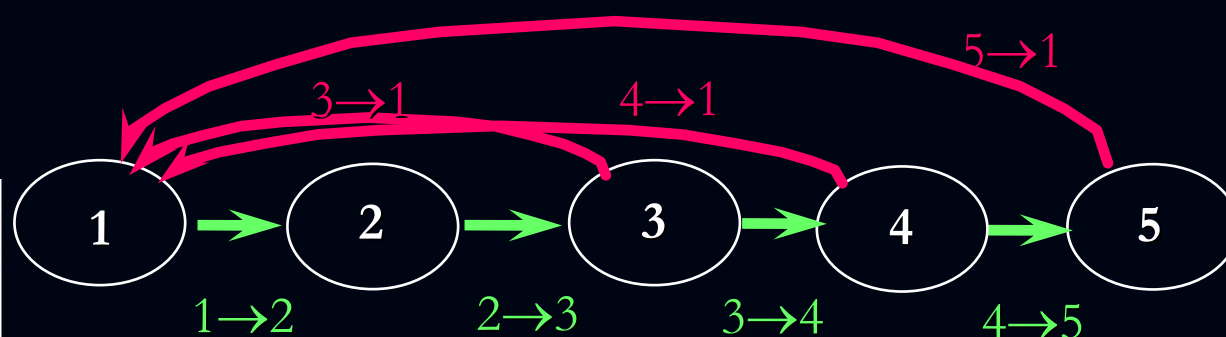




Chinook Salmon

O. tshawytscha





Control Populations

Four “control” populations: Coho, Ocean- and stream type Chinook, sockeye

Chum and steelhead not modeled

Represent a population that we can compare to an impacted population

Comments:
Hatchery fish
Data taken from field studies

Model 1:

Death of subyearling salmonids from acute exposure (96 hours)

Model 1: Acute lethality

Death of subyearling ocean type Chinook salmon: LC50 and slope

First Year Survival (S1)

Population model

$$A=\begin{bmatrix} 0 & 0 & R3=a_{13} & R4=a_{14} & R5=a_{15} \\ S1=a_{21} & 0 & 0 & 0 & 0 \\ 0 & S2=a_{32} & 0 & 0 & 0 \\ 0 & 0 & S3=a_{43} & 0 & 0 \\ 0 & 0 & 0 & S4=a_{54} & 0 \end{bmatrix}$$

Lambda (intrinsic population growth rate)

Model 1 Information

- Ocean- and stream-type Chinook, chum, coho, and sockeye

- All subyearlings exposed at sometime during their first year of survival

- Model repeats the lambda calculation 1000 times to integrate variability in transition values

- Lowest 96 hour salmonid LC_{50} selected

- Sigmoid slope of 3.63 used (probit slope of 4.5)

- Input a range of concentrations to bracket dose-response

Model 1: Inputs

Insecticide	96 h LC50 ug/L	96 h LC50 Slope
Carbaryl	250	3.63
Carbofuran	164	3.63
Methomyl	560	3.63

<u>96 hour exposure concentration (ug/L):</u>
Ran multiple concentrations to bracket the LC50 to determine a population's response

Output of models

- Percent change in Lambda between control and impacted population
- Percent mortality in population
- Survival rates of subyearling salmon (S_1) in control and impacted populations

When is a change in lambda significant?

Example of population model results from death of subyearling salmon

Table 74. Modeled output for Ocean-type Chinook salmon exposed to 4 d exposures of carbaryl, carbofuran, and methomyl reporting the impacted factors of survival as percent dead, lambda and standard deviation, and percent change in lambda compared to an unexposed population.

Carbaryl	0 µg/L	50 µg/L	100 µg/L	200 µg/L	250 µg/L	350 µg/L	500 µg/L	750 µg/L
% dead	0	0	3	31	50	77	93	98
Lambda (STD)	1.09 (0.1)	1.08 (0.1)	1.08 (0.1)	0.98 (0.09)	0.89 (0.08)	0.71 (0.06)	.53 (0.05)	0.36 (0.03)
% change in lambda	NA	NS	NS (-1)	-10	-18	-34	-52	-67
Threshold for significant change in lambda	-9.1 % ~ 190 µg/L							

Model 1: Mixtures

- Used an additivity model based on dose-addition
- 4 day exposure
- Three scenarios:

Scenario	Carbamate	Application	Concentration ug/L
1 PRZM-EXAMS	Carbaryl Carbofuran Methomyl	2 lbs/acre, 4 apps, apples 2 lb/acre, artichoke 0.9 lb/acre, 10 apps	19 35 88
2 GENEEC	Carbaryl Carbofuran Methomyl	Corn Corn Corn	229 53 49
3 Off-channel habitat	Carbaryl Carbofuran Methomyl	5 lb/acre 1 lb/acre 0.9 lbs/acre	335 67 17.1

Scenario 1: PRZM-EXAMS 24-h averages	Ocean-type Chinook	Stream-type Chinook	Sockeye	Coho
% dead	5	5	5	5
Lambda (STD)	1.07 (0.10)	0.99 (0.03)	1.00 (0.06)	1.01 (0.05)
% change in lambda	NS(-1)	NS(-1)	NS(-1)	NS(-2)
Scenario 2: GENEEC 90-d averages	**Ocean-type Chinook**	**Stream-type Chinook**	**Sockeye**	**Coho**
% dead	74	74	74	74
Lambda (STD)	0.74 (0.07)	0.72 (0.02)	0.74 (0.04)	0.66 (0.04)
% change in lambda	-32	-28	-27	-36
Scenario 3: Offchannel habitats 0.5 m deep	**Ocean-type Chinook**	**Stream-type Chinook**	**Sockeye**	**Coho**
% dead	89	89	89	89
Lambda (STD)	0.59 (0.05)	0.58 (0.02)	0.60 (0.03)	0.49 (0.03)
% change in lambda	-46	-42	-41	-52

NA denotes non applicable; NS denotes values less than one standard deviation of lambda expressed as the percent of lambda. (Calculated value, omitted when less than or equal to one)

Model 2:

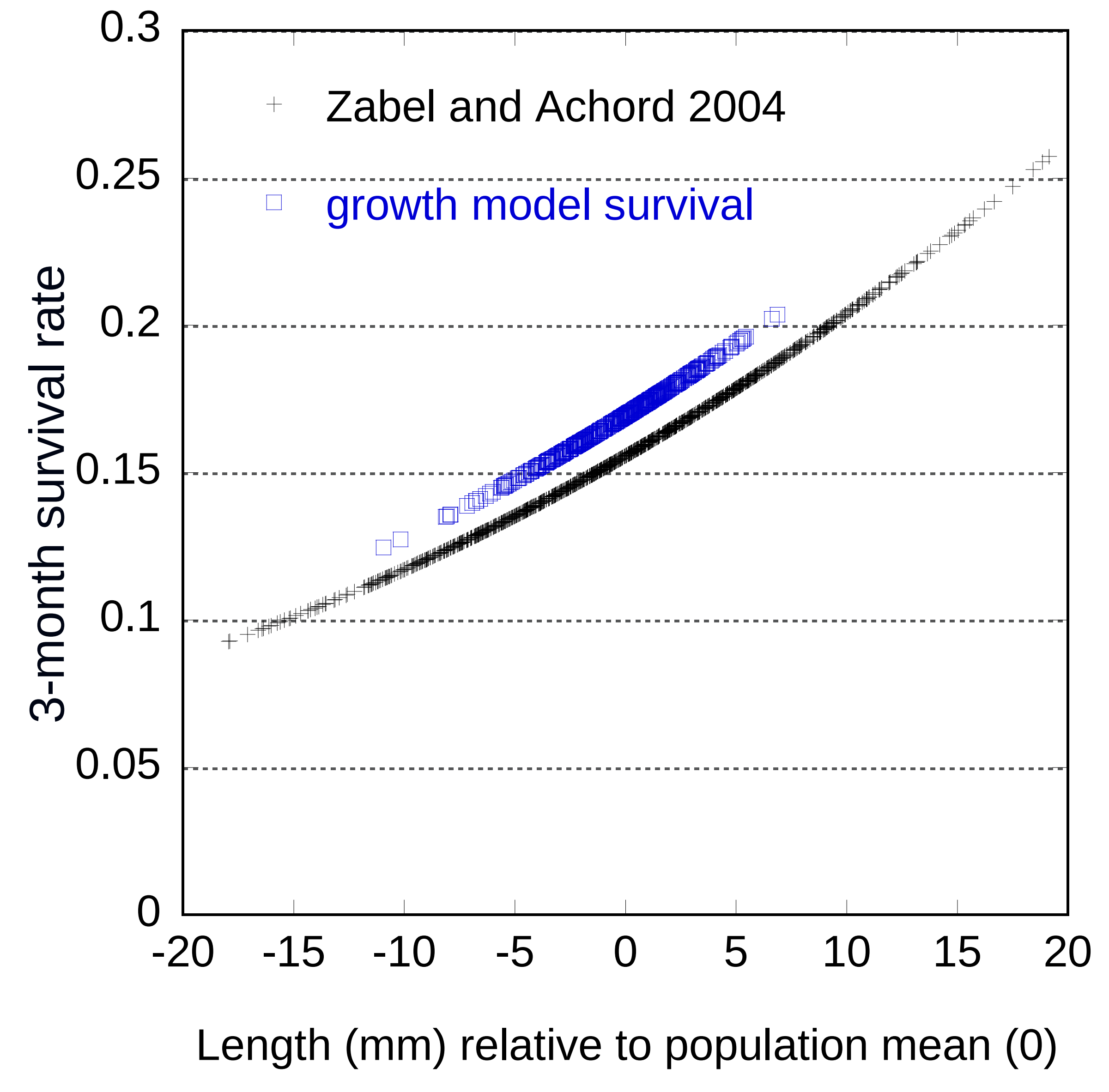
Effects to growth and subsequent size of subyearling salmon from:

1. Reduced feeding

and

2. Reduced abundance of salmon prey

Linking reductions in juvenile size to reductions in individual survival for ocean-type Chinook



Modeling sublethal effects from AChE inhibition

reduced feeding behavior* → slower juvenile growth ← reduced ration

slower juvenile growth

↓

smaller size

↓

reduced survival (size-selective mortality)

} *Somatic growth model*

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lower individual first year survival rates

↓

less productive wild populations over time

↓

slower recovery of ESA-listed species

} *Population model*

*Baldwin, D.H., Spromberg, J.A., and Scholz, N.L. (2009). A fish of many scales: extrapolating sublethal pesticide exposures to the productivity of wild salmon populations. *In press.*

Model 2:

Acetylcholinesterase (AChE) inhibition of subyearlings

Reduction in prey availability

Salmon growth (Size)

First Year Survival (S1)

Population model

$$A=\begin{bmatrix} 0 & 0 & R3=a_{13} & R4=a_{14} & R5=a_{15} \\ S1=a_{21} & 0 & 0 & 0 & 0 \\ 0 & S2=a_{32} & 0 & 0 & 0 \\ 0 & 0 & S3=a_{43} & 0 & 0 \\ 0 & 0 & 0 & S4=a_{54} & 0 \end{bmatrix}$$

Lambda (Intrinsic population growth rates)

Growth model control values

Table 2. Species specific control parameters to model organismal growth and survival rates. Growth period and survival rate are determined from the literature data listed for each species. Gc and α were calculated to make the basic model produce the appropriate size and survival values from the literature.

	Chinook Stream-type[1]	Chinook Ocean-type[2]	Coho[3]	Sockeye[4]
days to run organismal growth model	184	140	184	168
growth rate % body wt/day (Gc)	1.28	1.30	0.90	1.183
α from equation S	-0.33	-1.99	-0.802	-0.871
Control Survival ϕ	0.418	0.169	0.310	0.295

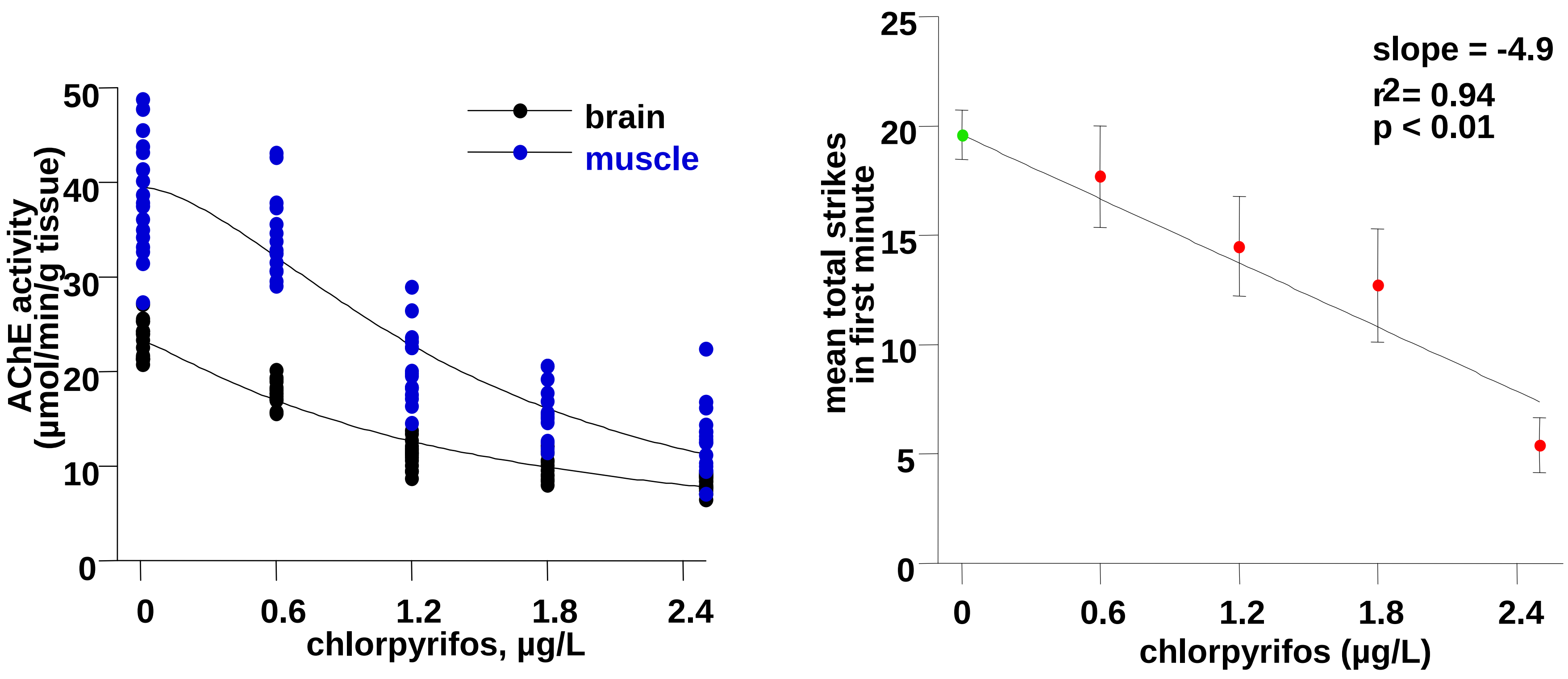
[1] Values from data in Healy and Heard 1984, Fast et al., 1988, Beckman et al., 2000, Knudsen et al., 2006

[2] Values from data in Healey and Heard 1984, Howell et al., 1985, Roni and Quinn 1995, Ratner et al.,1997, PSCCTC 2002, Green and Beechie, 2004, Johnson et al., 2007

[3] Values from data in Pess et al., 2002, Knudsen et al., 2002

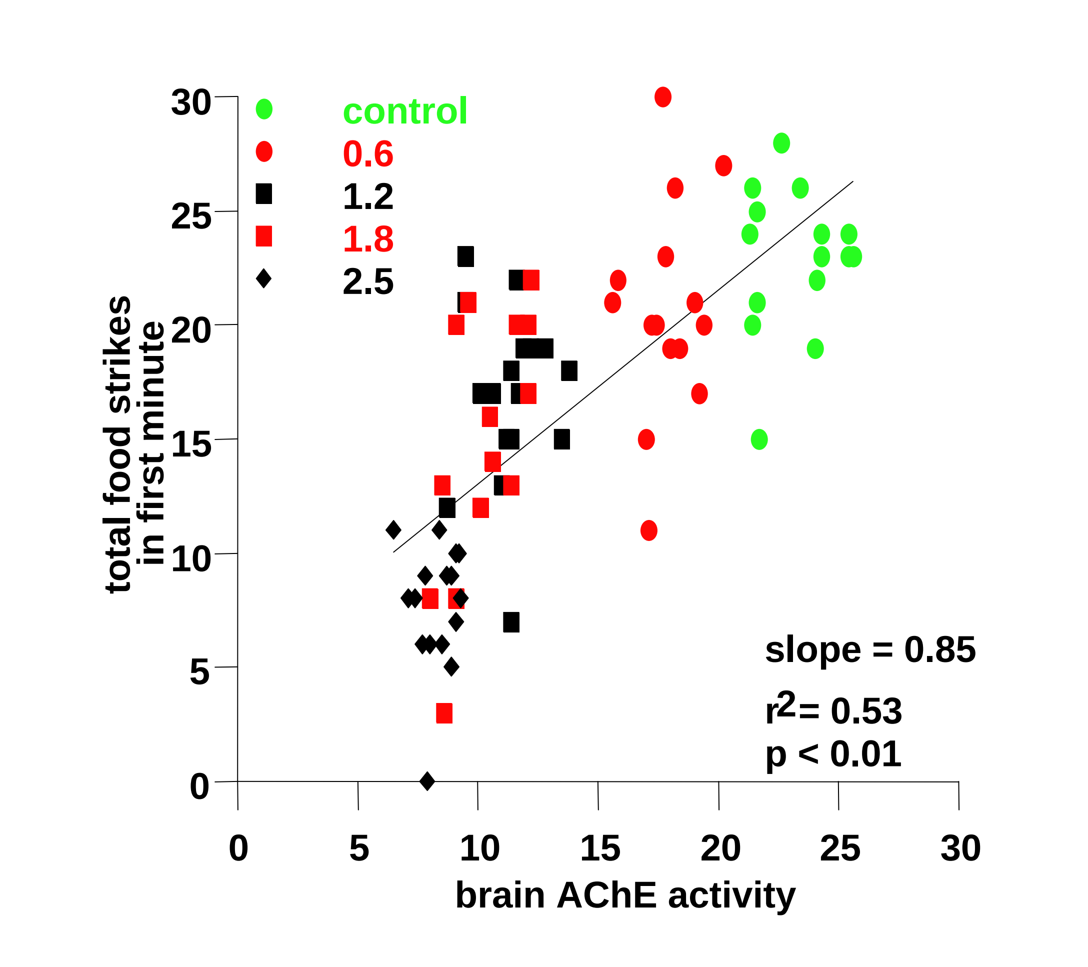
[4] Values from data in Pauley et al., 1989, Gustafson et al., 1997, McGurk 2000

Impact of chlorpyrifos on the AChE activity and feeding behavior of coho



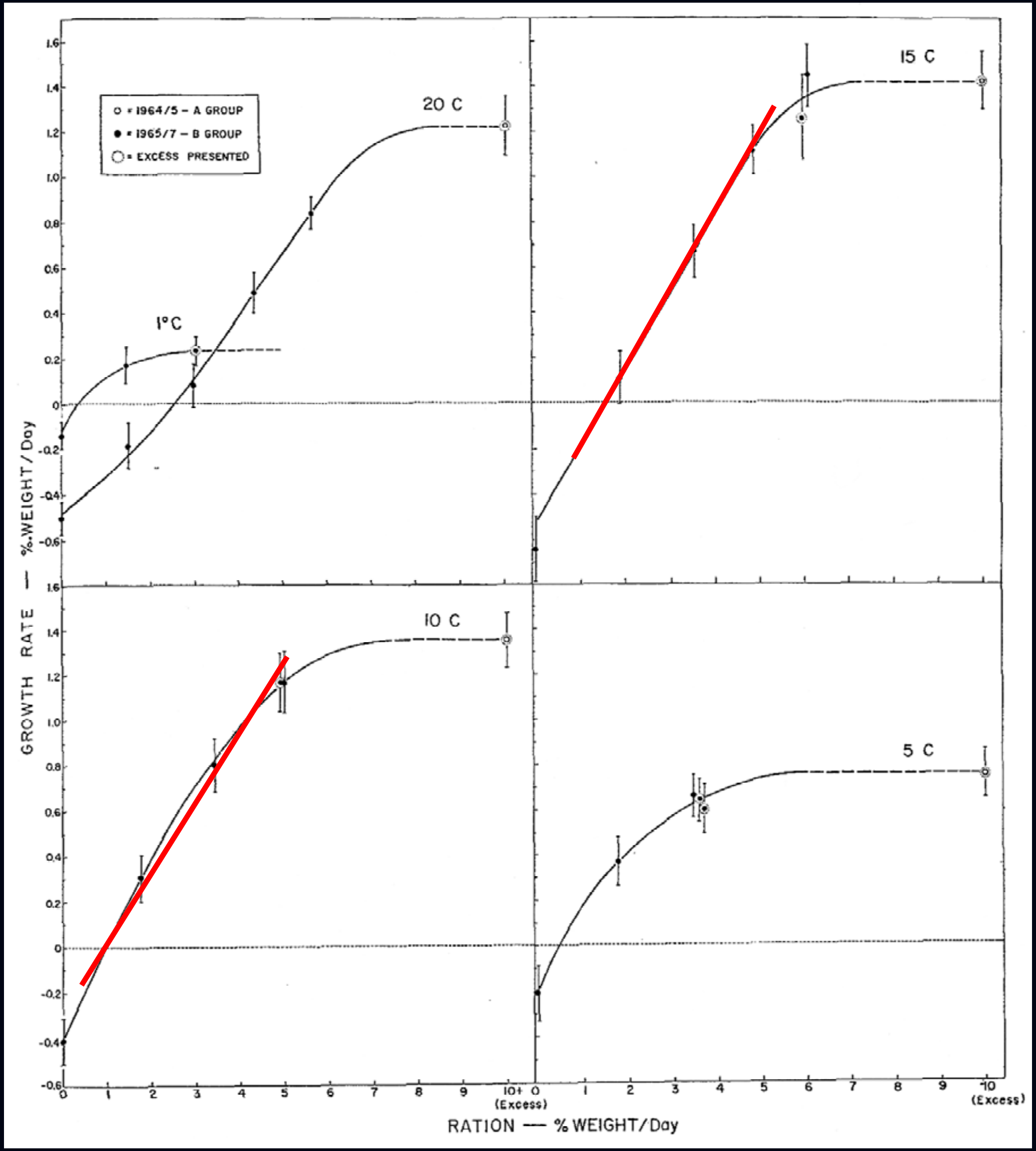
Sandahl et al. (2005)

Impact of chlorpyrifos on the AChE activity of coho links to feeding behavior



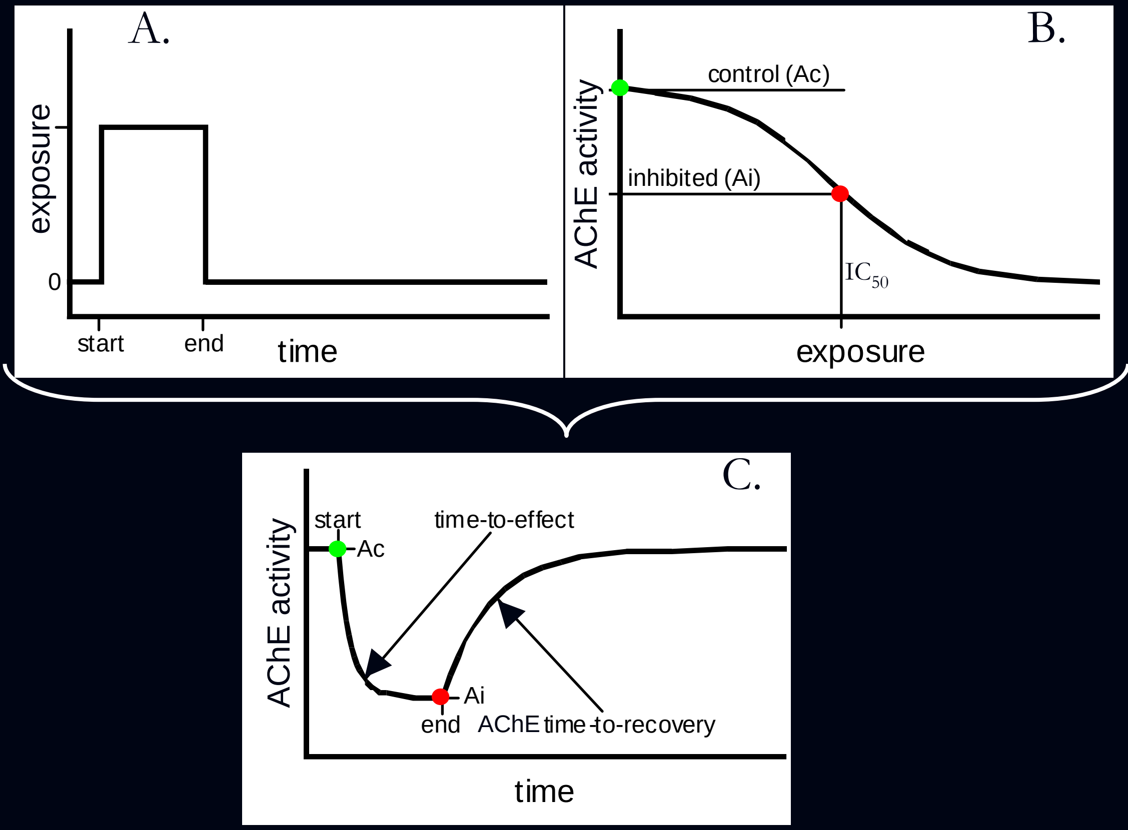
Sandahl et al. (2005)

Ration (food uptake) can be linked to growth rate



Brett et al. (1969)

Creating a model to link AChE inhibition to reduced growth

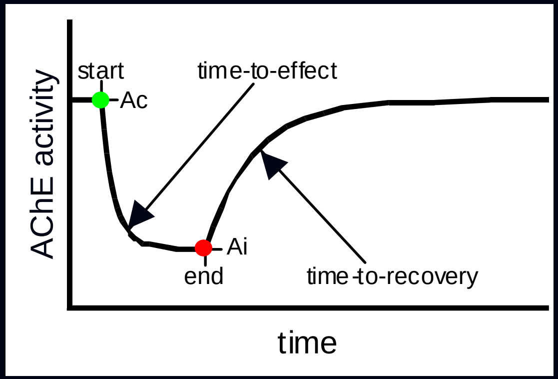


Step 1: Define…

- pesticide exposure
- magnitude of AChE inhibition
- timecourse for effect and recovery

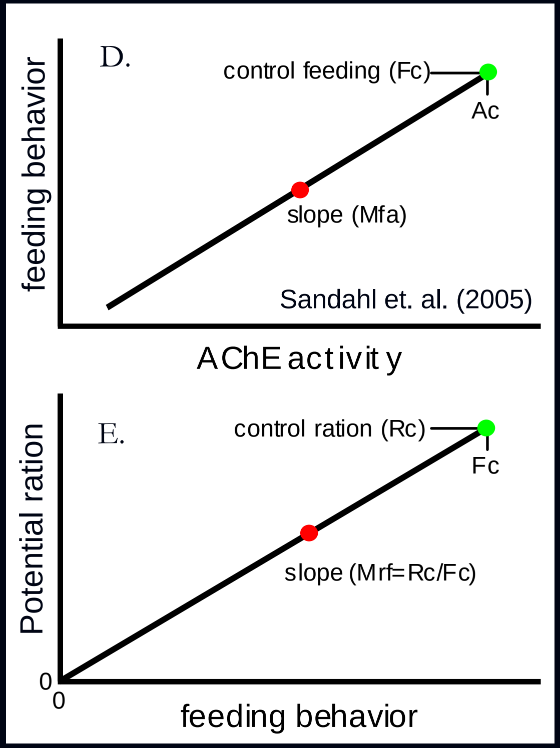
Creating a model to link AChE inhibition to reduced growth

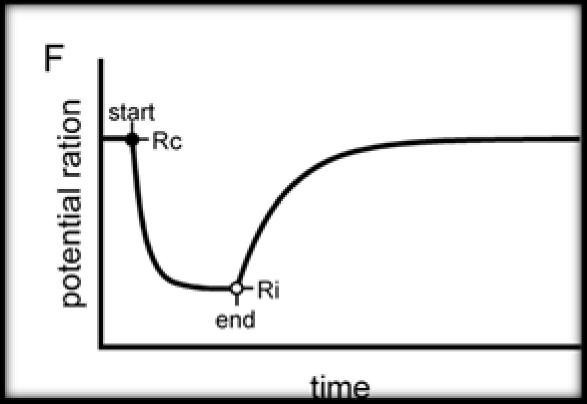
On any given day…

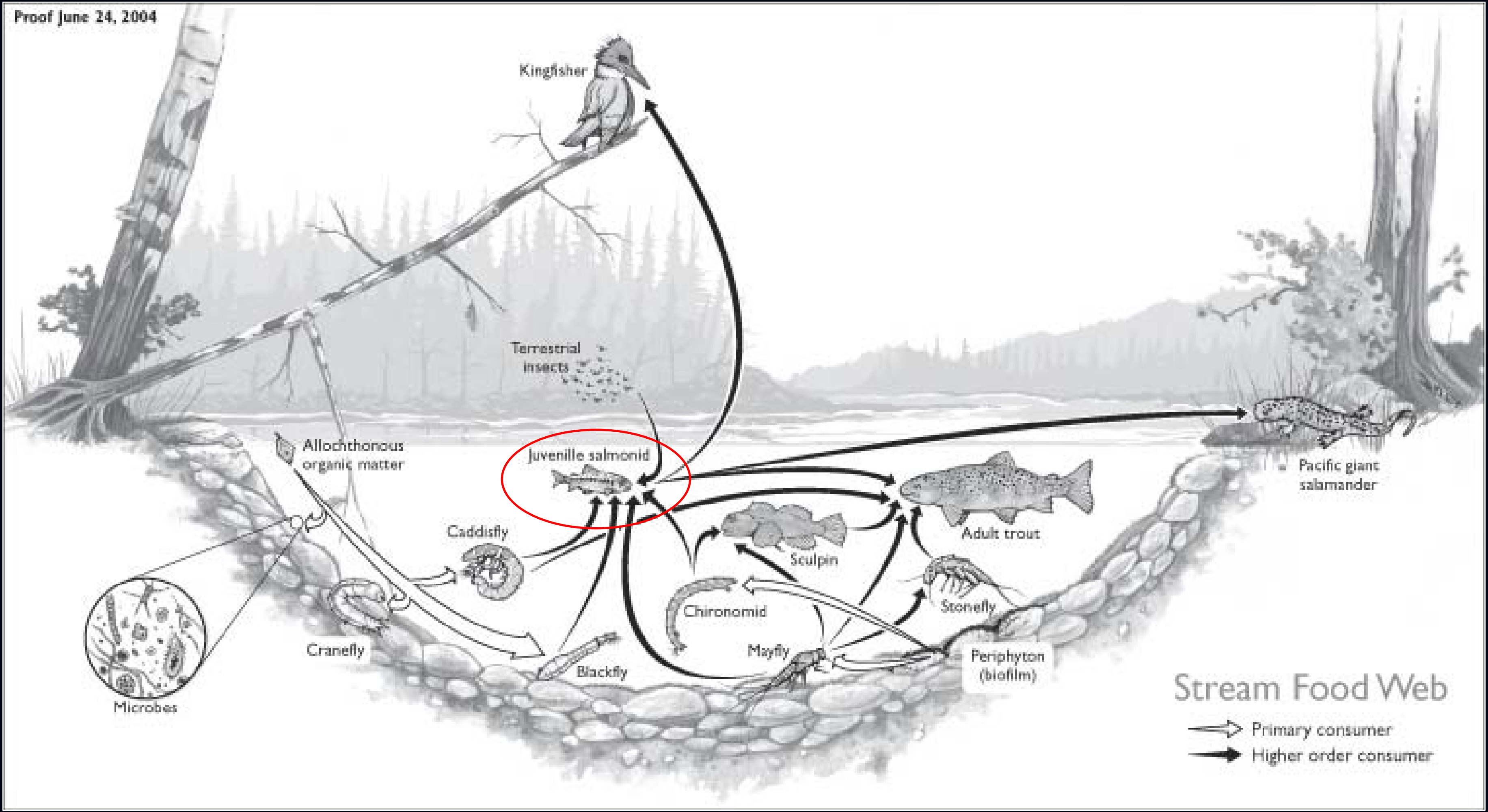


Step 2: Connect the dots…

- AChE inhibition
- reduced feeding
- reduced ration

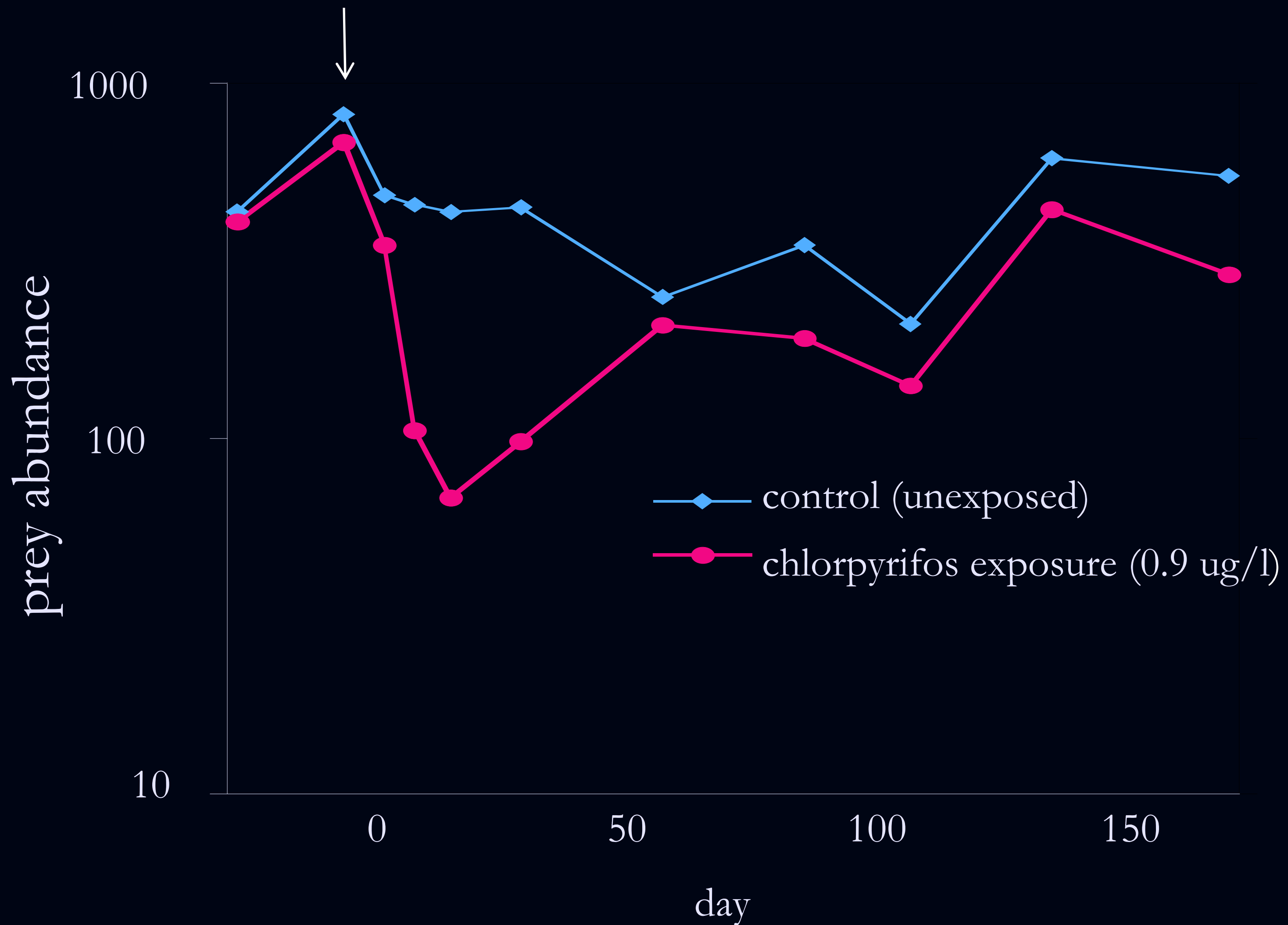






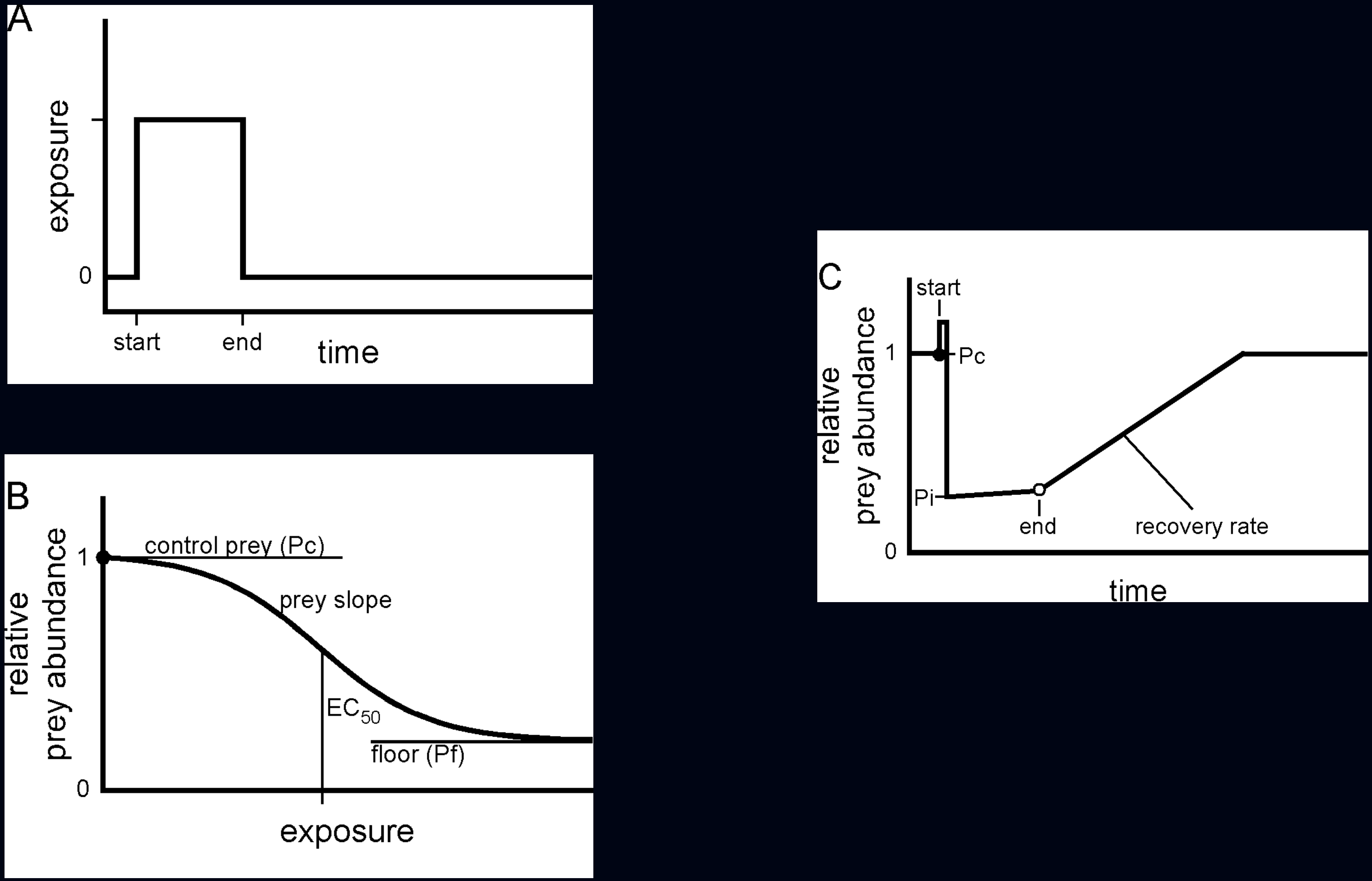
- Freshwater exposure to insecticides reduces abundances of salmonid prey
- Reductions of prey potentially affects growth and size which impacts survival

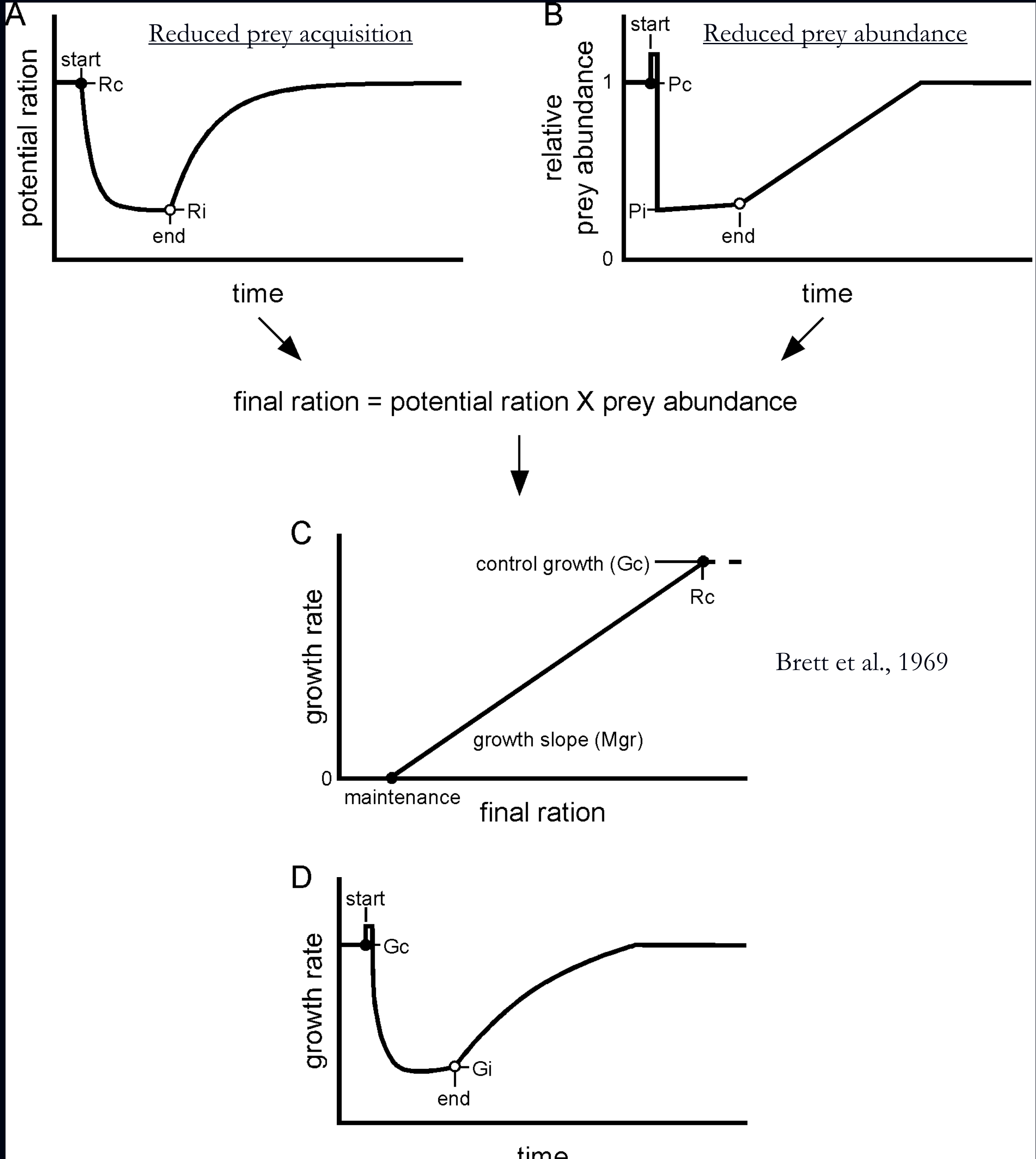
Recovery: Abundances of 16 salmonid prey taxa



Compiled data supplied by van den Brink et al. 1996. ET&C (15):1143-1153

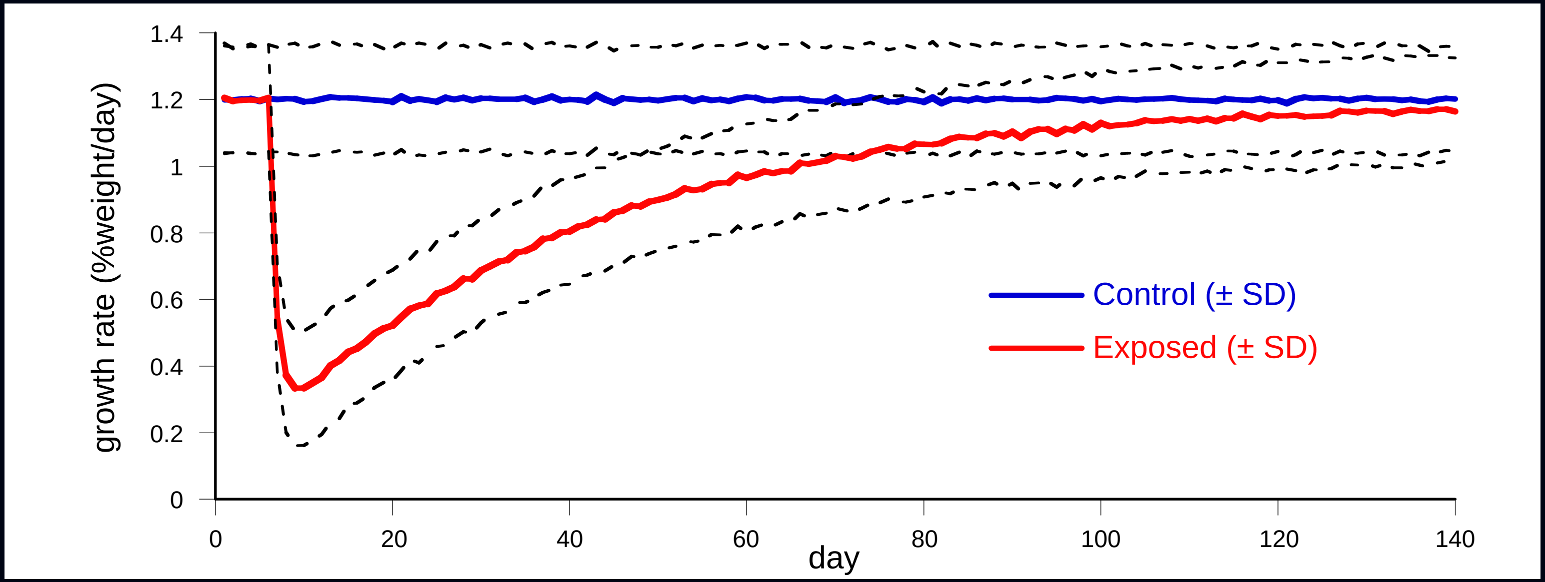
Model 2: Modeling reductions in prey abundance

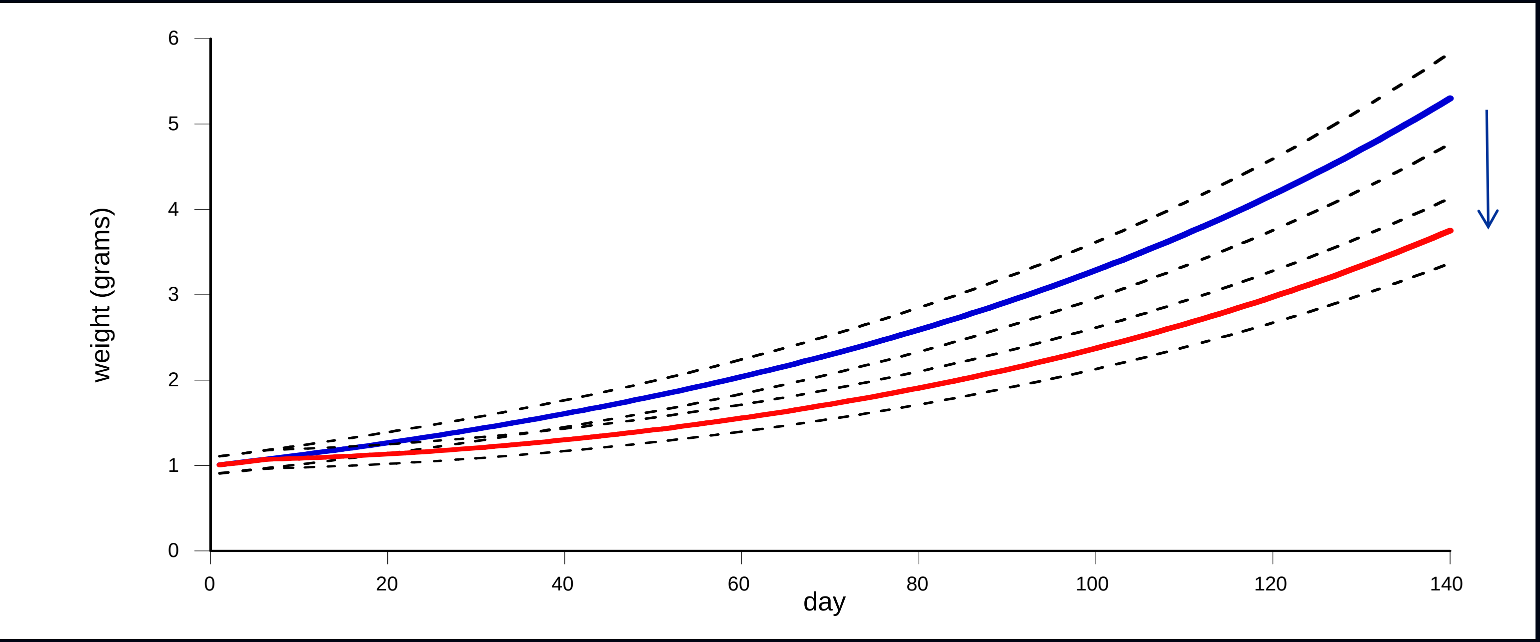




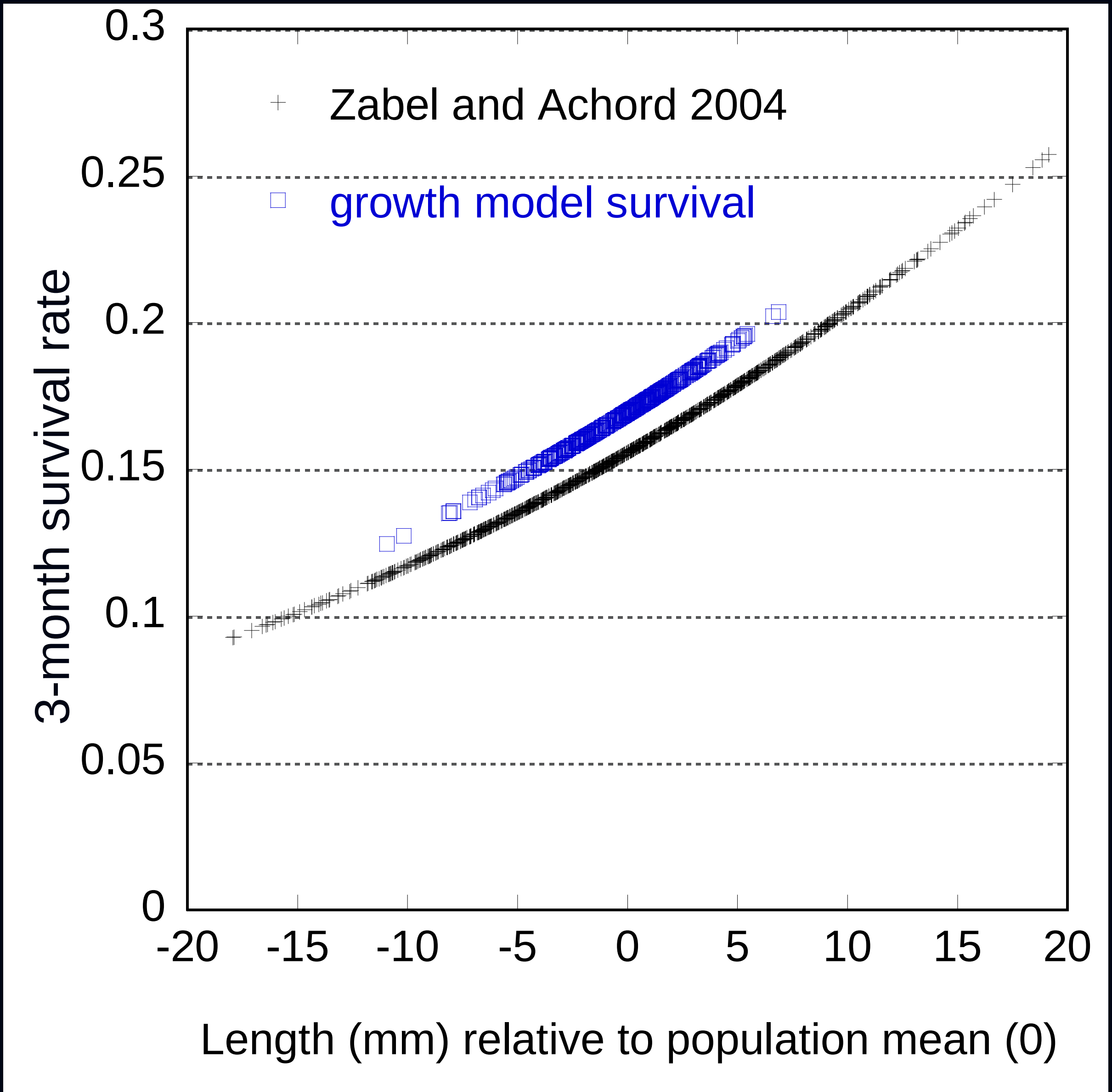
Brett et al., 1969

Consequences of reduced growth on final weight of subyearling Chinook salmon



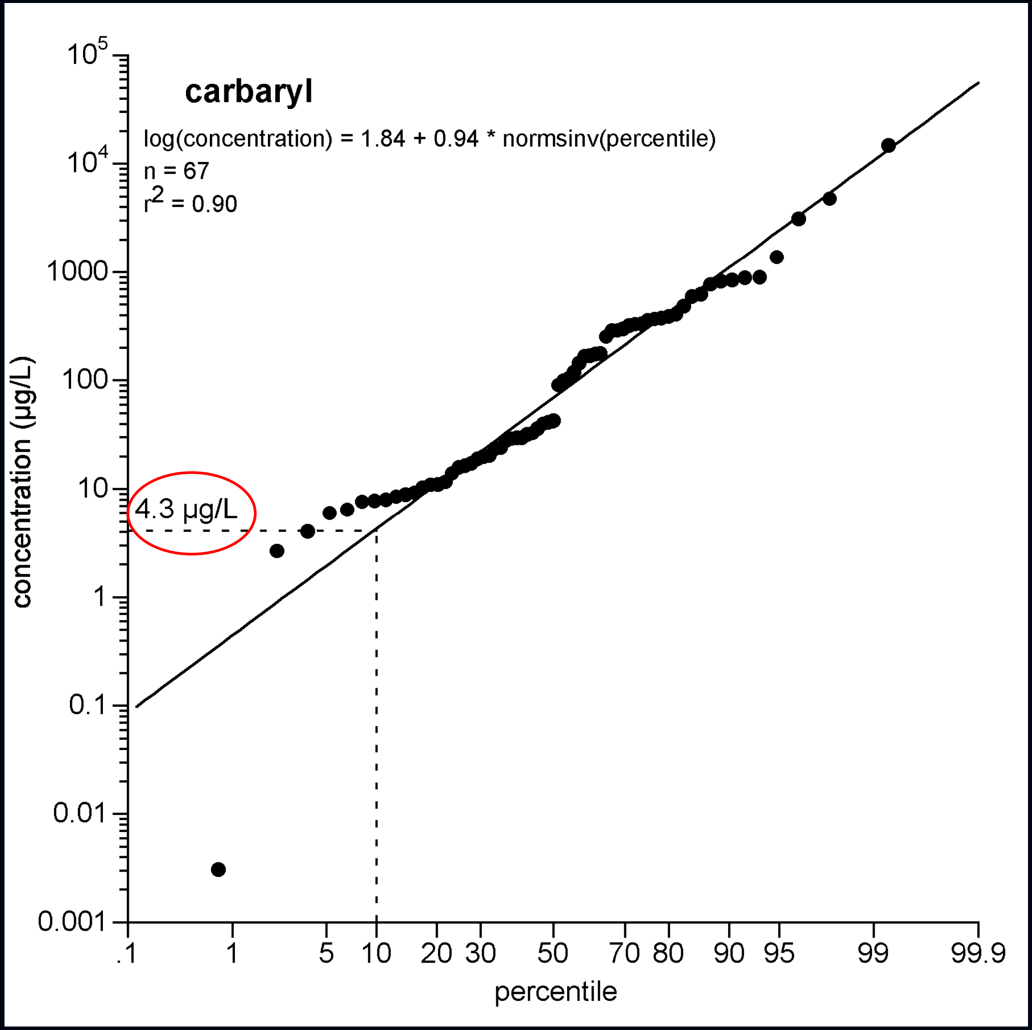


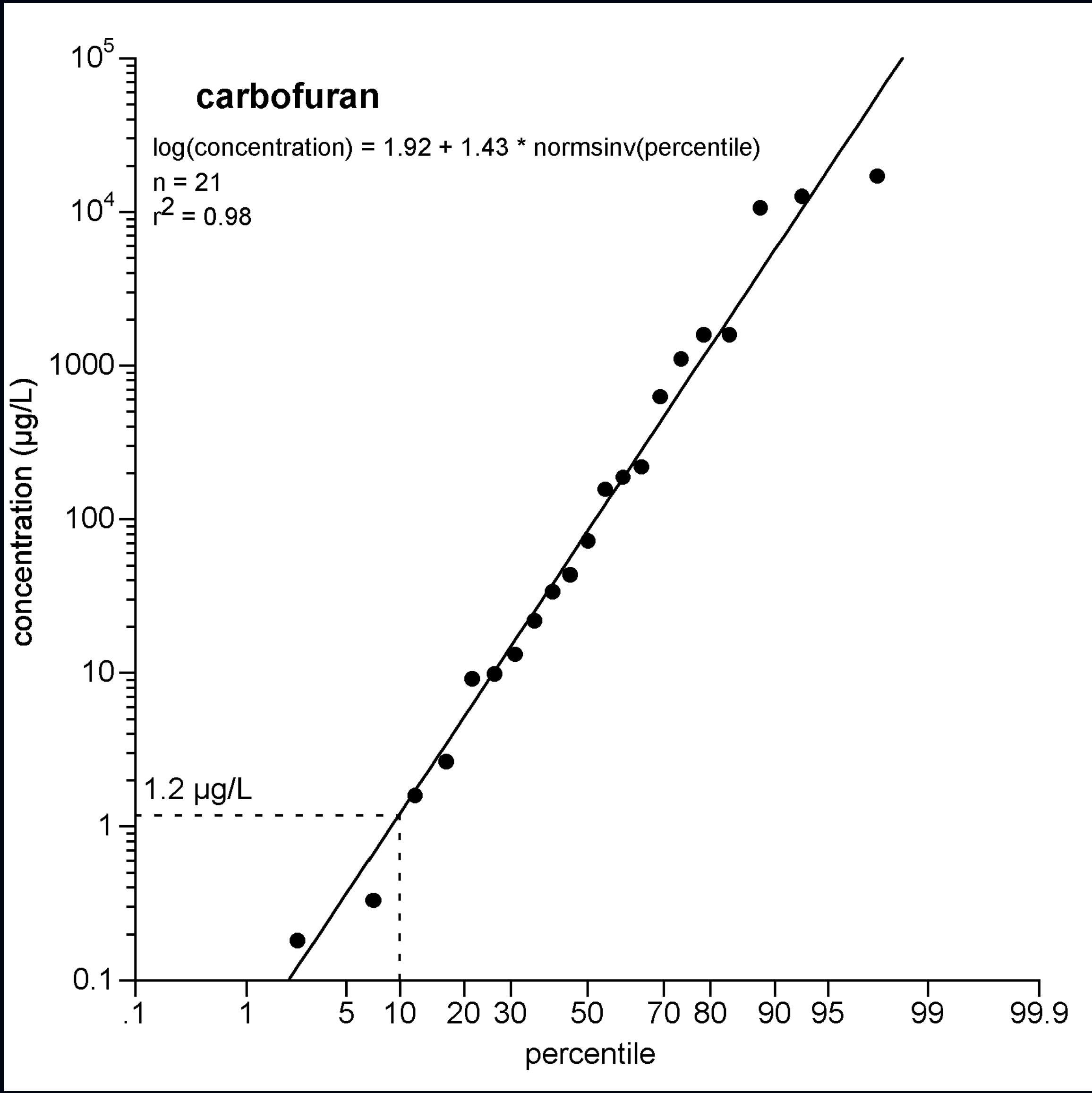
Linking reductions in juvenile size to reductions in individual survival for ocean-type Chinook



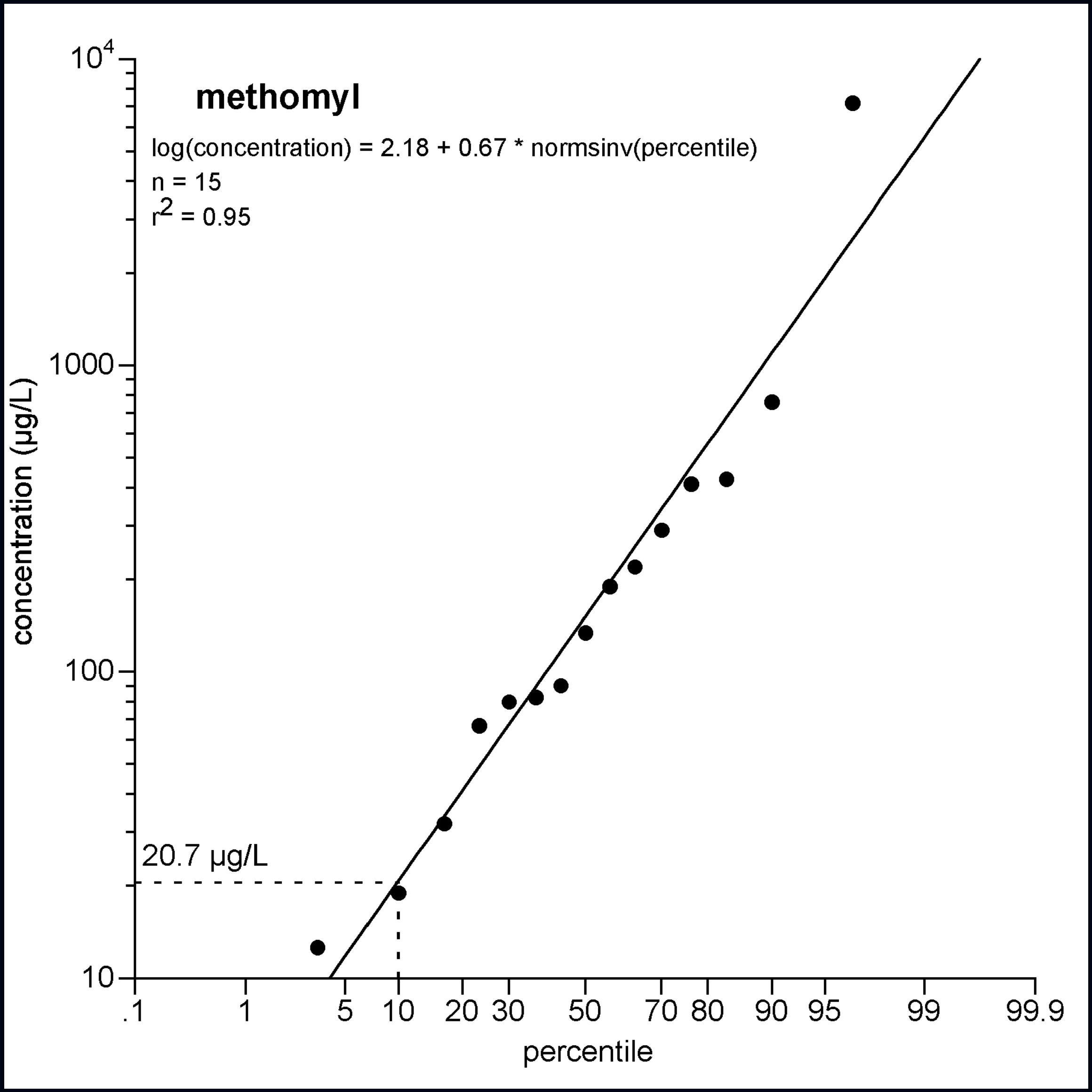
Noteworthy input parameters for Model 2

How we selected salmon prey sensitivity (LC50)





carbofuran
log(concentration) = 1.92 + 1.43 * normsinv(percentile)
n = 21
r2 = 0.98
1.2 µg/L
concentration (µg/L)
10^5
10^4
1000
100
10
1
0.1
.1
1
5
10
20
30
50
70
80
90
95
99
99.9
percentile



methomyl
log(concentration) = 2.18 + 0.67 * normsinv(percentile)
n = 15
r2 = 0.95
20.7 µg/L
concentration (µg/L)
10
100
1000
10⁴
percentile
.1
1
5
10
20
30
50
70
80
90
95
99
99.9

Selection of a community prey slope

96 hour static bioassays with carbaryl on several salmonid prey taxa collected from PNW streams

Species	Survival EC50 ug/L	95% CI ug/L	Probit slope	Sigmoid slope
Stonefly- *Calineuria californica*	17.3	14.06-20.2	8.24	6.0
Mayfly- *Cinygma sp.*	11.1	7.7-13.9	4.10	3.0
Mayfly- *Ameletus sp.*	20.4	na	5.34	3.9
Caddisfly- *Brachycentrus americanus*	41.2	37.6-50.5	15.0	10.9
Caddisfly- *Psychoglypha sp. early instar*	30.3	25.0-40.4	9.10	6.6
Caddisfly- *Psychoglypha sp. Late instar*	61	55.6-68.54	7.50	5.5
Caddisfly- *Lepidostoma unicolor*	29	19.5-37.0	4.80	3.5

Peterson et al. 2001

Median sigmoid slope = 5.5

Dose-response relationship for Ocean-type Chinook

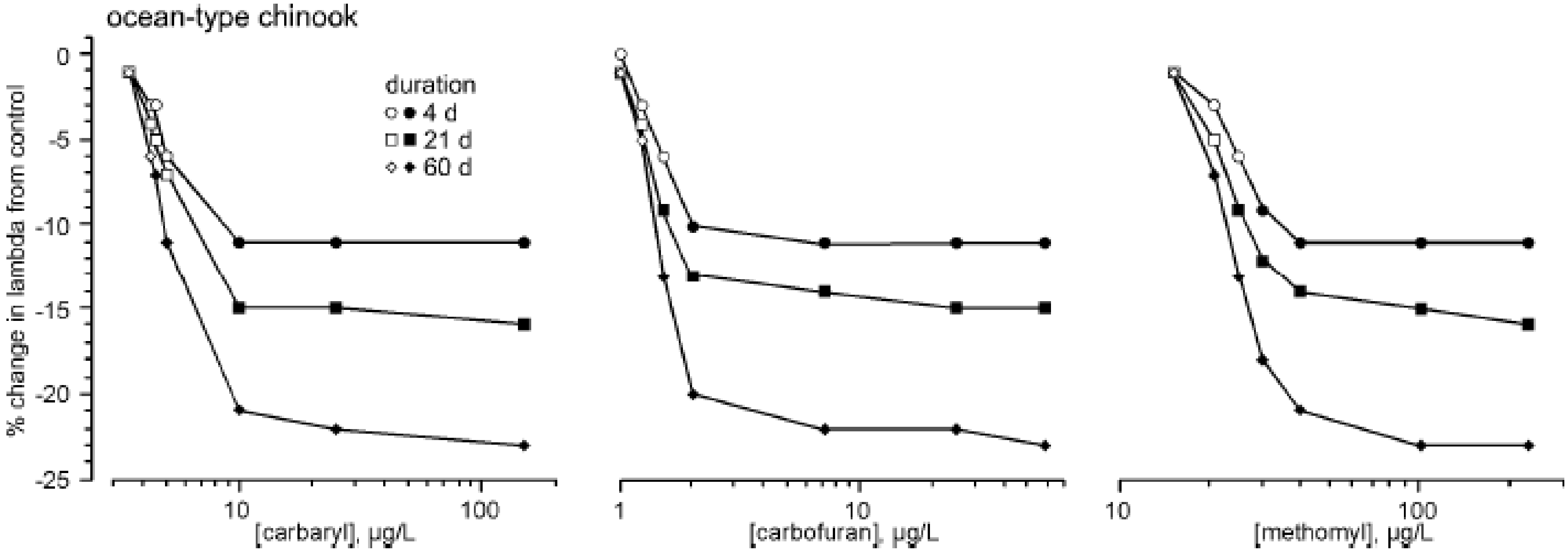


Figure 44. Percent change in lambda for Ocean-type Chinook salmon following 4 d, 21 d, and 60 d exposures to carbaryl, carbofuran, and methomyl. Open symbols denote a percent change in lambda of less than one standard deviation from control population. Closed symbols represent a percent change in lambda of more than one standard deviation from control population.

Table 80. Multiple application scenarios for carbaryl and methomyl and predicted percent change in lambdas for salmon populations

	Carbaryl	Methomyl
Crop examples	Almonds, chestnuts, pecans, filberts, walnuts, pistachios	Sweet corn
Application rate	5 lbs a.i./acre	0.45 lbs a.i./acre
Number of applications/yr	4	10
Application interval	14 days	3 days
Method of application	Aerial (fine-medium droplet distribution)	aerial (fine-medium droplet distribution)
No-application Buffer	none	100 ft
Off-channel habitat characteristics	water depth = 0.5 m Initial average concentration 335 µg/L; 24 h exposure	water depth = 0.5 m Initial average concentration 8.55 µg/L; 96 h exposure
% change in Lambda		
Ocean-type Chinook	-19%	-8%
Stream-type Chinook	-15%	-6%
Sockeye	-16%	-7%
Coho	-18%	-8%

Application of population modeling results

Comparison of change in lambdas with ESA-listed independent populations

Relationship of results to exposure

- Pesticides
- Subyearling salmonids

Population modeling results are one line of evidence

- Results address risk hypotheses related to juvenile growth, survival, and prey availability

- Results of other non-modeled risk hypotheses also evaluated at the population level including:
    - survival of adults
    - swimming ability
    - olfaction-mediated behaviors (carbofuran)
    - starvation

Risk at the Species level (ESU/DPS)

Integration and Synthesis

- Status of the Species
- Environmental Baseline
- Cumulative Effects

Thank you