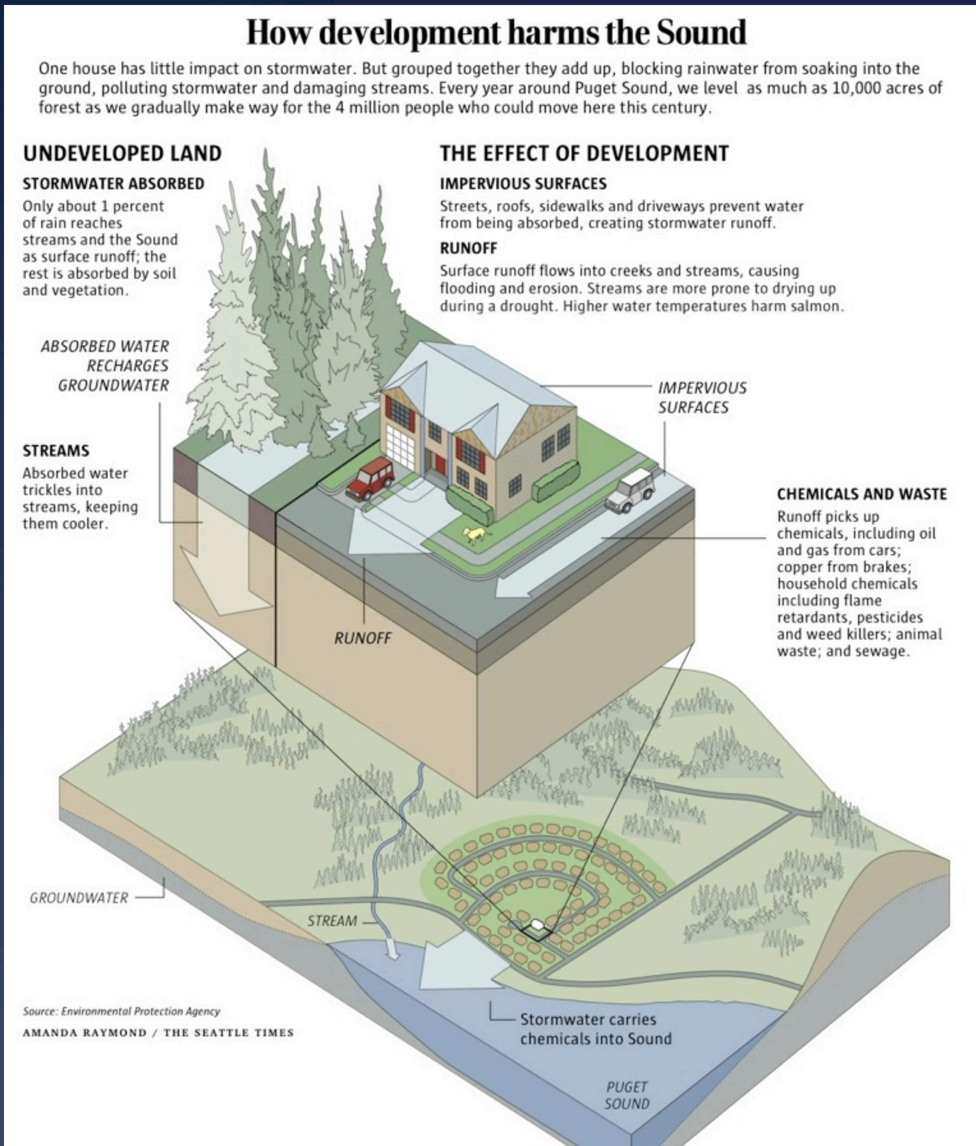
Stormwater and Salmon, Risks and Remedies

Nat Scholz

March 3rd, 2015 - NPCC, Portland

Photo by John McMillan

The environmental health impacts of toxic runoff



Seattle Times, 5/11/08

- **What are they?**
- **How can they be effectively minimized?**
- **Are ongoing efforts to reduce impacts working?**

Underwater video of an urban stormwater outfall

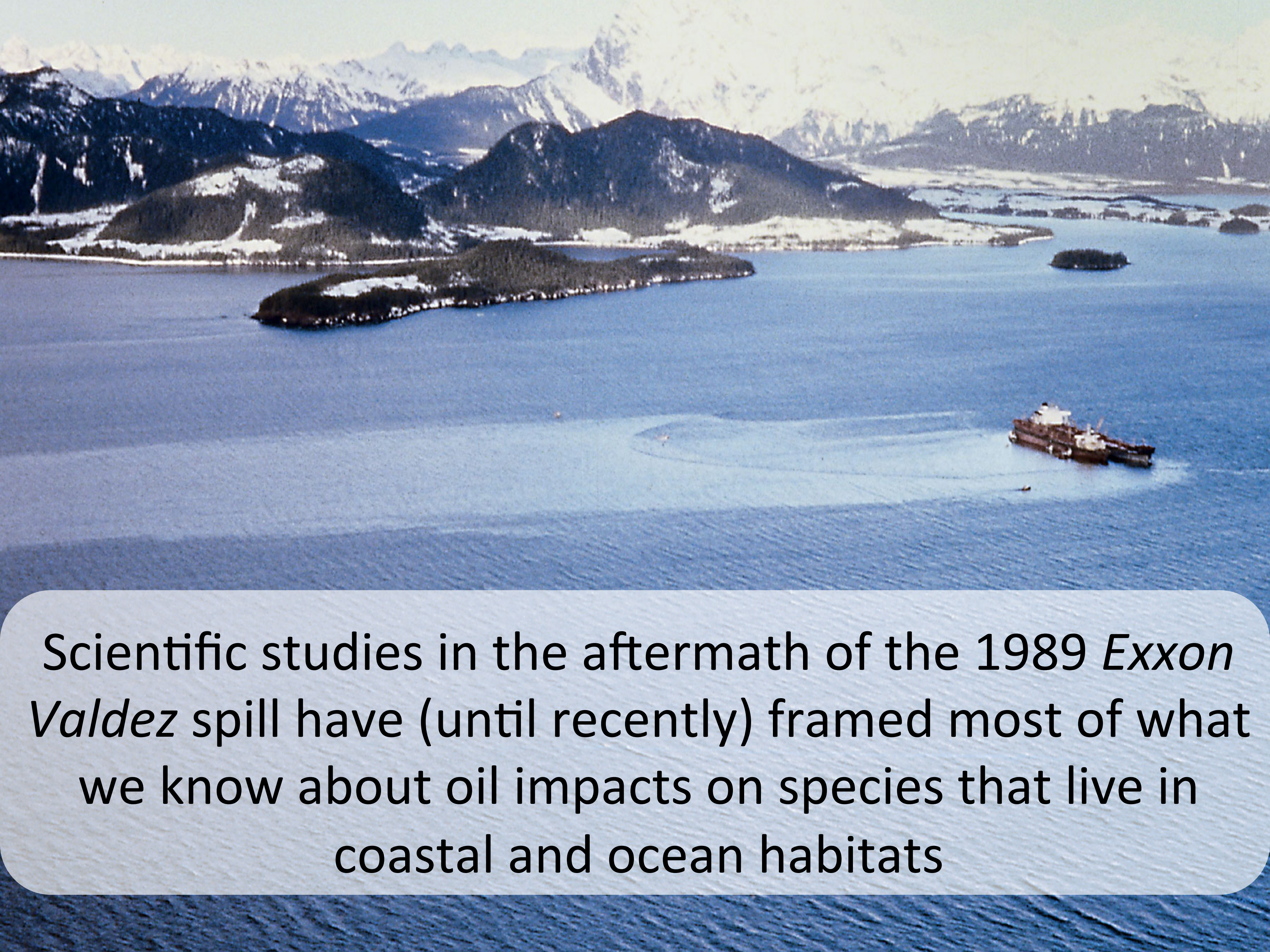
West Seattle diving footage by Laura James (www.tox-ick.org)

Montlake Cut, Seattle, November 19th 2012

Photo by Blake Feist, NOAA Fisheries

Montlake Cut, Seattle, November 19th 2012

Photo by Blake Feist, NOAA Fisheries


Scientific studies in the aftermath of the 1989 *Exxon Valdez* spill have (until recently) framed most of what we know about oil impacts on species that live in coastal and ocean habitats

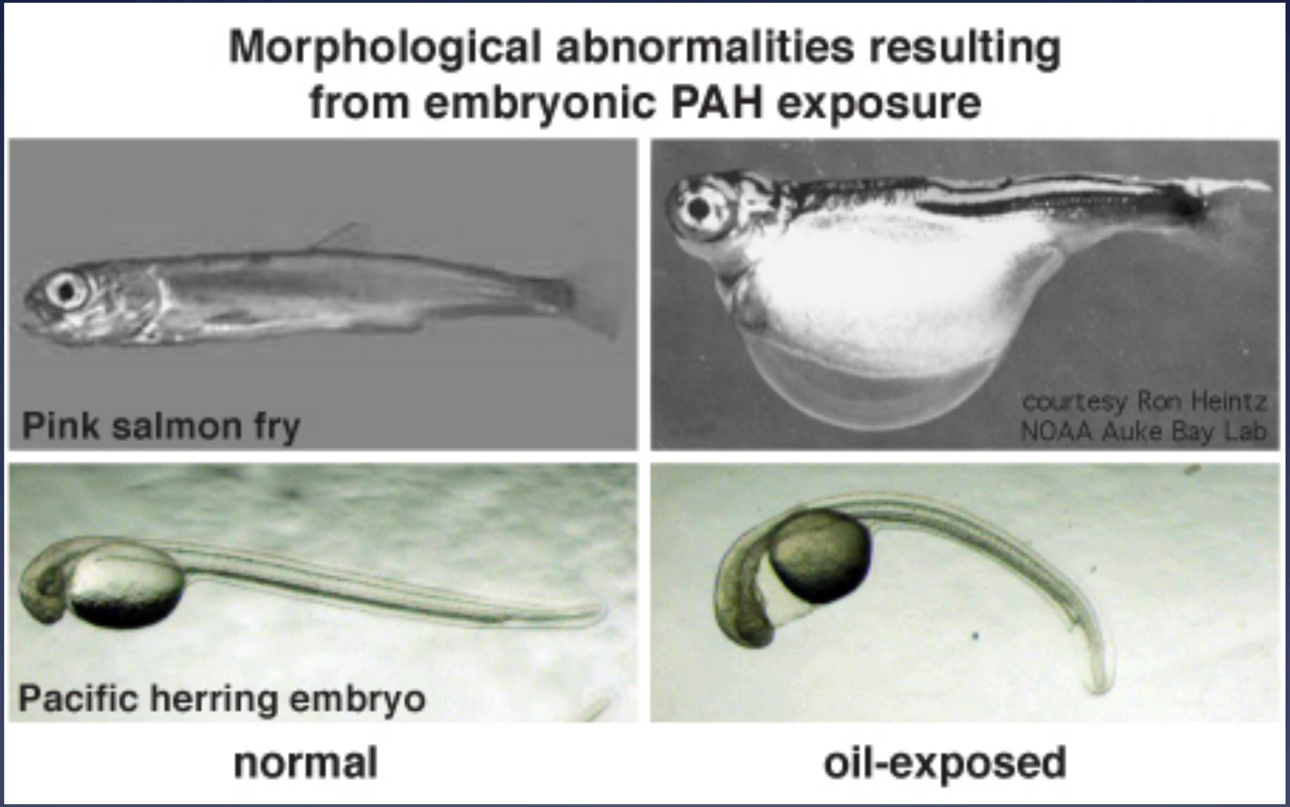
March 24, 1989

pink salmon spawning habitat

Pacific herring spawning habitat

A lesson learned from the Exxon Valdez spill

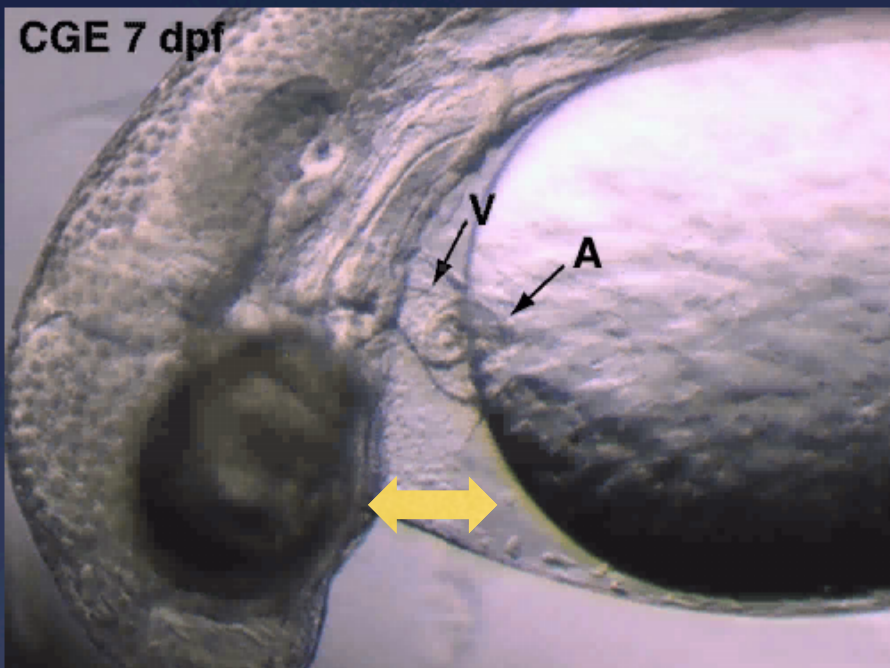
Jeep Rice, Mark Carls, Ron Heintz, NOAA Auke Bay Lab, Juneau



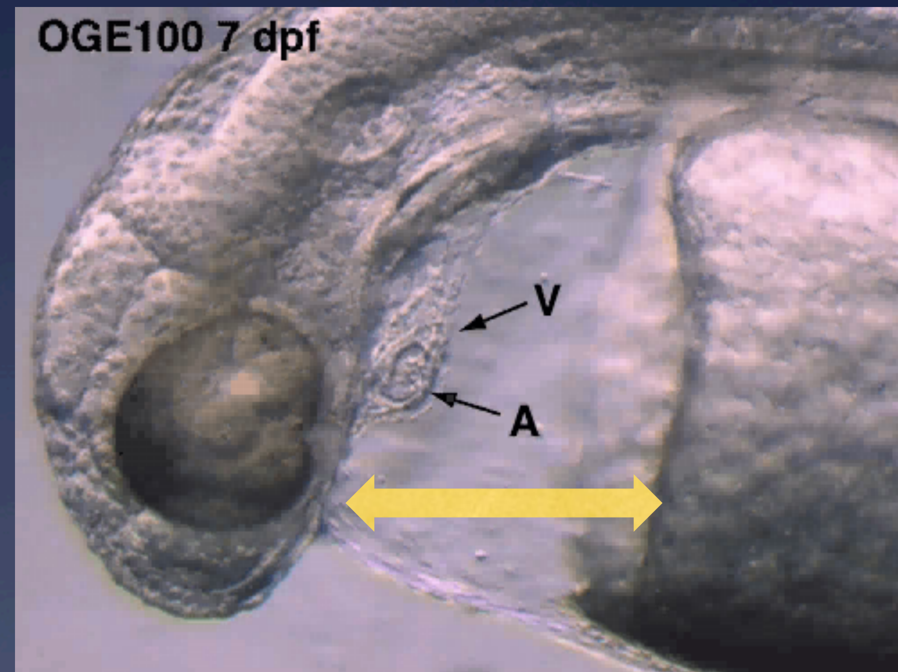
"PAH" refers to polycyclic aromatic hydrocarbons, a key toxic component of crude oil (and stormwater)

The developing heart is the primary target for crude oil-derived PAHs

unexposed



crude-oil exposed

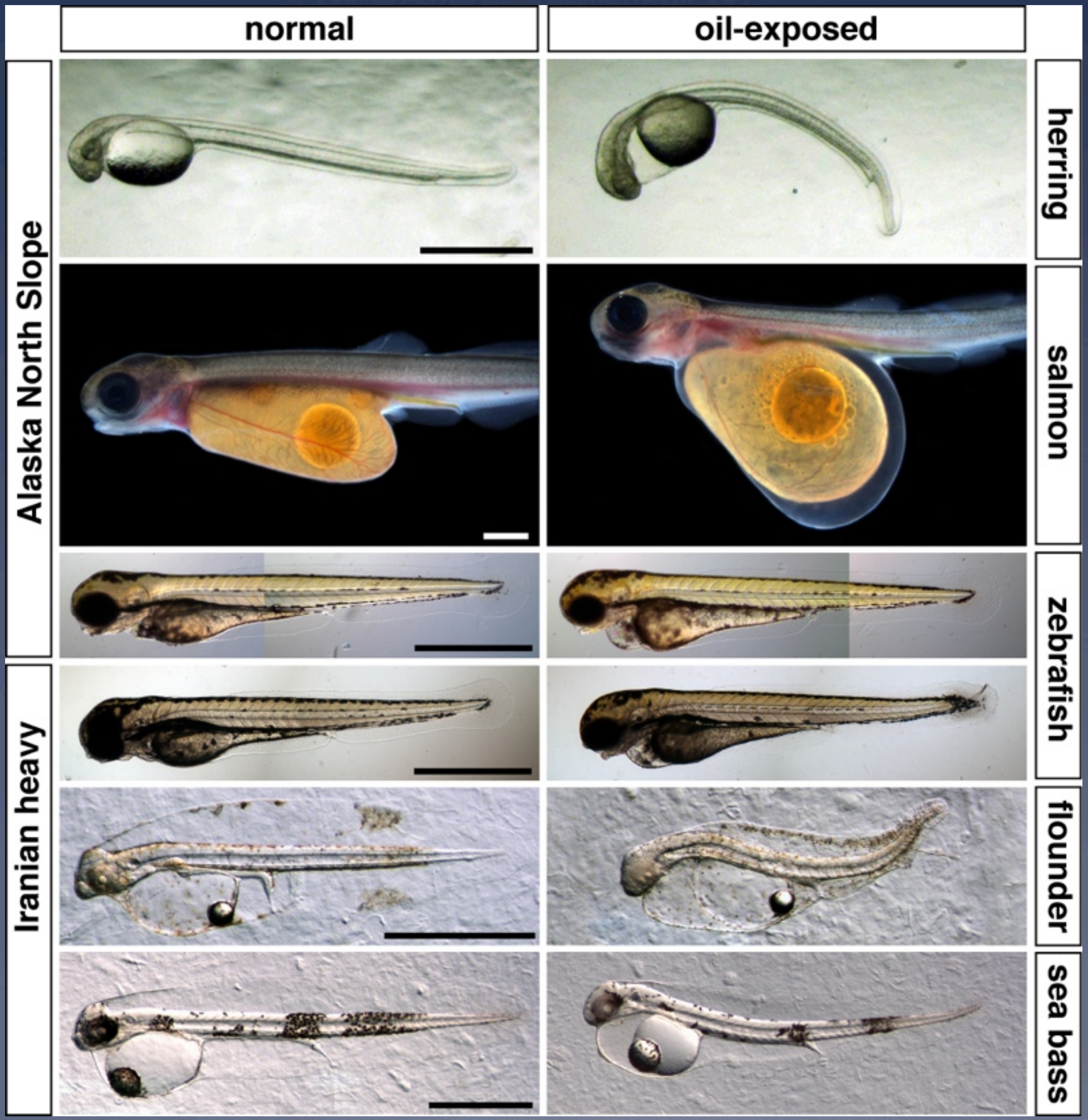


Cardiac Arrhythmia Is the Primary Response of Embryonic Pacific Herring (*Clupea pallasi*) Exposed to Crude Oil during Weathering

JOHN P. INCARDONA,*,†
MARK G. CARLS,‡ HEATHER L. DAY,†
CATHERINE A. SLOAN,†
JENNIE L. BOLTON,†
TRACY K. COLLIER,† AND
NATHANIEL L. SCHOLZ†

ES&T, 2009

Toxicological impacts of PAHs are similar across all fish species evaluated to date



A subset of PAHs target the developing heart

Available online at www.sciencedirect.com
SCIENCE DIRECT
Toxicology and Applied Pharmacology 196 (2004) 191–205
Toxicology and Applied Pharmacology
www.elsevier.com/locate/ytaap

ELSEVIER

Defects in cardiac function precede morphological abnormalities in fish embryos exposed to polycyclic aromatic hydrocarbons☆

John P. Incardona,* Tracy K. Collier, and Nathaniel L. Scholz

Ecotoxicology and Environmental Fish Health Program, Environmental Conservation Division, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA 98112, USA

Received 19 August 2003; accepted 6 November 2003

Abstract

F … clic aromatic hydrocarbons (PAHs) from petrogenic sources show a characteristic suite … ma, spinal curvature, and reduction in the size of the jaw and other craniofacial struc… hese different defects, we exposed zebrafish (*Danio rerio*) embryos to seven non-alkyl… nds that are abundant in crude oil and two compounds less abundant in oil but infor… analyzed two PAH mixtures that approximate the composition of crude oil at diffe… g PAHs dibenzothiophene and phenanthrene alone was sufficient to induce the chara… ardiac function using a cardiac troponin T antisense morpholino oligonucleotide. The … ne or phenanthrene appears to be direct effects on cardiac conduction, which have seco… phogenesis, kidney development, neural tube structure, and formation of the crani… ent mixtures was directly proportional to the amount of phenanthrene, or the diben… ne, a four-ring PAH, induced a different syndrome of anemia, peripheral vascular defe… iously described for potent aryl hydrocarbon receptor ligands. Therefore, different PAH… n at early life history stages.
© 20…

Keyw… …genesis; *silent heart* gene; CYP1A

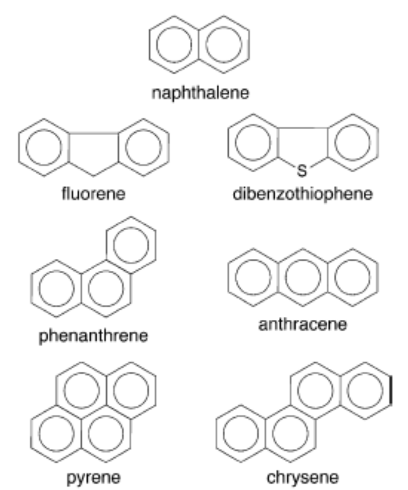
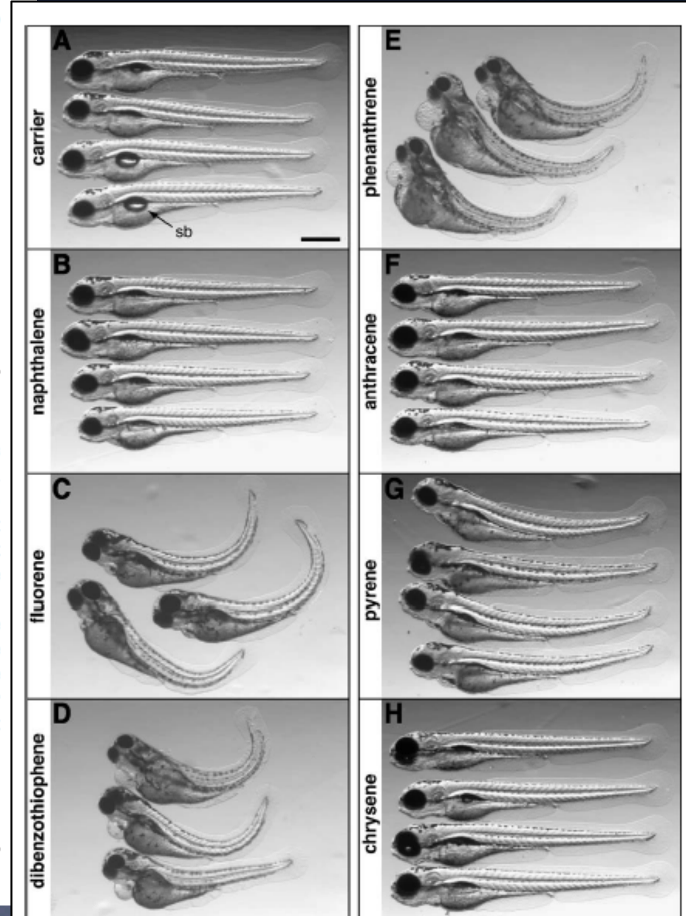
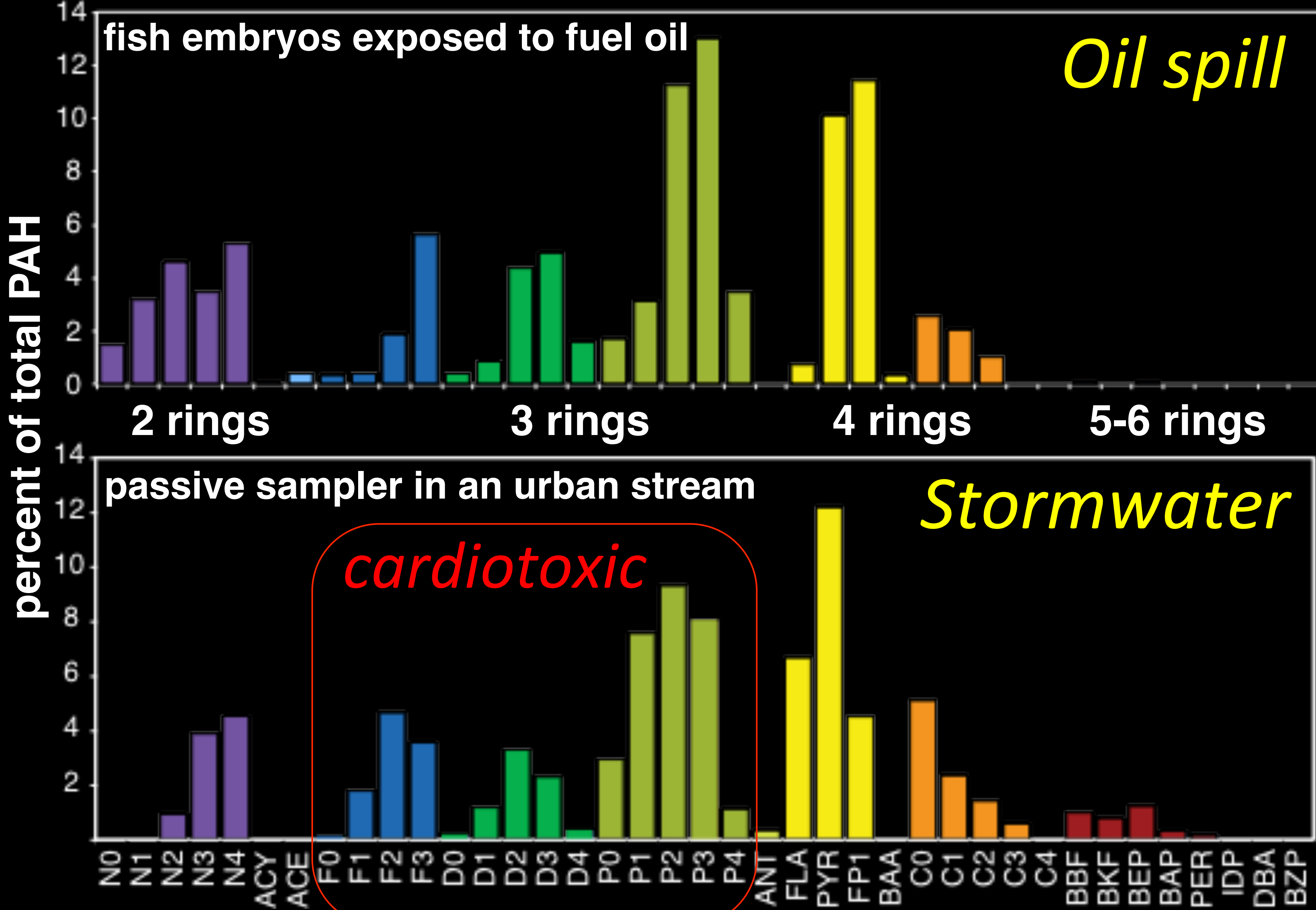


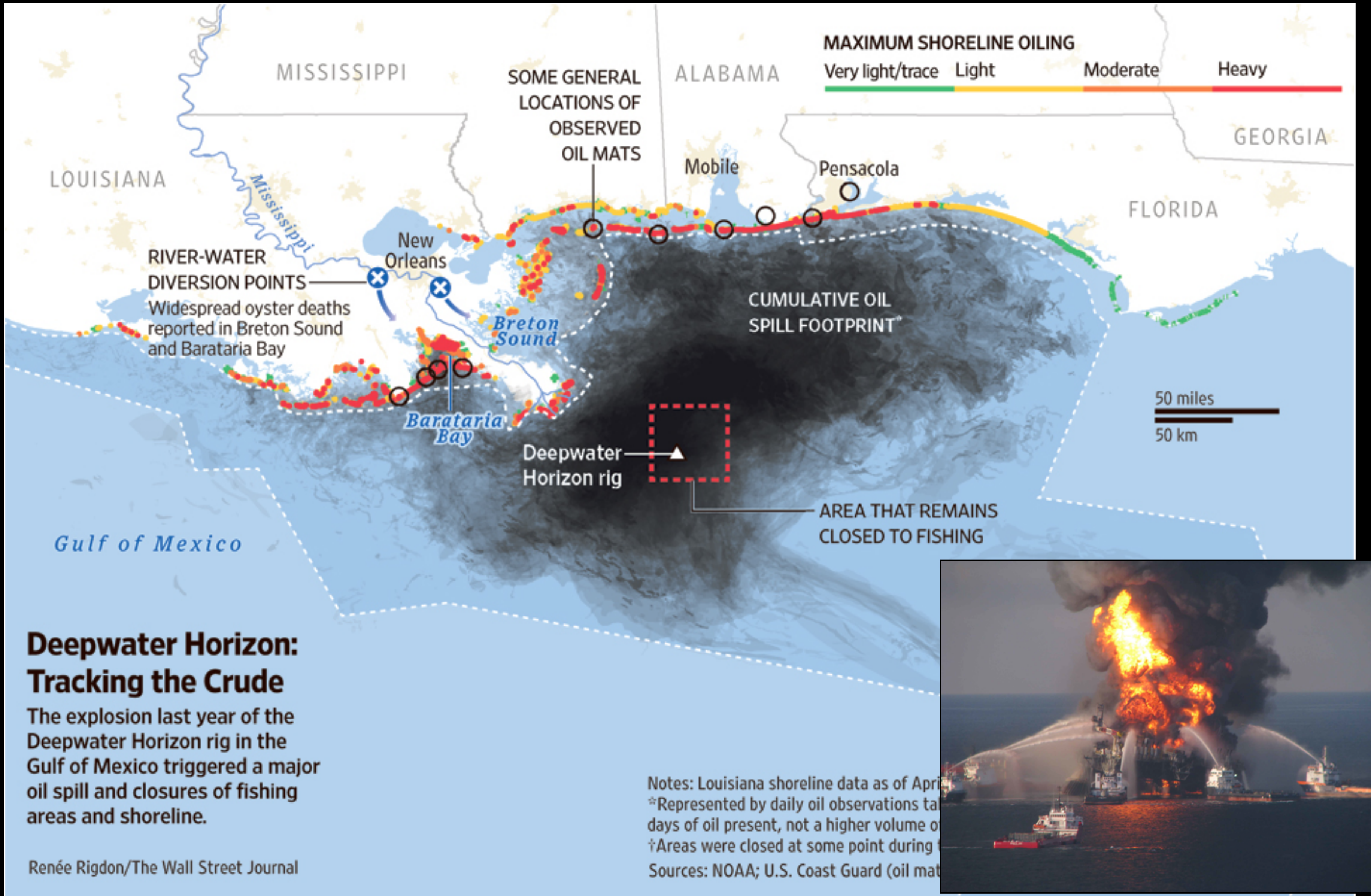
Fig. 1. Structures of the PAHs used in this study.



Polycyclic aromatic hydrocarbons (PAHs): common patterns from oil spills and stormwater



Deepwater Horizon, April 17th, 2010



Pacific bluefin tuna

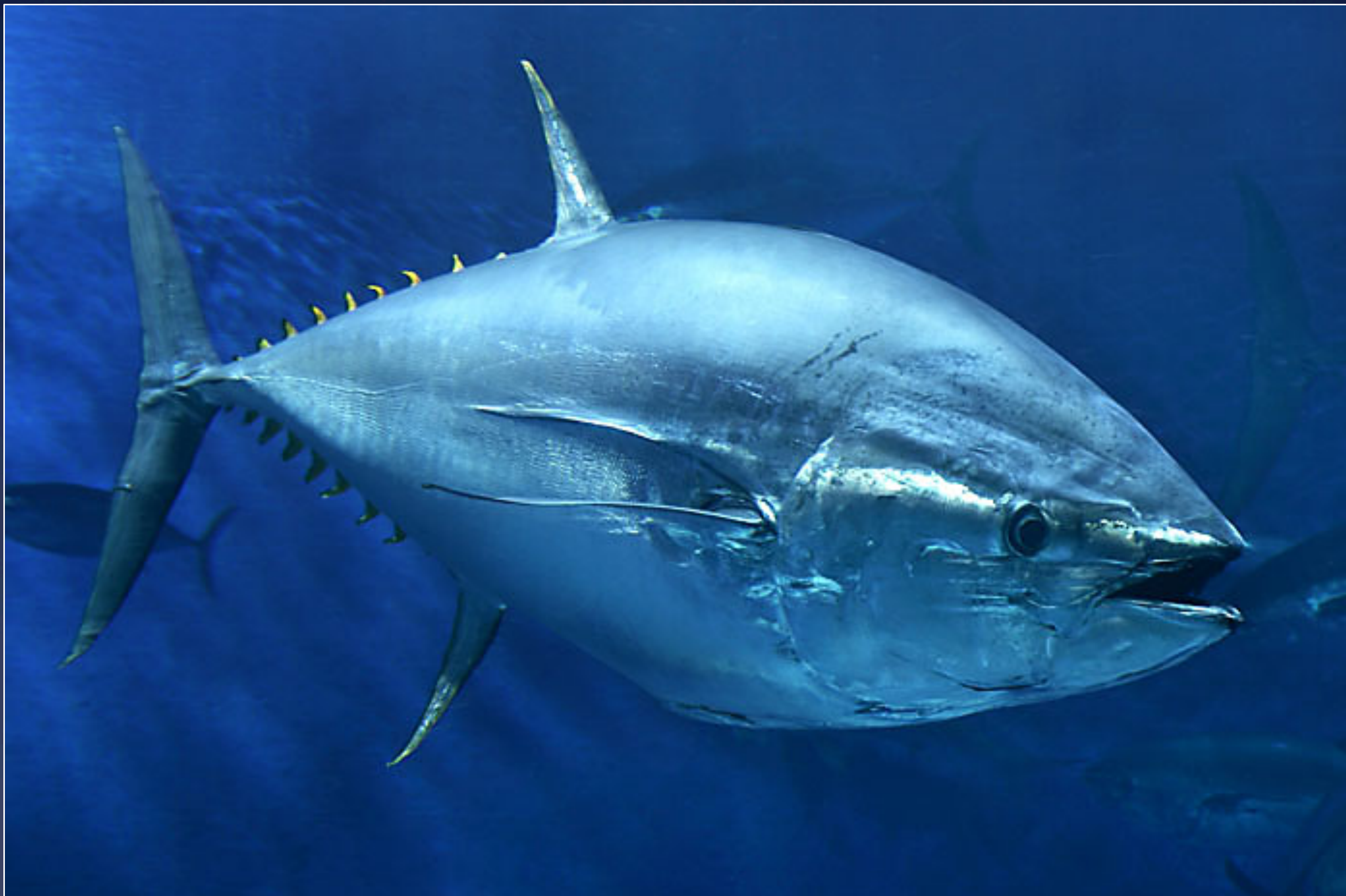
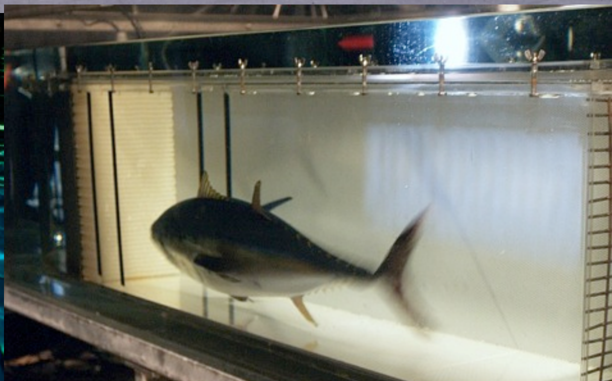
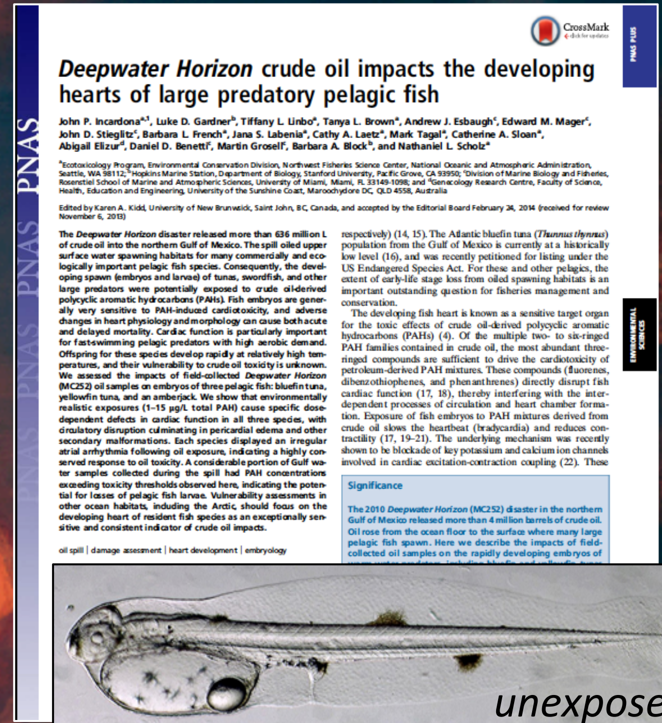


Photo by Randy Wilder, Monterey Bay Aquarium

Tuna Research & Conservation Center
Collaborative Facility (Stanford and Monterey Bay Aquarium)





PNAS PNAS PNAS PNAS PNAS

PNAS PLUS

Deepwater Horizon crude oil impacts the developing hearts of large predatory pelagic fish

John P. Incardona[a,1], Luke D. Gardner[b], Tiffany L. Linbo[a], Tanya L. Brown[a], Andrew J. Esbaugh[c], Edward M. Mager[c], John D. Stieglitz[c], Barbara L. French[a], Jana S. Labenia[a], Cathy A. Laetz[a], Mark Tagal[a], Catherine A. Sloan[a], Abigail Elizur[d], Daniel D. Benetti[c], Martin Grosell[c], Barbara A. Block[b], and Nathaniel L. Scholz[a]

[a]Ecotoxicology Program, Environmental Conservation Division, Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, Seattle, WA 98112; [b]Hopkins Marine Station, Department of Biology, Stanford University, Pacific Grove, CA 93950; [c]Division of Marine Biology and Fisheries, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149-1098; and [d]Genecology Research Centre, Faculty of Science, Health, Education and Engineering, University of the Sunshine Coast, Maroochydore DC, QLD 4558, Australia

Edited by Karen A. Kidd, University of New Brunswick, Saint John, BC, Canada, and accepted by the Editorial Board February 24, 2014 (received for review November 6, 2013)

The *Deepwater Horizon* disaster released more than 636 million L of crude oil into the northern Gulf of Mexico. The spill oiled upper surface water spawning habitats for many commercially and ecologically important pelagic fish species. Consequently, the developing spawn (embryos and larvae) of tunas, swordfish, and other large predators were potentially exposed to crude oil-derived polycyclic aromatic hydrocarbons (PAHs). Fish embryos are generally very sensitive to PAH-induced cardiotoxicity, and adverse changes in heart physiology and morphology can cause both acute and delayed mortality. Cardiac function is particularly important for fast-swimming pelagic predators with high aerobic demand. Offspring for these species develop rapidly at relatively high temperatures, and their vulnerability to crude oil toxicity is unknown. We assessed the impacts of field-collected *Deepwater Horizon* (MC252) oil samples on embryos of three pelagic fish: bluefin tuna, yellowfin tuna, and an amberjack. We show that environmentally realistic exposures (1–15 µg/L total PAH) cause specific dose-dependent defects in cardiac function in all three species, with circulatory disruption culminating in pericardial edema and other secondary malformations. Each species displayed an irregular atrial arrhythmia following oil exposure, indicating a highly conserved response to oil toxicity. A considerable portion of Gulf water samples collected during the spill had PAH concentrations exceeding toxicity thresholds observed here, indicating the potential for losses of pelagic fish larvae. Vulnerability assessments in other ocean habitats, including the Arctic, should focus on the developing heart of resident fish species as an exceptionally sensitive and consistent indicator of crude oil impacts.

oil spill | damage assessment | heart development | embryology

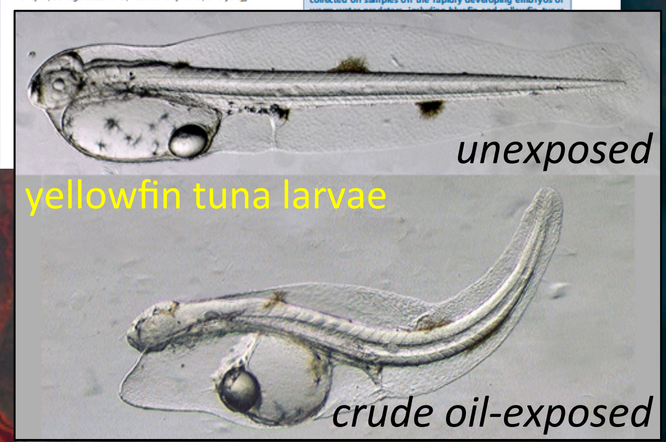
respectively) (14, 15). The Atlantic bluefin tuna (*Thunnus thynnus*) population from the Gulf of Mexico is currently at a historically low level (16), and was recently petitioned for listing under the US Endangered Species Act. For these and other pelagics, the extent of early-life stage loss from oiled spawning habitats is an important outstanding question for fisheries management and conservation.

The developing fish heart is known as a sensitive target organ for the toxic effects of crude oil-derived polycyclic aromatic hydrocarbons (PAHs) (4). Of the multiple two- to six-ringed PAH families contained in crude oil, the most abundant three-ringed compounds are sufficient to drive the cardiotoxicity of petroleum-derived PAH mixtures. These compounds (fluorenes, dibenzothiophenes, and phenanthrenes) directly disrupt fish cardiac function (17, 18), thereby interfering with the interdependent processes of circulation and heart chamber formation. Exposure of fish embryos to PAH mixtures derived from crude oil slows the heartbeat (bradycardia) and reduces contractility (17, 19–21). The underlying mechanism was recently shown to be blockade of key potassium and calcium ion channels involved in cardiac excitation-contraction coupling (22). These

ENVIRONMENTAL SCIENCES

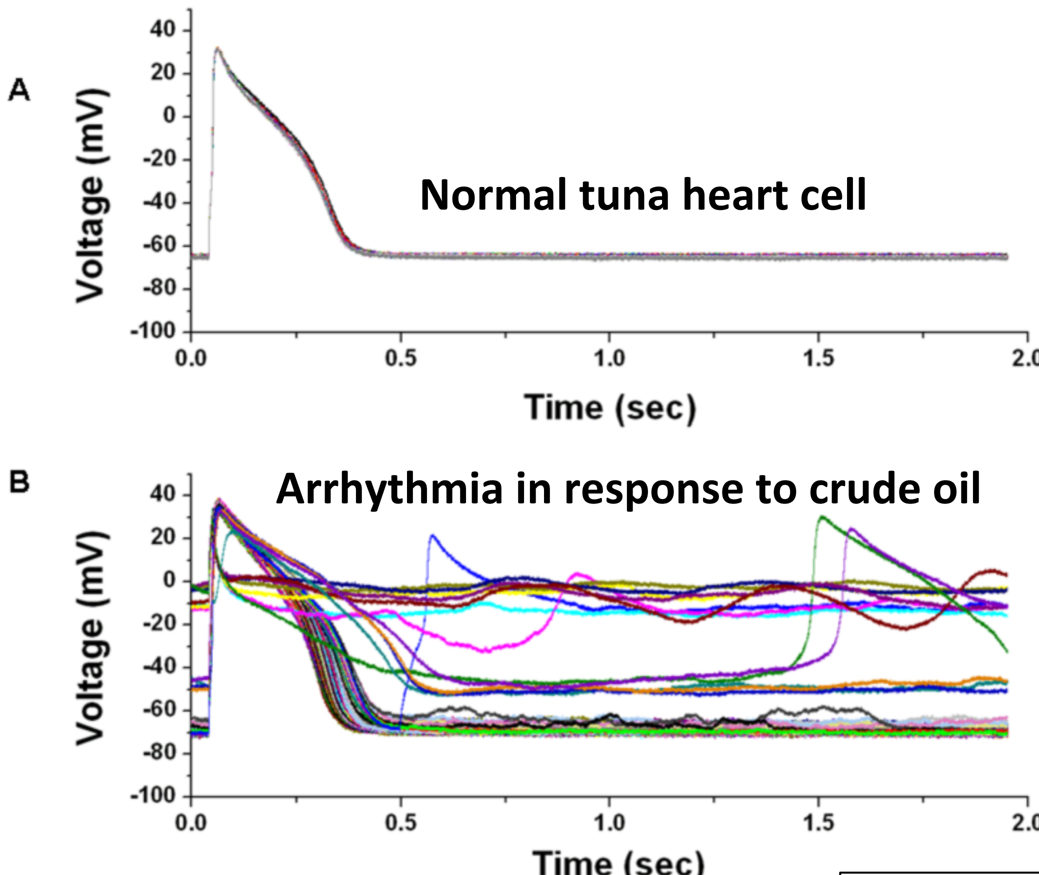
Significance

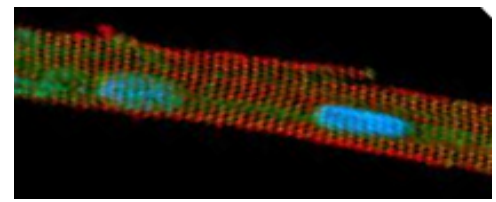
The 2010 *Deepwater Horizon* (MC252) disaster in the northern Gulf of Mexico released more than 4 million barrels of crude oil. Oil rose from the ocean floor to the surface where many large pelagic fish spawn. Here we describe the impacts of field-collected oil samples on the rapidly developing embryos of



Deepwater Horizon surface oil, May 6, 2010 (photo by Daniel Beltrá)

Crude oil exposure disrupts the repolarization of fish heart muscle cells, explaining cardiac irregularities observed in developing embryos





Individual cardiomyocyte

Science, 2014

Crude Oil Impairs Cardiac Excitation-Contraction Coupling in Fish

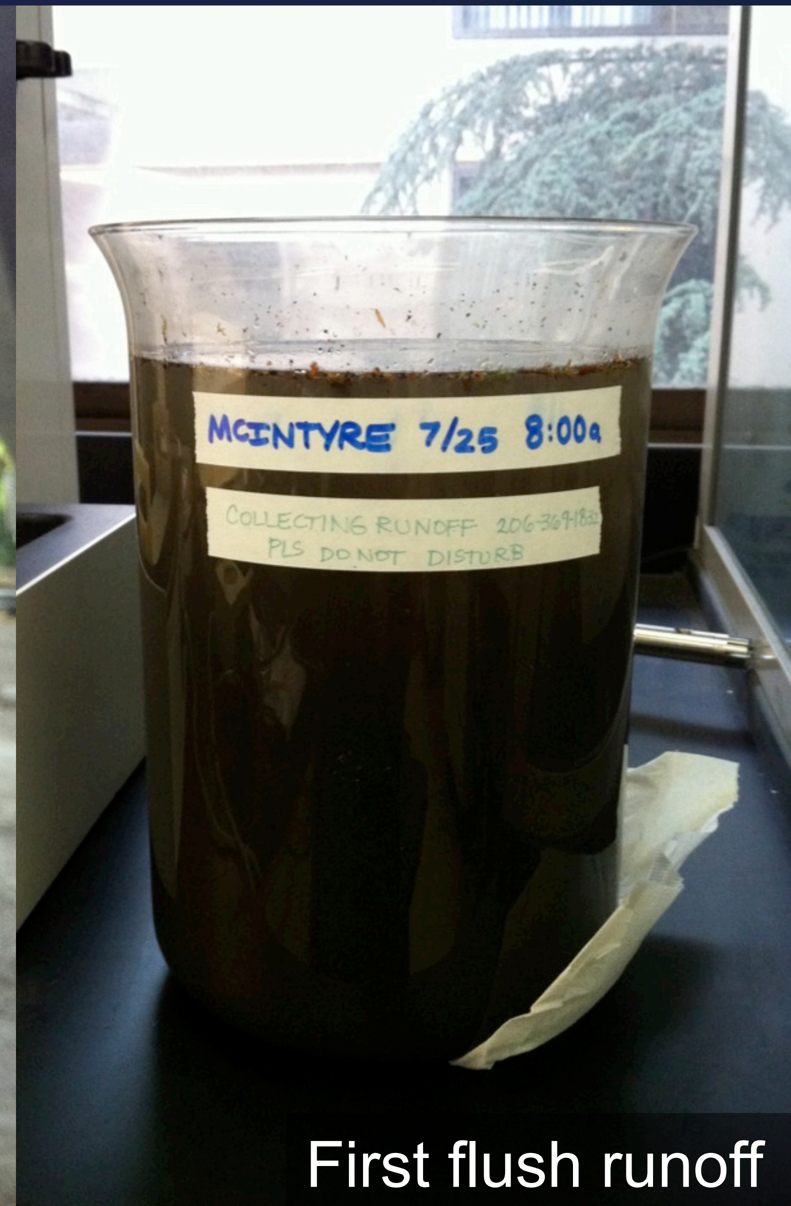
Fabien Brette,[1] Ben Machado,[1] Caroline Cros,[1] John P. Incardona,[2]
Nathaniel L. Scholz,[2] Barbara A. Block[1*]

Crude oil is known to disrupt cardiac function in fish embryos. Large oil spills, such as the Deepwater Horizon (DWH) disaster that occurred in 2010 in the Gulf of Mexico, could severely

Collect runoff, characterize baseline toxicity

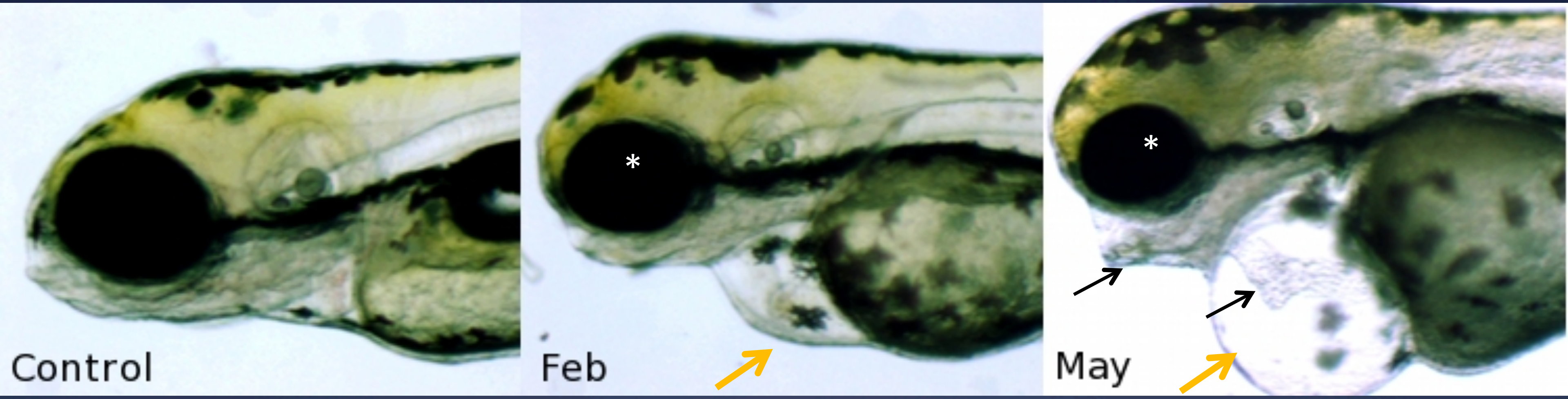
Project lead: Jenifer McIntyre, postdoc, Washington State University

Downspout from highway



First flush runoff

Sublethal stormwater toxicity to zebrafish



- Inability to hatch (or hatching delay)
- Developmental delays
- Small eye phenotype (*)
- Pericardial edema (yellow arrow)
- Deformed jaws and hearts (black arrows)

Baseline molecular indicators for urban runoff (zebrafish embryos/larvae)

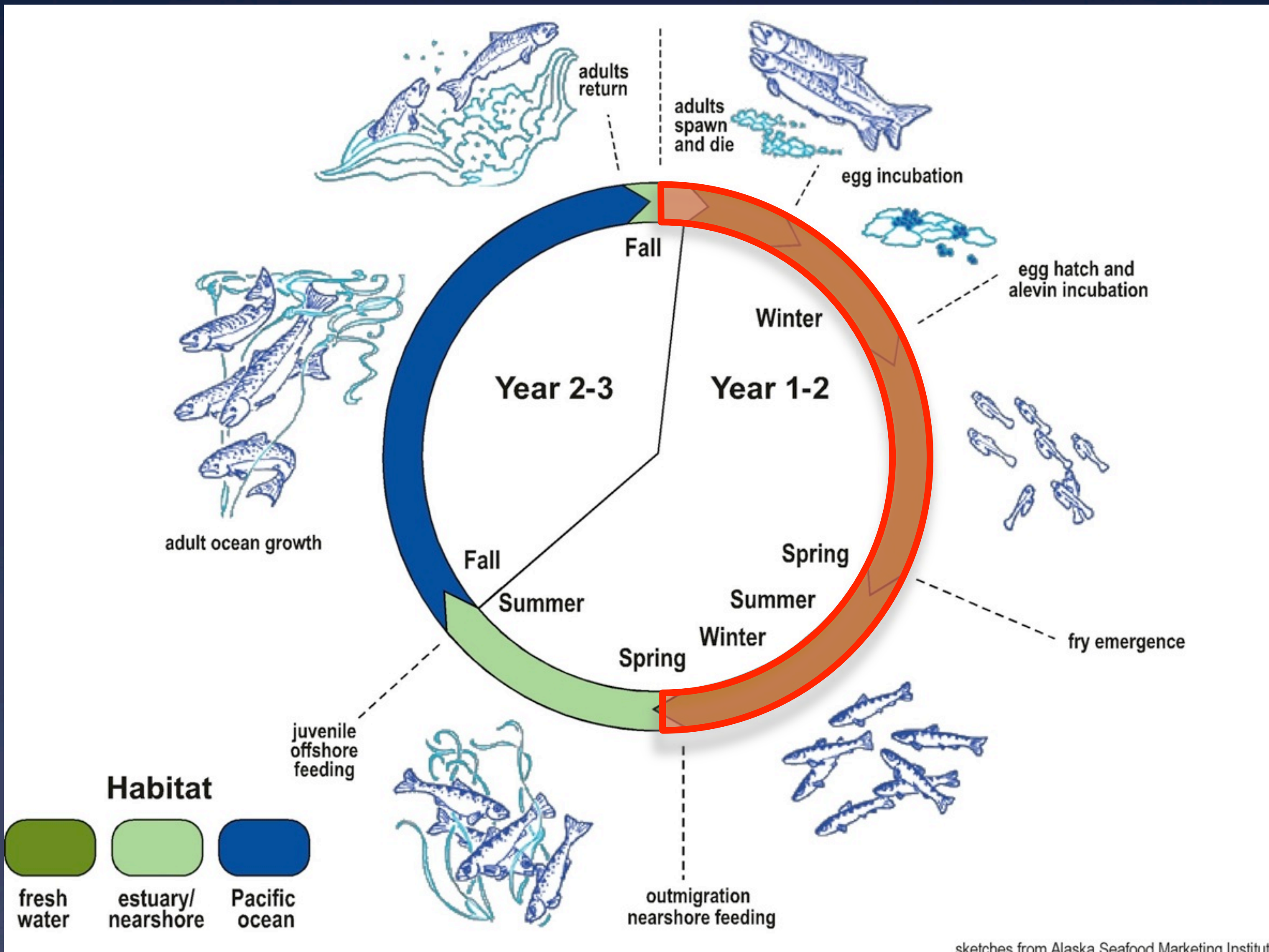
Gene	Name	Description	Fold-change	SE	p
CYP1a	Cytochrome P450; AhR pathway	Detoxification (e.g. PAHs)	+32.7	5.8	<0.001
ANP	Atrial natriuretic peptide	Heart: injury	+4.2	1.0	<0.001
BNP	B-type natriuretic peptide	Heart: injury	+2.6	0.7	0.006
cmlc1	Cardiac myosin light chain	Heart: structural	+2.5	0.7	0.007
rpe	Retinal pigment	Time course	+2.1	0.3	0.054
cmlc2	Cardiac myosin light chain 2	Heart: structural	1.3	0.1	0.318
MITFa	Microphthalmia-associated TF	Eye development	1.3	0.1	0.365

QPCR confirms PAH exposure and cardiac stress

A focus on freshwater coho salmon life stages

Higher Risk of Stormwater Impacts

Coho salmon life cycle



Symptomatic adult coho spawner

Pipers Creek, Seattle, Fall 2000

Coho spawner mortality is widespread and recurrent (60-90% of total fall runs)

Longfellow Creek 2003

Des Moines Creek 2004

Longfellow Creek 2005

Longfellow Creek 2012

A common suite of symptoms across years

Longfellow Creek 2002

Longfellow Creek 2005

Longfellow Creek 2012

Coho prespawn mortality study #1:
forensic investigation

Major findings:

- Adult spawners are consistently dying each fall
- The phenomenon is widespread in urban watersheds
- Mortality rates are typically high (60-90% of total run)
- Toxic urban runoff appears to be causal

OPEN ACCESS Freely available online *(2011, 6(8):e28013)* PLoS one

Recurrent Die-Offs of Adult Coho Salmon Returning to Spawn in Puget Sound Lowland Urban Streams

Nathaniel L. Scholz[1]*, Mark S. Myers[1], Sarah G. McCarthy[2], Jana S. Labenia[1], Jenifer K. McIntyre[1], Gina M. Ylitalo[1], Linda D. Rhodes[1], Cathy A. Laetz[1], Carla M. Stehr[1], Barbara L. French[1], Bill McMillan[3], Dean Wilson[2], Laura Reed[4], Katherine D. Lynch[4], Steve Damm[5], Jay W. Davis[5], Tracy K. Collier[1]

1 Northwest Fisheries Science Center, NOAA Fisheries, Seattle, Washington, United States of America, **2** Department of Natural Resources and Parks, King County, Seattle, Washington, United States of America, **3** Wild Fish Conservancy, Duvall, Washington, United States of America, **4** Seattle Public Utilities, City of Seattle, Seattle, Washington, United States of America, **5** Washington Fish and Wildlife Office, U.S. Fish and Wildlife Service, Lacey, Washington, United States of America

Coho prespawn mortality study #2: *population-scale implications*

Major findings:

- Models predict rapid local extinctions at spawner mortality rates observed in Seattle-area streams
- Mortality may drag down coho abundance in non-urban watersheds as a consequence of straying

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Integrated Environmental Assessment and Management — Volume 7, Number 4—pp. 648–656

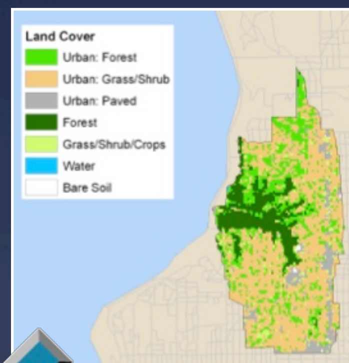
Estimating the Future Decline of Wild Coho Salmon Populations Resulting from Early Spawner Die-Offs in Urbanizing Watersheds of the Pacific Northwest, USA

Julann A Spromberg† and Nathaniel L Scholz†*
†National Oceanic and Atmospheric Administration (NOAA) Fisheries, Northwest Fisheries Science Center, 2725 Montlake Boulevard East, Seattle, Washington 98112, USA

(2011, 7:648)

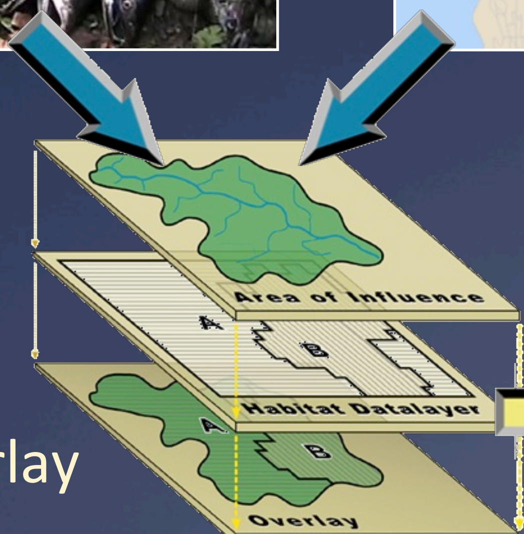
Coho prespawn mortality study #3:
predictive modeling based on land use
(across multiple surveyed watersheds)

Spawner Mortality



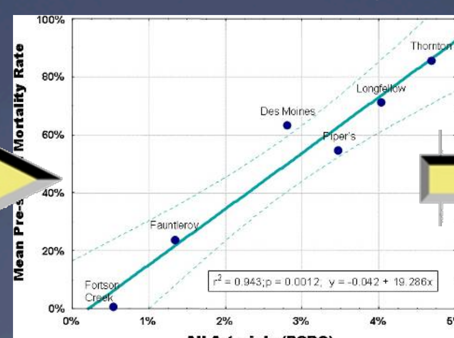
Urban Land Cover

(GIS datalayers)

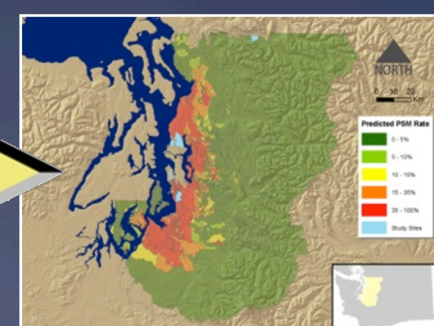


Overlay

Statistical Analyses



Predictive Mapping



Model output summary

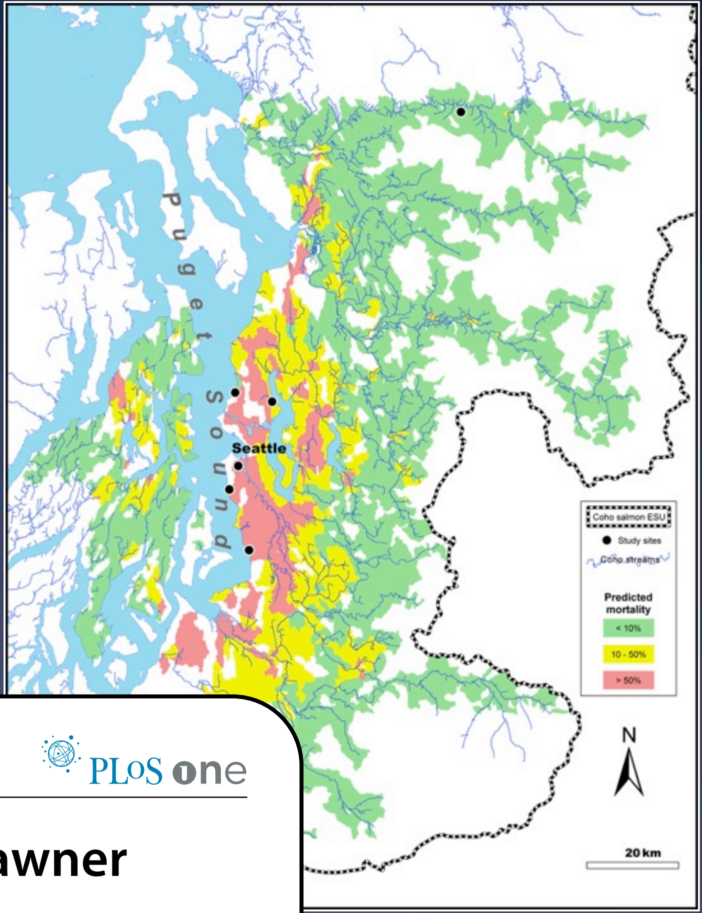
Predictive value for coho mortality

Datalayer	Variable	AICc weight	Model averaged coefficient	Unconditional SE
Impervious	Impervious surfaces	0.7158	16.8425	14.5376
Roadways	Local roads	0.5647	-15.6199	68.3331
Property type	Commercial	0.5107	7.9375	8.2616
Land cover	Dense urban	0.3865	-7.7776	16.1614
Property type	Apartments & condominiums	0.2409	-9.5330	31.1917
Roadways	Heavily used roads	0.2019	5.3445	31.5073
Land cover	Forest	0.1163	-0.7793	6.2249
Land cover	Light to medium urban	0.1149	0.3250	2.9751
Land cover	Grass, shrubs & crops	0.0993	0.1664	5.4517
Property type	Residential	0.0975	0.0738	16.8920
Property type	Industrial	0.0547	-0.2475	4.7008
Property type	Parks & open space	0.0000	0.0000	0.0000

Coho prespawn mortality study #2: *predictive modeling based on land use*

Major findings:

- Spawner mortality rates correlate closely with land cover (% impervious, roads, etc.)
- Coho are likely to be impacted across large geographic areas



OPEN ACCESS Freely available online *(2011, 6(8):e23424)* PLoS one

Landscape Ecotoxicology of Coho Salmon Spawner Mortality in Urban Streams

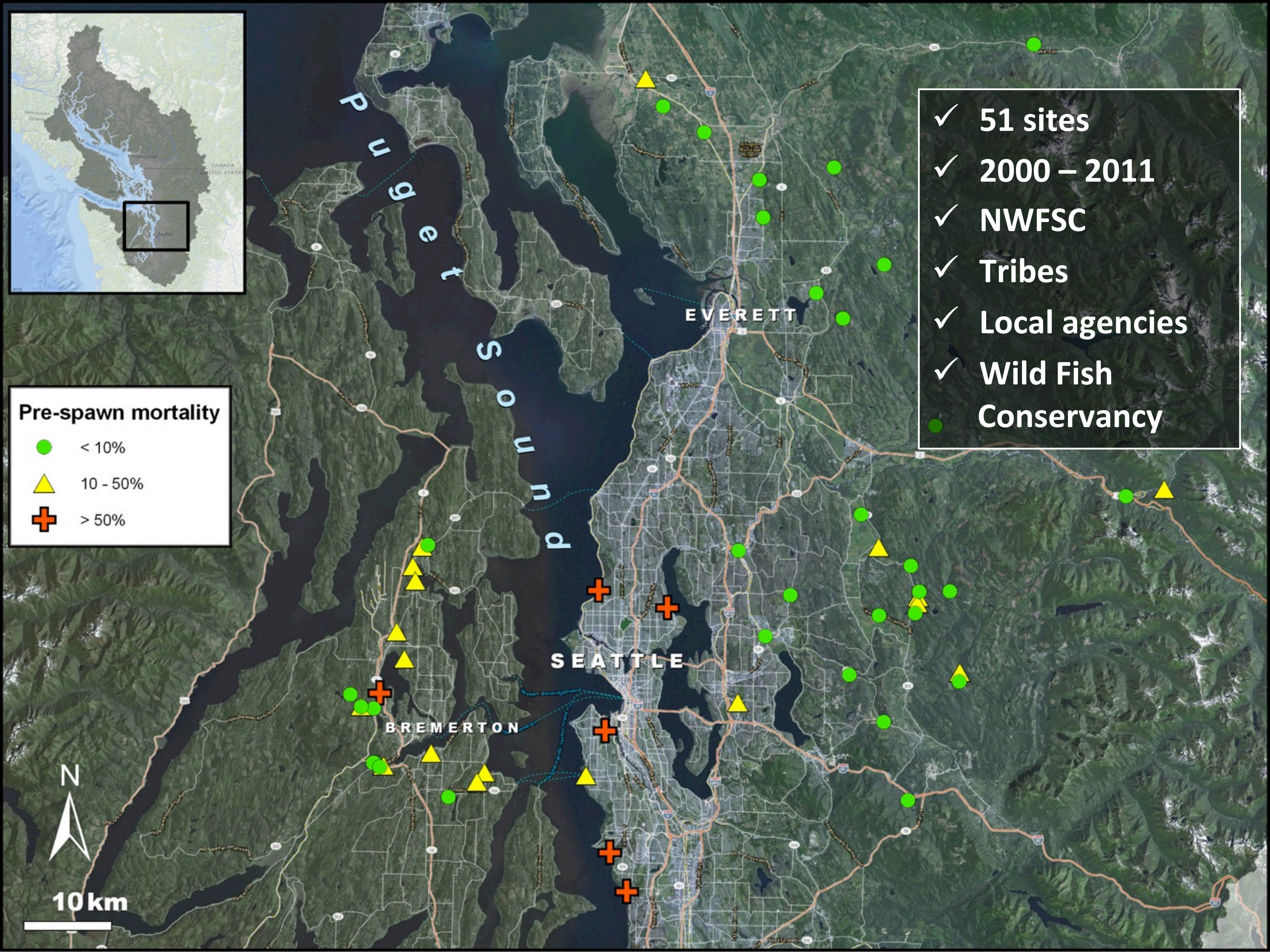
Blake E. Feist[1]*, Eric R. Buhle[1], Paul Arnold[2], Jay W. Davis[2], Nathaniel L. Scholz[1]

1 Northwest Fisheries Science Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, Washington, United States of America, **2** Washington Fish and Wildlife Office, United States Fish and Wildlife Service, Lacey, Washington, United States of America

Refined Estimates of Premature Coho Salmon Spawner Mortality in Puget Sound Urban Basins in Relation to Landscape Condition and Precipitation Patterns

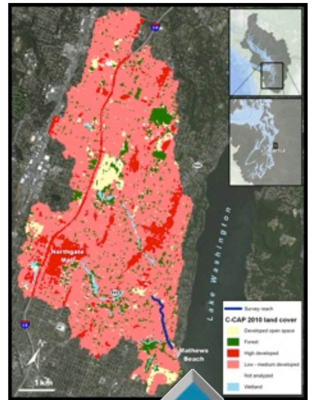
Blake Feist
Eric Buhle
David Baldwin
Julann Spromberg
Nat Scholz

Steve Damm
Jay Davis



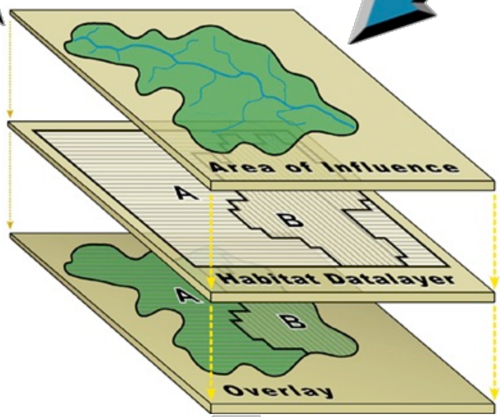
Puget Sound
EVERETT
SEATTLE
BREMERTON
N
10 km
Pre-spawn mortality
< 10%
10 - 50%
> 50%
✓ 51 sites
✓ 2000 – 2011
✓ NWFSC
✓ Tribes
✓ Local agencies
✓ Wild Fish Conservancy

Model Overview

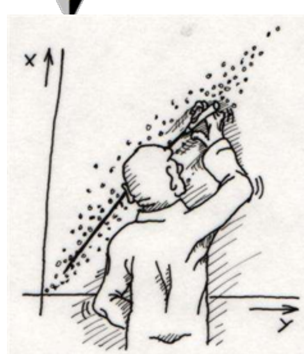


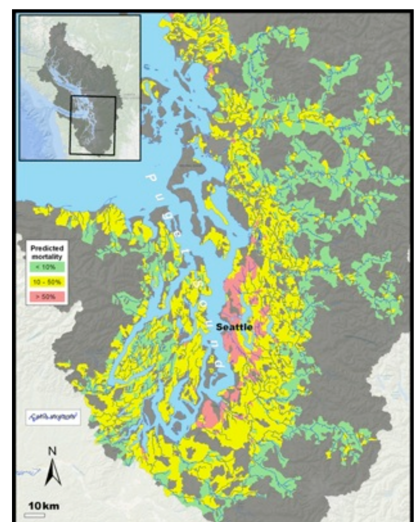
Landscape Data

Spatial Analyses



Statistical Analyses

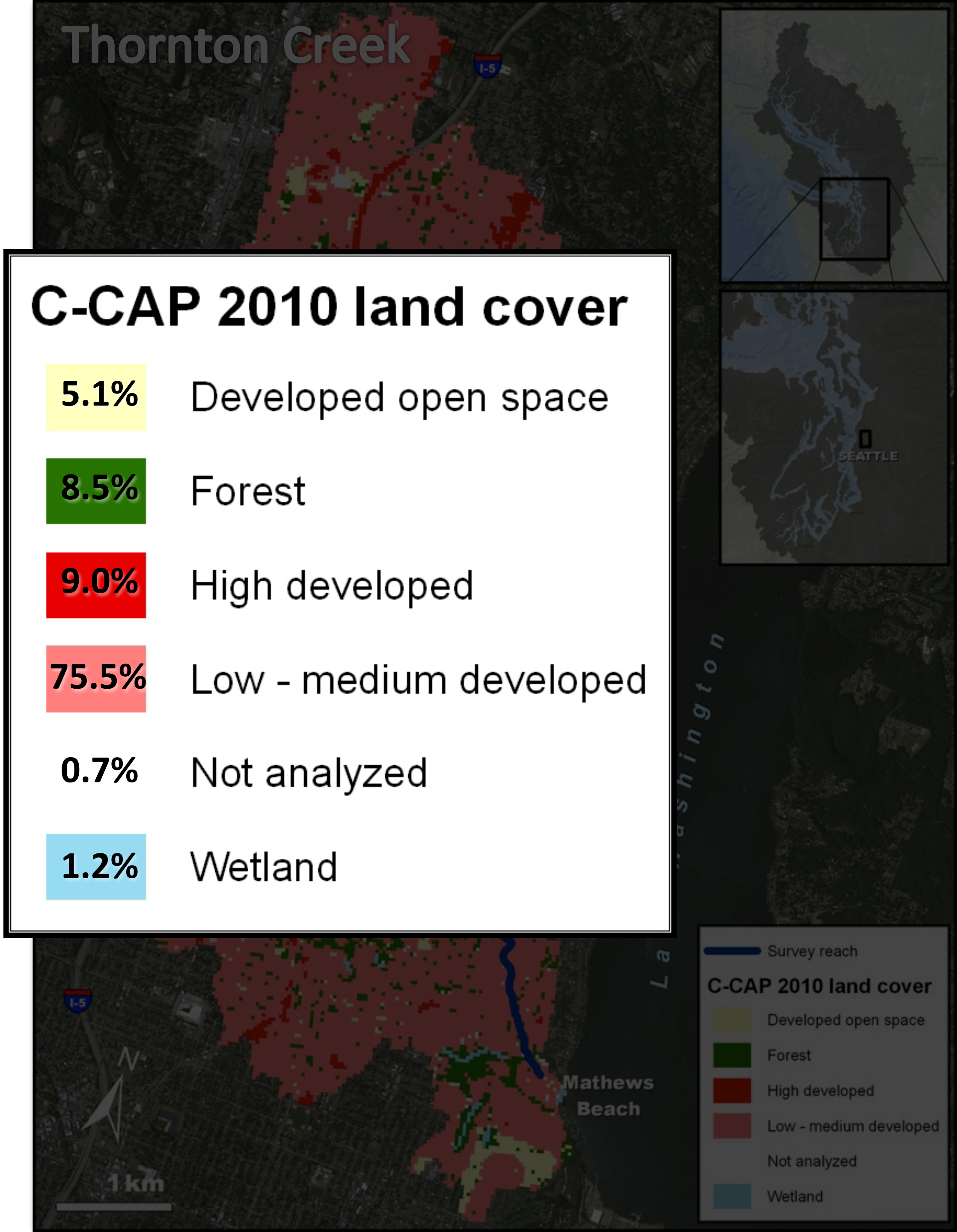


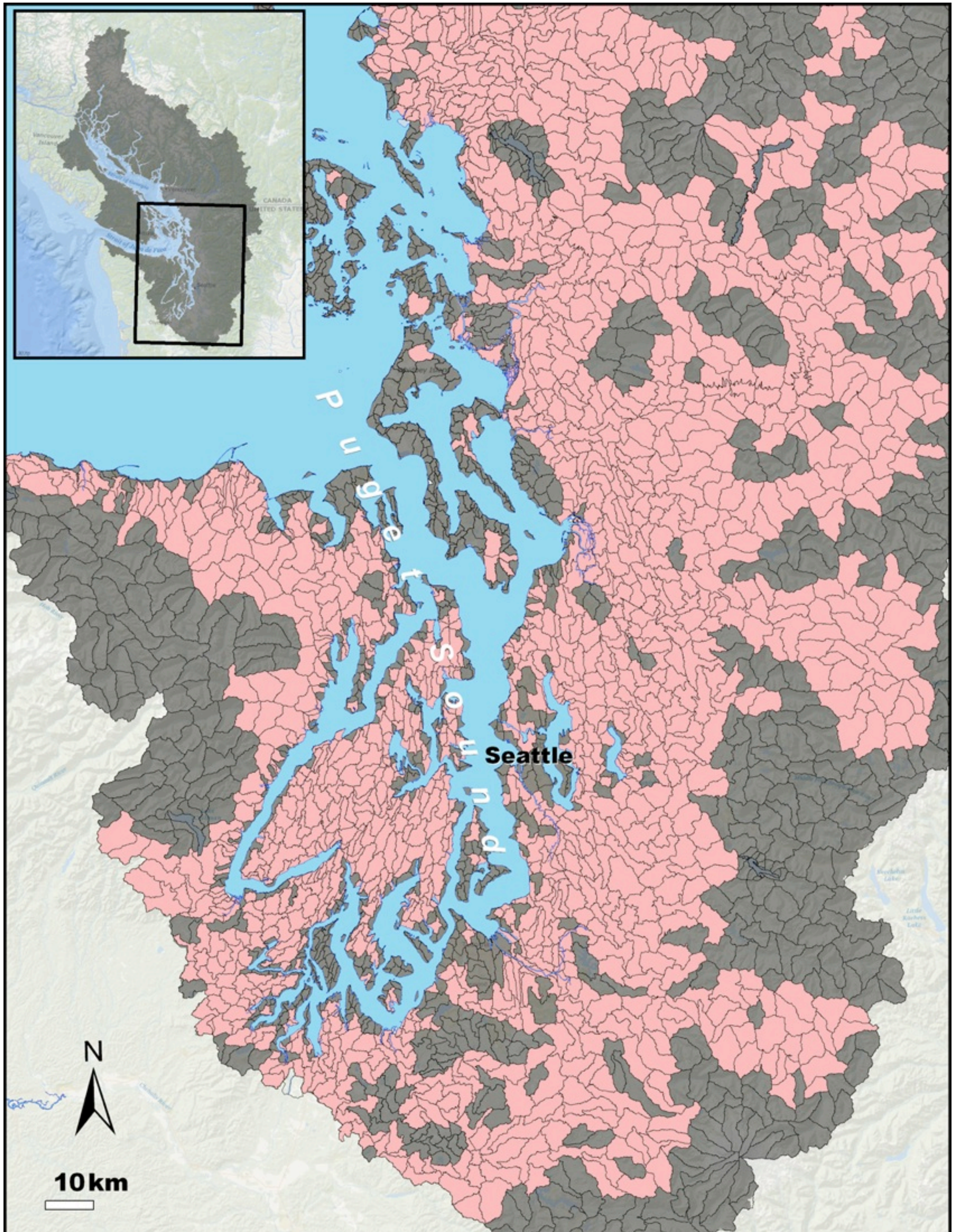


- Correlated Variables
- Predictive Model of Spawner Mortality

Spatial Overlay

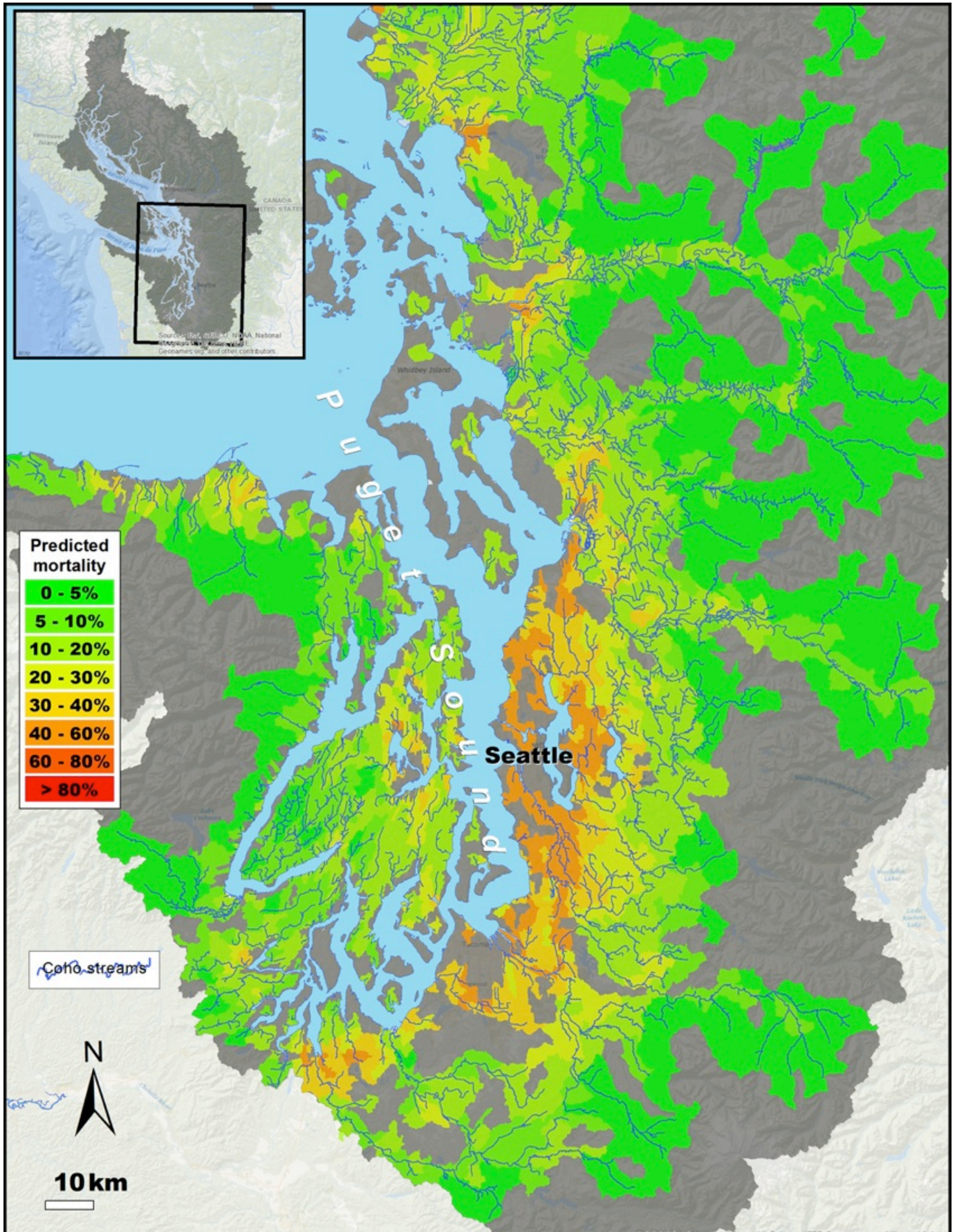
- Survey reach
- Delineate basin
- Intersect with each landscape datalayer
- Calculate proportion of landscape types





PSM Risk Predictions

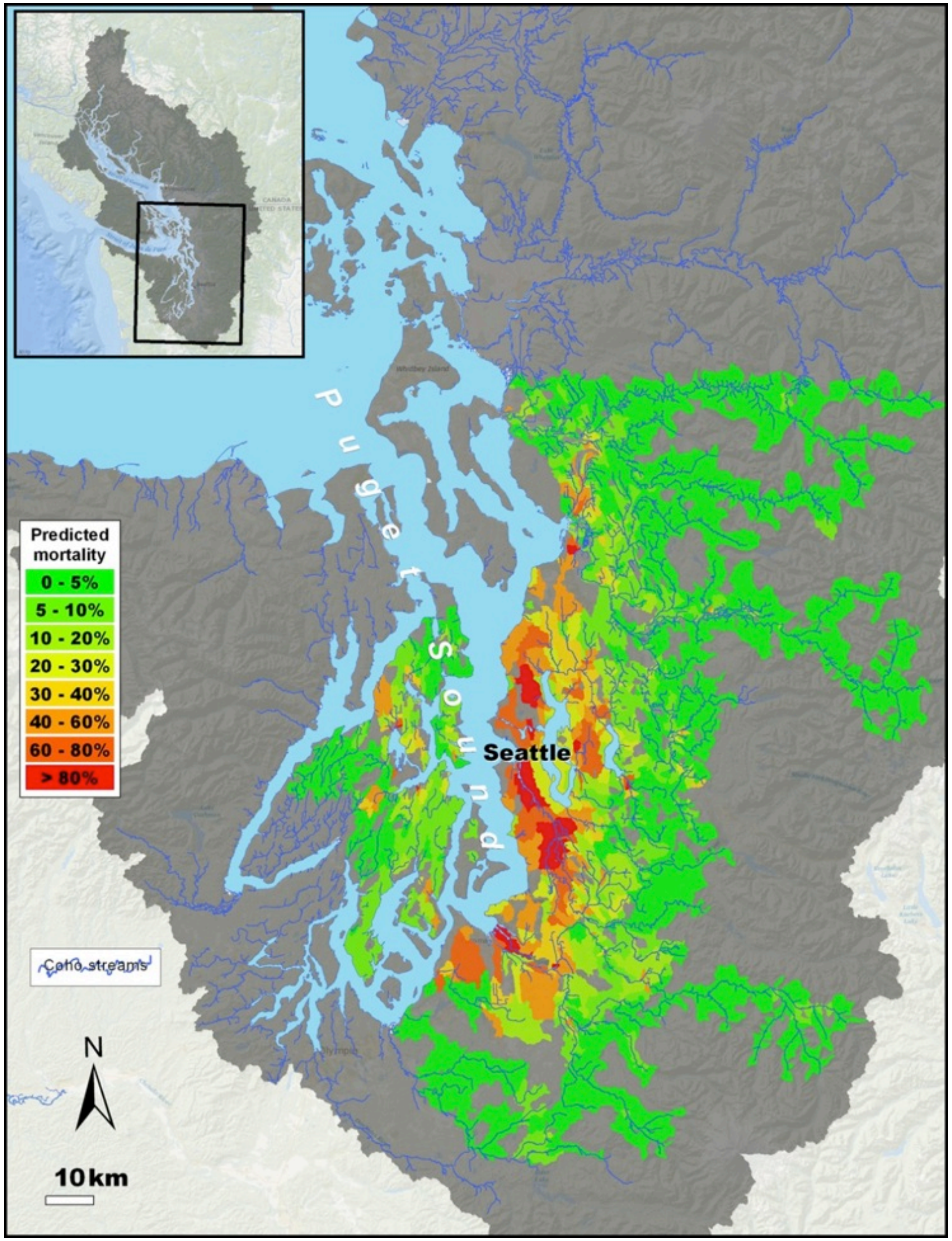
- WADOE Puget Sound Watershed Characterization Project basins
- Limit to coho basins
- Overlay basins with landscape datalayers
- Calculate proportion of landscape types
- Fit the model to landscape data from **all** sites (PSM sampling plus unsampled)



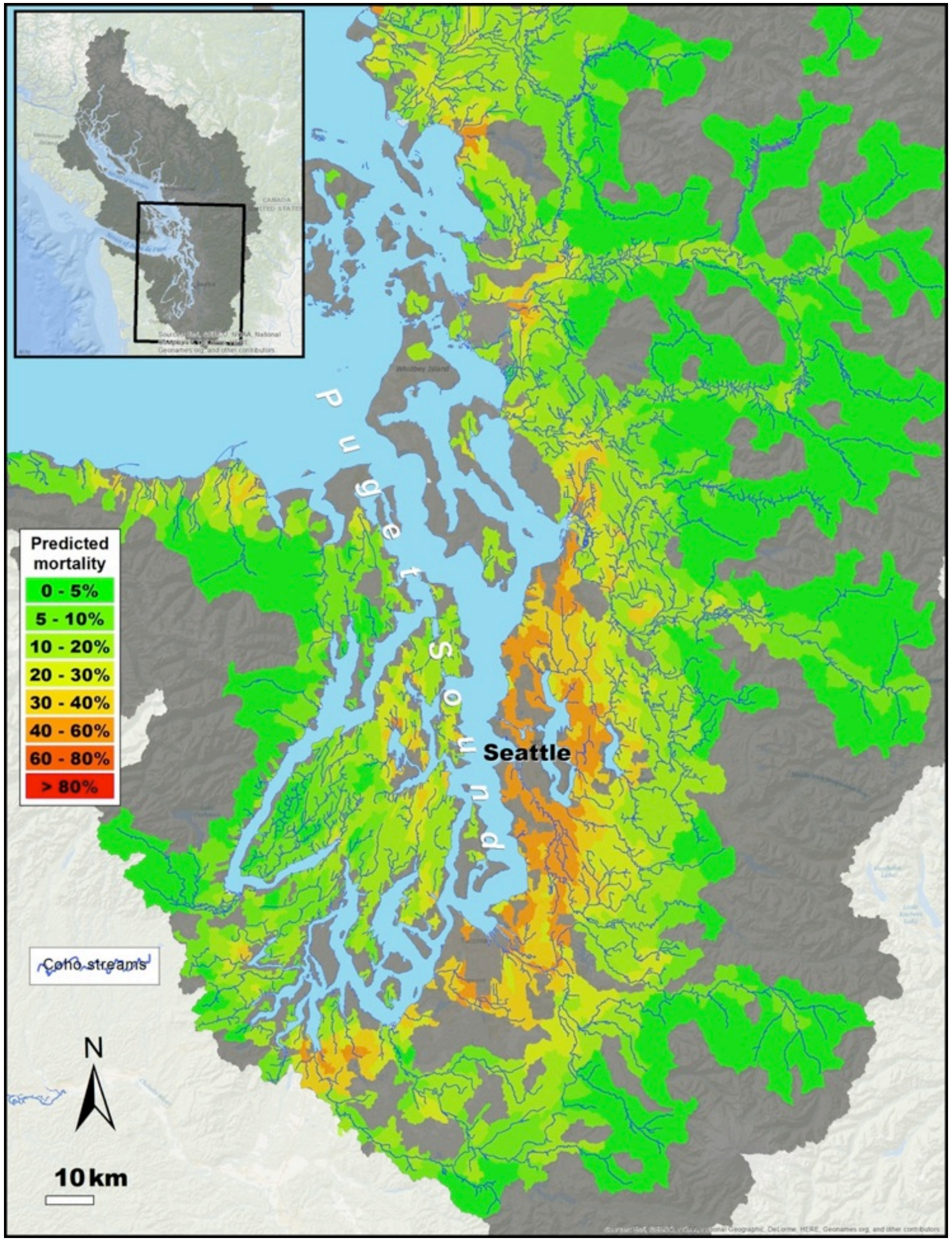
PSM Risk Predictions

- WADOE Puget Sound Watershed Characterization Project basins
- Limit to coho basins
- Overlay basins with landscape datalayers
- Calculate proportion of landscape types
- Fit the model to landscape data from **all** sites (PSM sampling plus unsampled)
- Predict P(PSM) for unsampled sites
- Summarize mean and uncertainty using posterior distribution

Version One



Version Two



Fall 2011-14: Key Question

Is exposure to urban runoff sufficient to cause coho pre-spawn mortality?

Grover's Creek facility, Suquamish Tribe

Metal and PAH exposures (2011)

Spawners exposed to environmentally-relevant mixtures…

PAHs:

Water accommodated fraction (crude oil)

e.g., Phenanthrene (0.240 µg/L)

Pyrene (0.365 µg/L)

Fluoranthene (0.365 µg/L)

Metals:

Cadmium (0.3 µg/L)

Copper (7.0 µg/L)

Lead (1.0 µg/L)

Nickel (2.0 µg/L)

Zinc (9.0 µg/L)

… showed no significant increase in mortality!

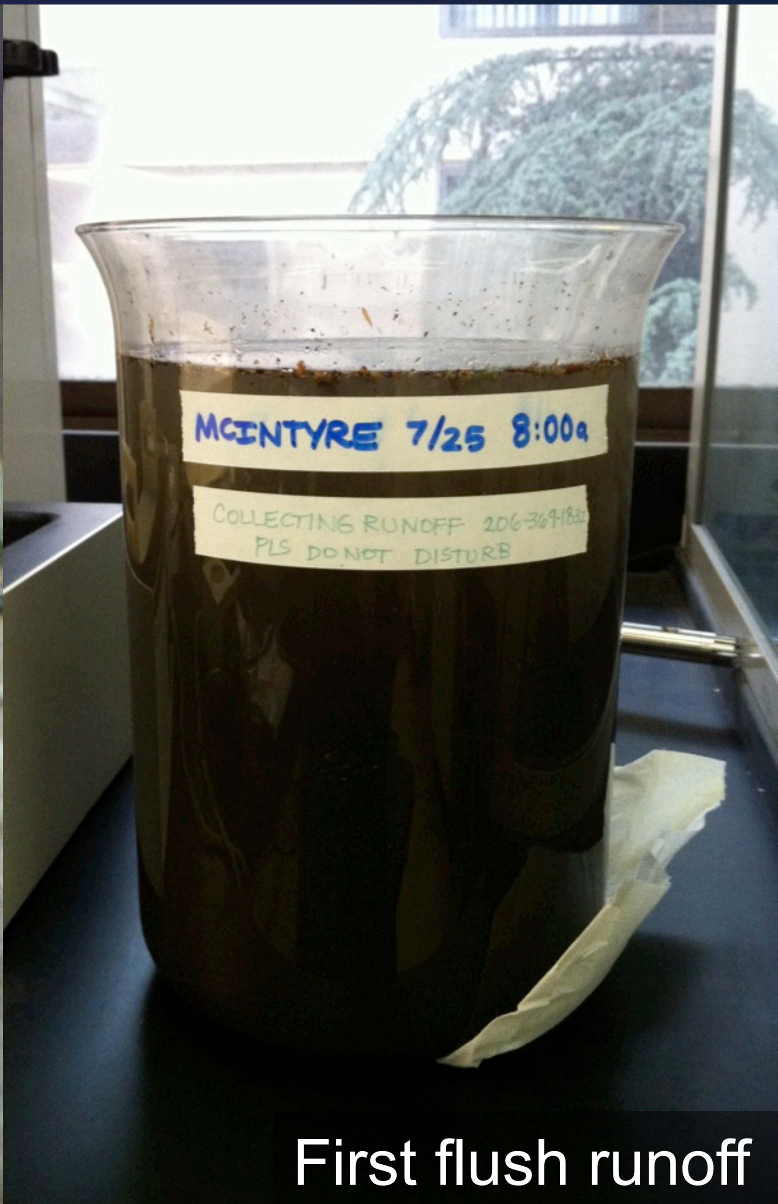
Runoff from a high-density urban arterial (highway, downtown Seattle)

SR 520, Seattle

Collect runoff, characterize baseline toxicity

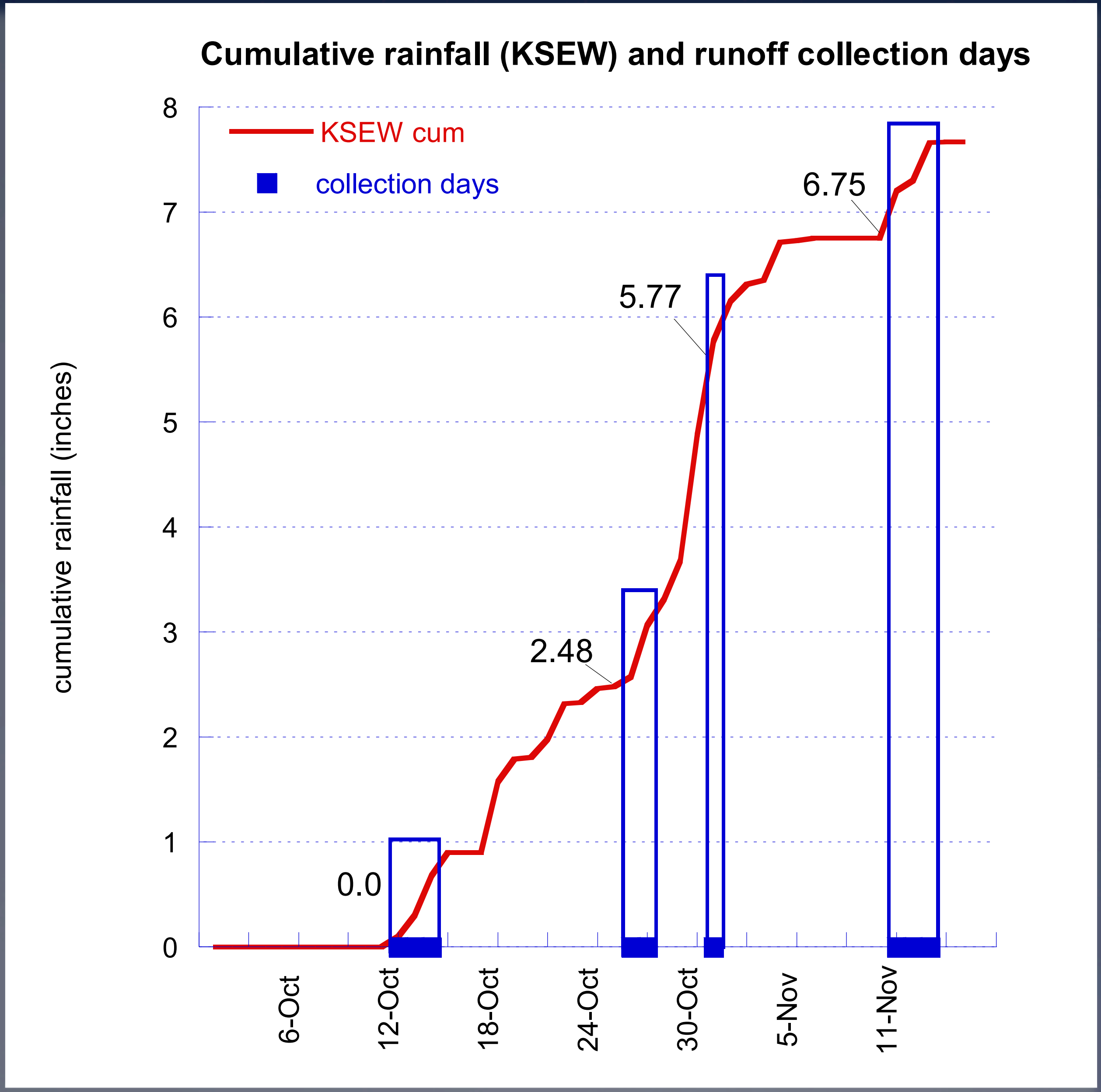
Project lead: Jenifer McIntyre, postdoc, Washington State University

Downspout from highway



First flush runoff

Stormwater runoff collections (fall, 2012)



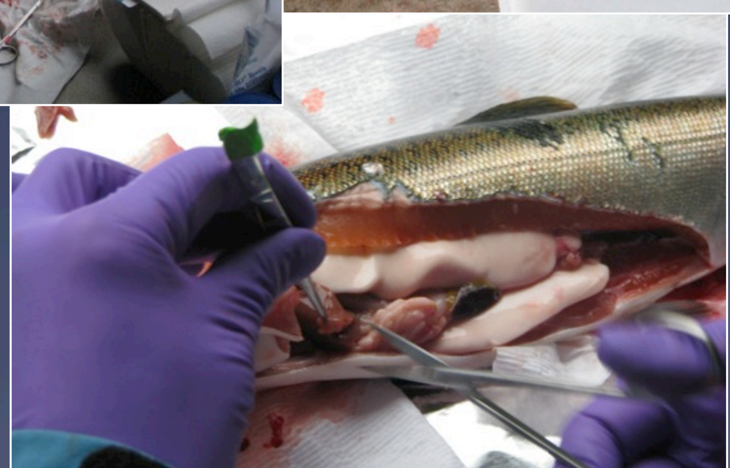
Exposing adult coho spawners to stormwater under controlled experimental conditions

Exposures following sequential rainfall events in 2012-14

clean well water

collected stormwater

Experimental operations at the Suquamish hatchery facility (exposures and sampling)



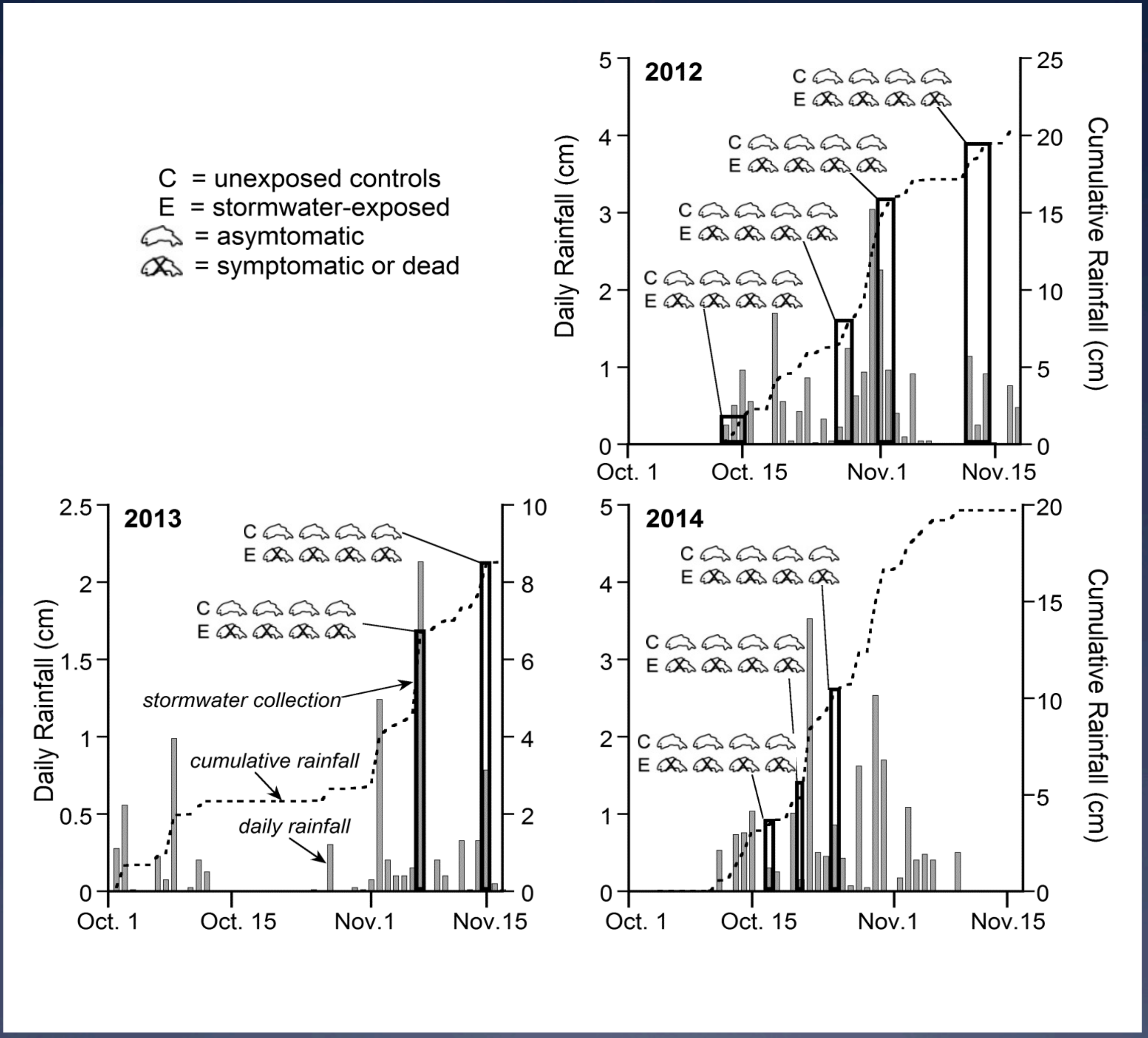
Grovers Creek Hatchery, Fall 2012

Exposure to urban runoff is sufficient to cause adult coho pre-spawner mortality

unexposed (3.5 hrs)

stormwater-exposed (3.5 hr)

November 11th, 2012


C = unexposed controls
E = stormwater-exposed
= asymtomatic
= symptomatic or dead
2012
2013
2014
Daily Rainfall (cm)
Cumulative Rainfall (cm)
stormwater collection
cumulative rainfall
daily rainfall
Oct. 1
Oct. 15
Nov.1
Nov.15

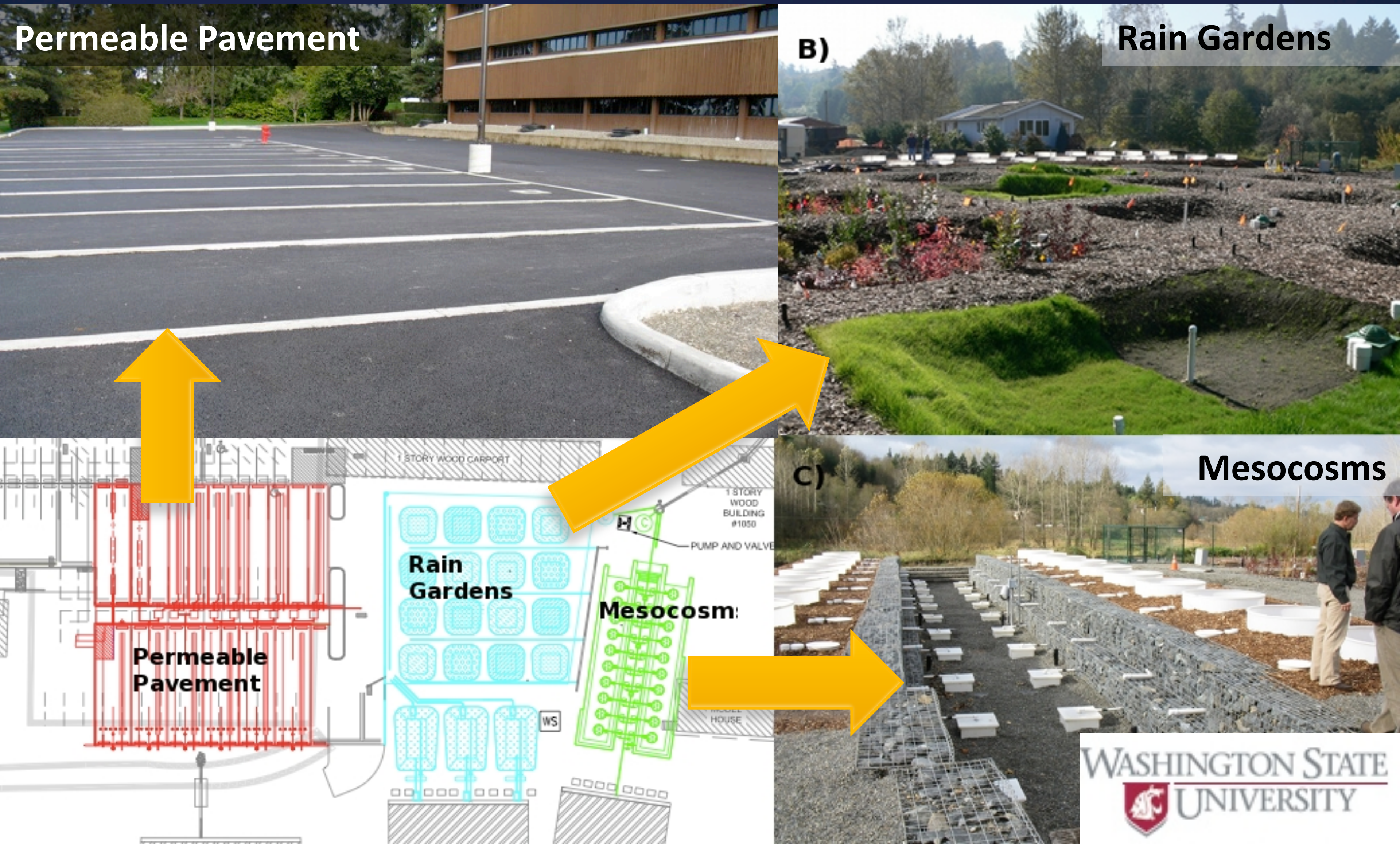
Evolving science, from…

"What's the problem?"

to

"What's the solution?"

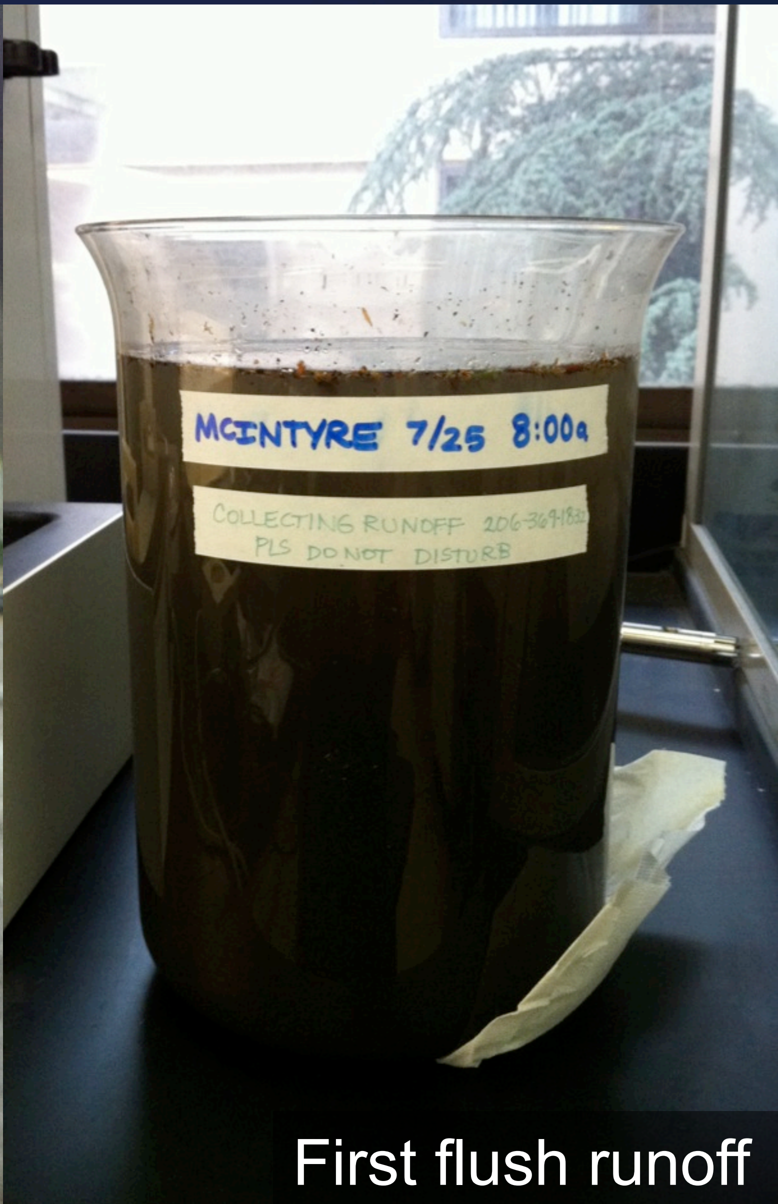
Green Stormwater Research Facility (Washington State University)



Collect runoff, characterize baseline toxicity

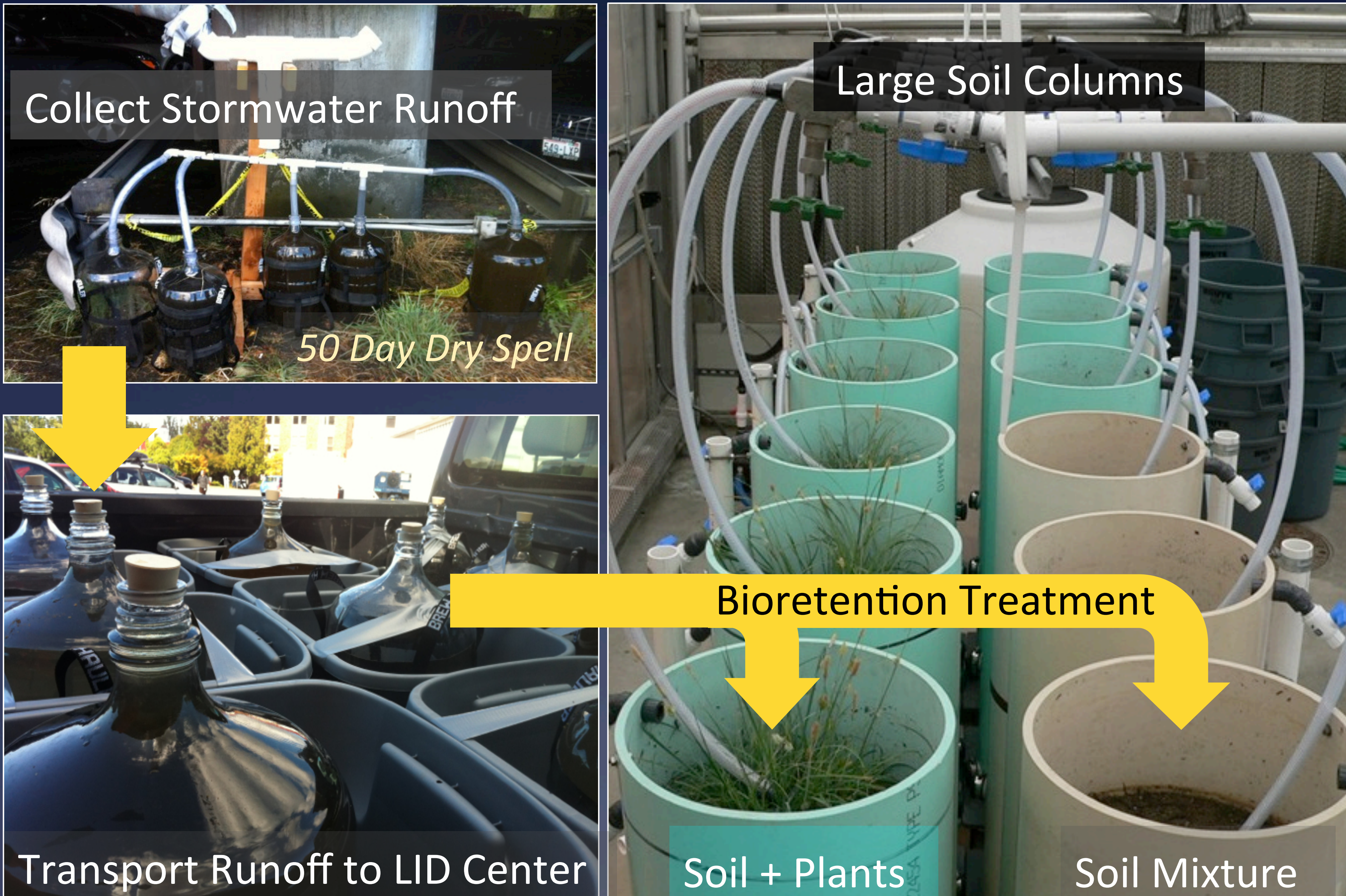
Project lead: Jenifer McIntyre, postdoc, Washington State University

Downspout from highway



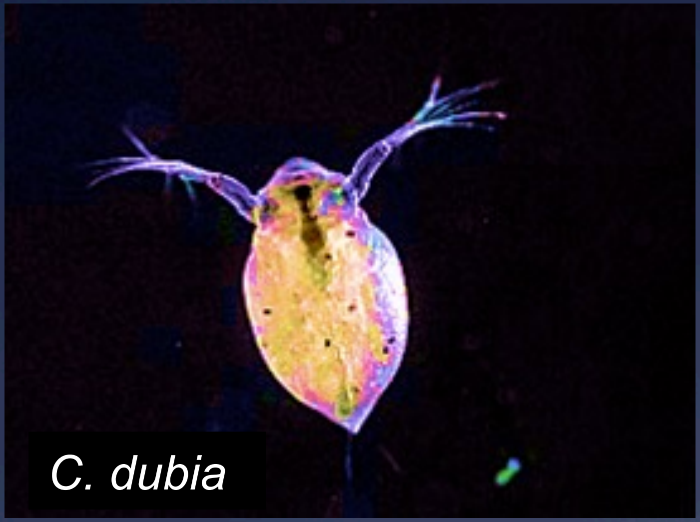
First flush runoff

Experimental design, Fall 2012-14

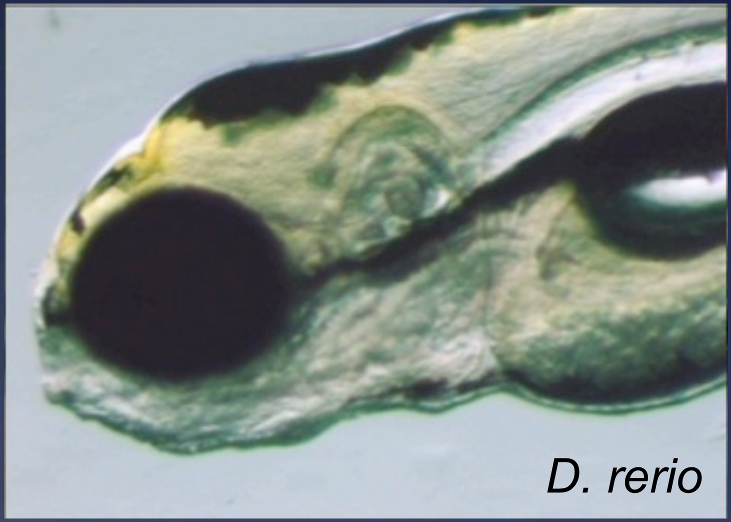


Developing Toolbox for Testing Runoff

Invertebrate



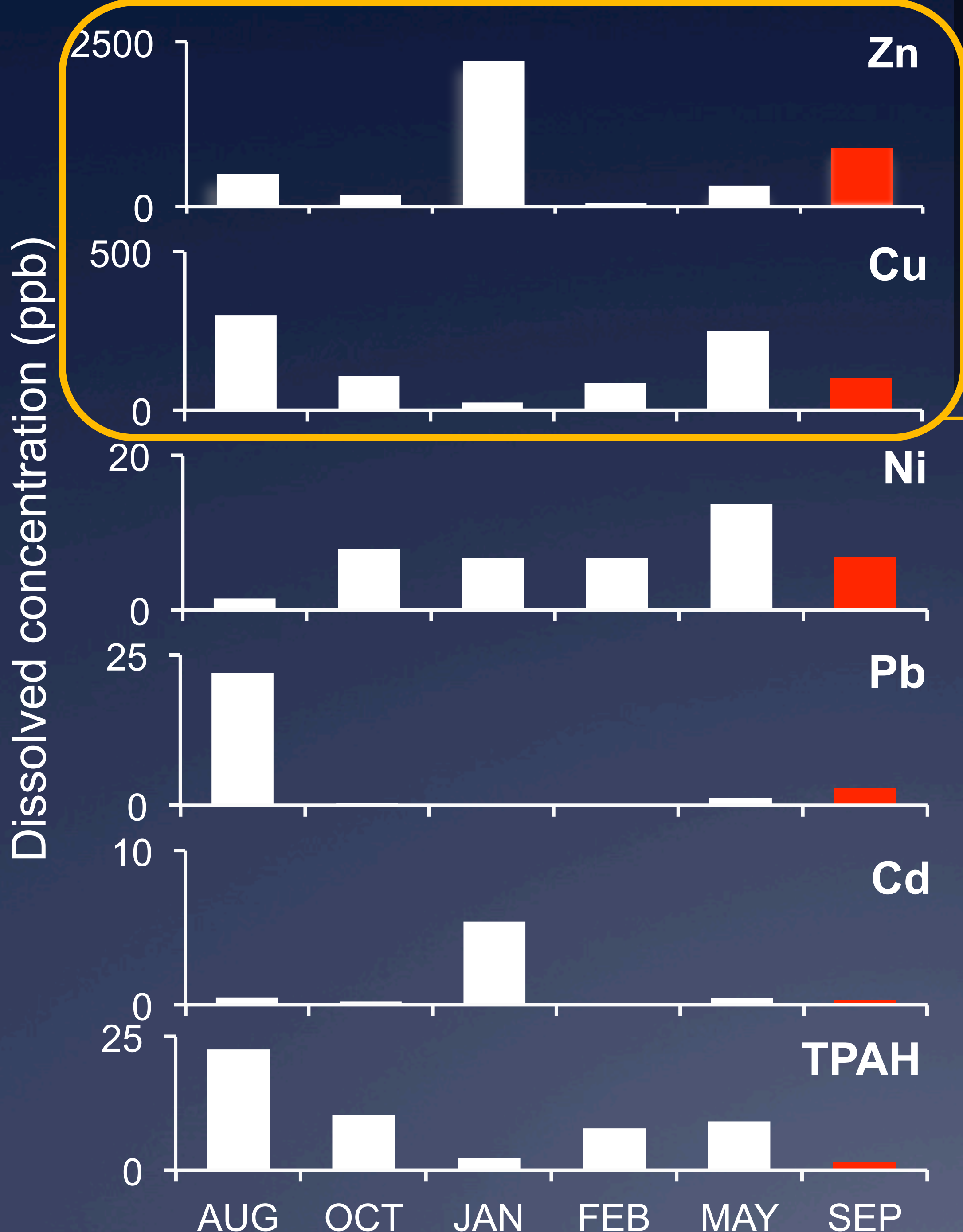
Fish: Zebrafish



- Acute lethality (48 h)
- Reproductive/growth impairment (7 d)

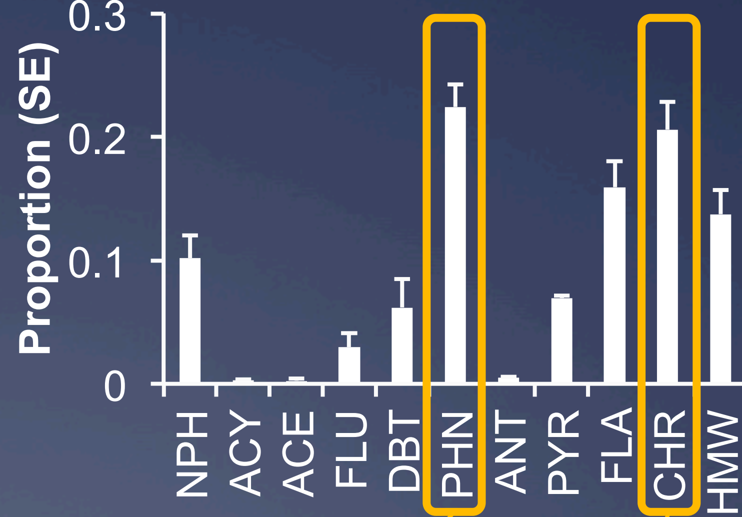
- Survival/morphology (48-96 h)
- Cardiovascular toxicity
- Neurotoxicity (3 h)

Metals and PAHs in highway runoff events tested



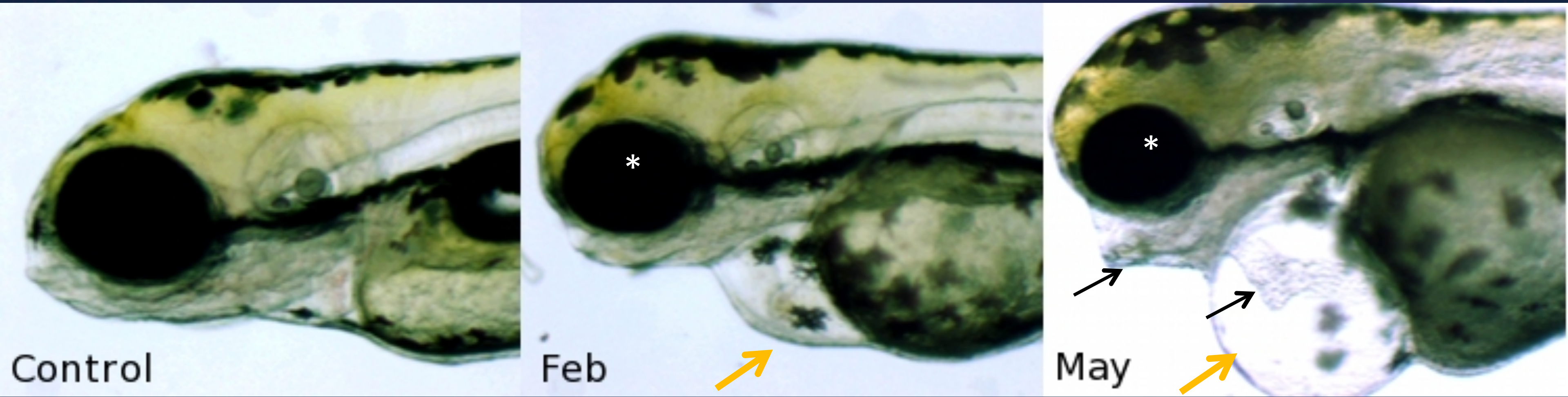
Zinc & Copper

Average PAH Composition



Phenanthrenes & Chrysenes

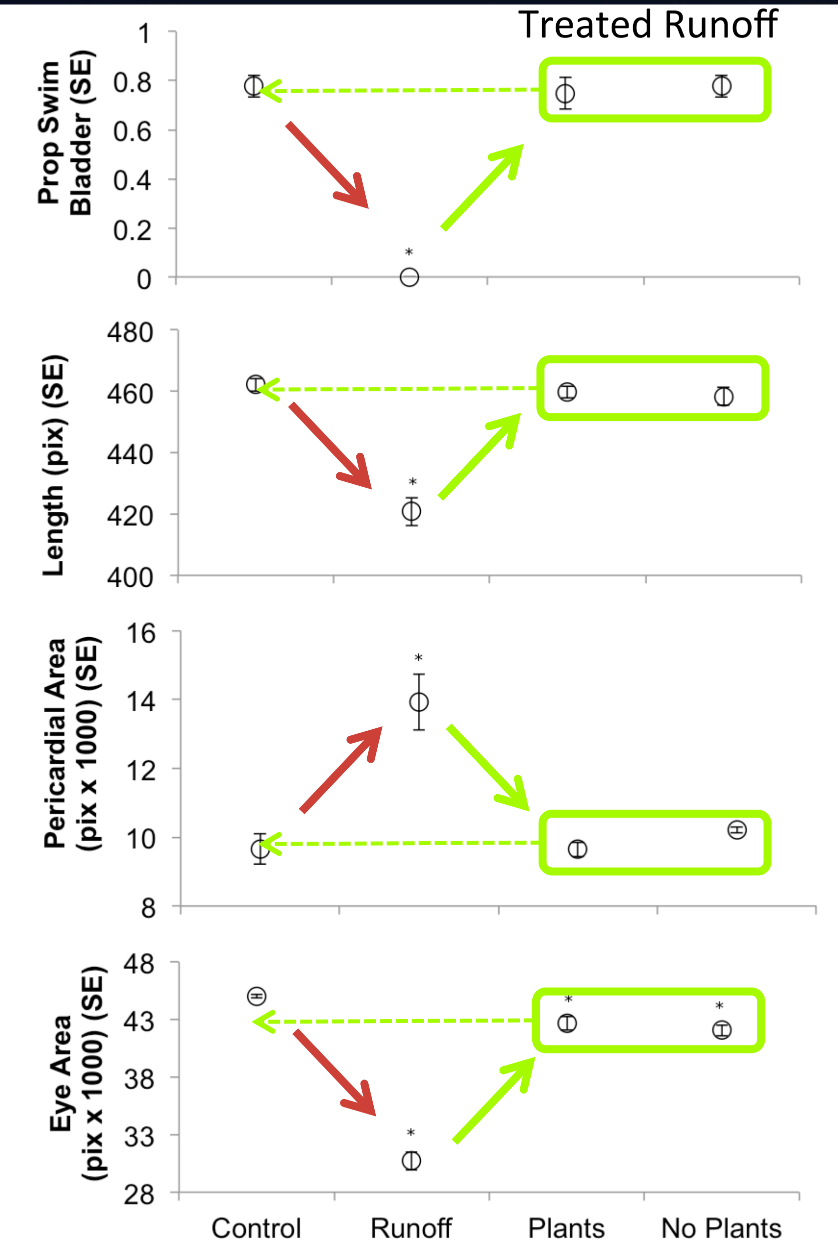
Sublethal effects of runoff on developing fish

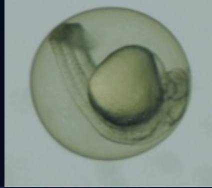


Sublethal effects of runoff on developing fish include:

- Developmental delays
- Inability/delay to hatch
- Lack of swim bladder inflation
- Pericardial edema (yellow arrow)
- Small eye phenotype (*)
- Deformed jaws and hearts (black arrows)

Prevents (most) Sublethal Effects





Normal Swim Bladders

Normal Length

Normal Hearts

Normal Eyes (Almost)

Science of the Total Environment 500–501 (2014) 173–180

Contents lists available at ScienceDirect

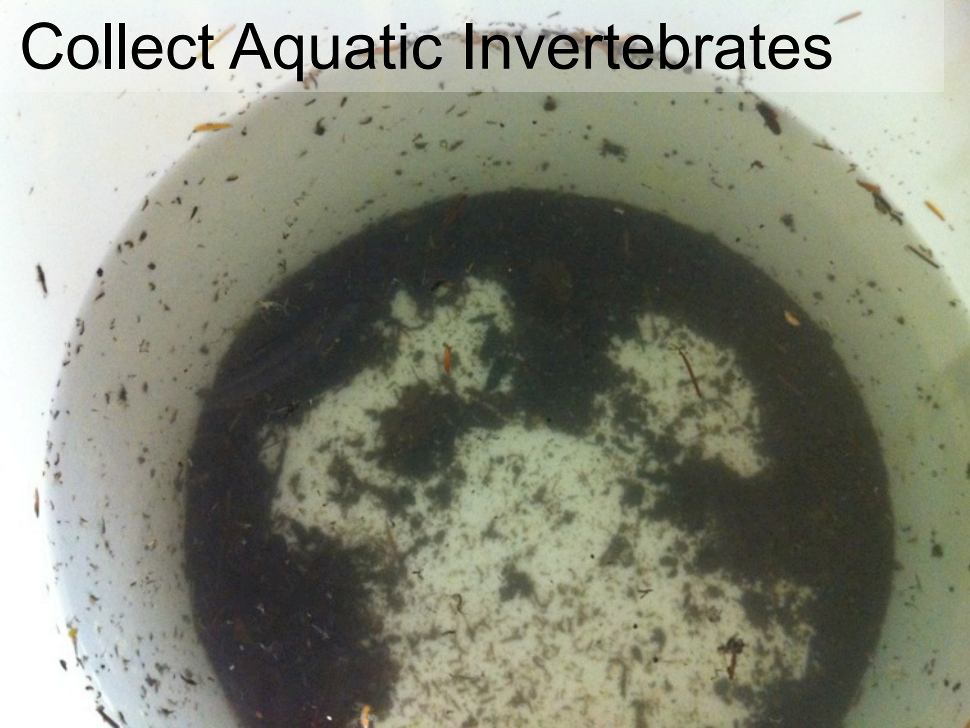
Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Zebrafish and clean water technology: Assessing soil bioretention as a protective treatment for toxic urban runoff

J.K. McIntyre [a,*], J.W. Davis [b], J.P. Incardona [c], J.D. Stark [a], B.F. Anulacion [c], N.L. Scholz [c]

[a] *Washington State University Puyallup Research & Extension Center, 2606 W Pioneer Ave, Puyallup, WA 98371, USA*
[b] *U.S. Fish & Wildlife Service Washington Fish & Wildlife Office, 510 Desmond Dr. SE, Lacey, WA 98503, USA*
[c] *NOAA–NMFS Northwest Science Center, 2725 Montlake Blvd E, Seattle, WA 98112, USA*


Collect Aquatic Invertebrates


Sort by Species

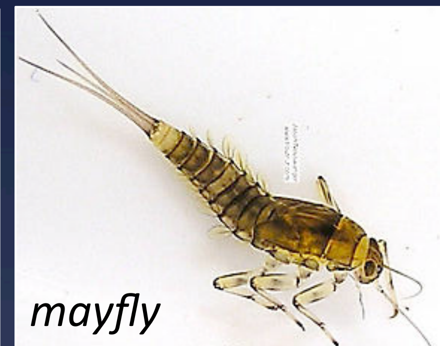

Rocks for structure

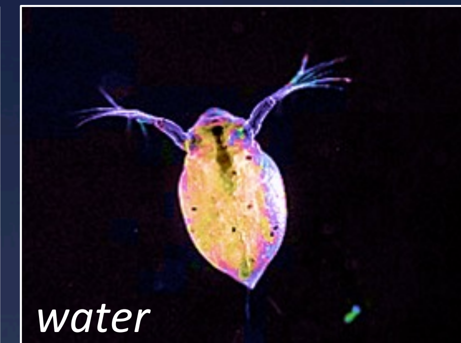

Water bath with aeration

Survival of salmon and their prey before and after soil mesocosm treatment

Fall 2012


juvenile coho salmon


mayfly


water flea

% MORTALITY

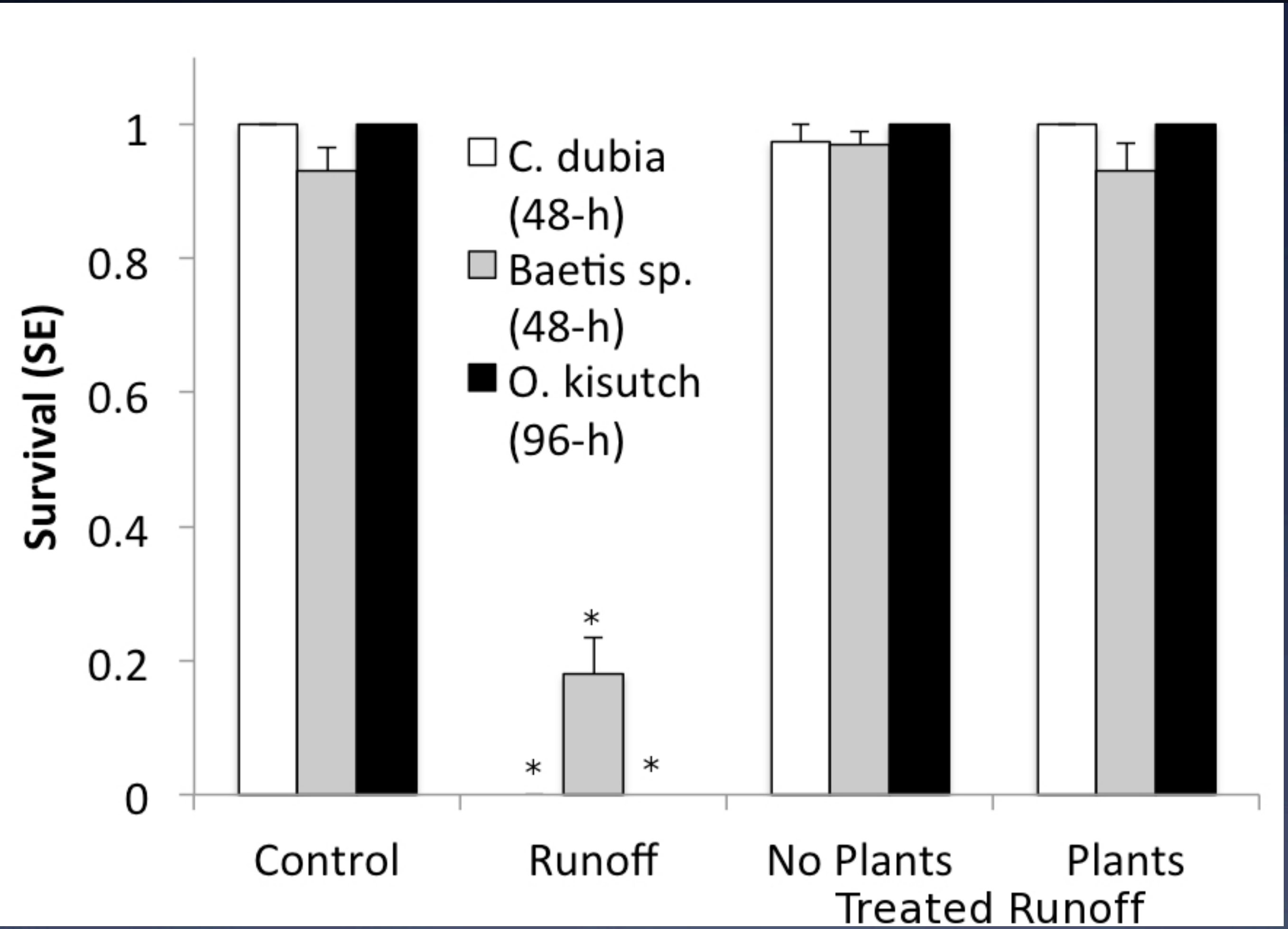

Straight Runoff


Treated Runoff

	juvenile coho salmon	mayfly	water flea
Straight Runoff	100%	85%	100%
Treated Runoff	0%	4%	0%

Result: toxicity largely eliminated

Bioretention Prevents Mortality



Lethal response abolished by soil bioretention treatment

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Chemosphere xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Chemosphere

journal homepage: www.elsevier.com/locate/chemosphere

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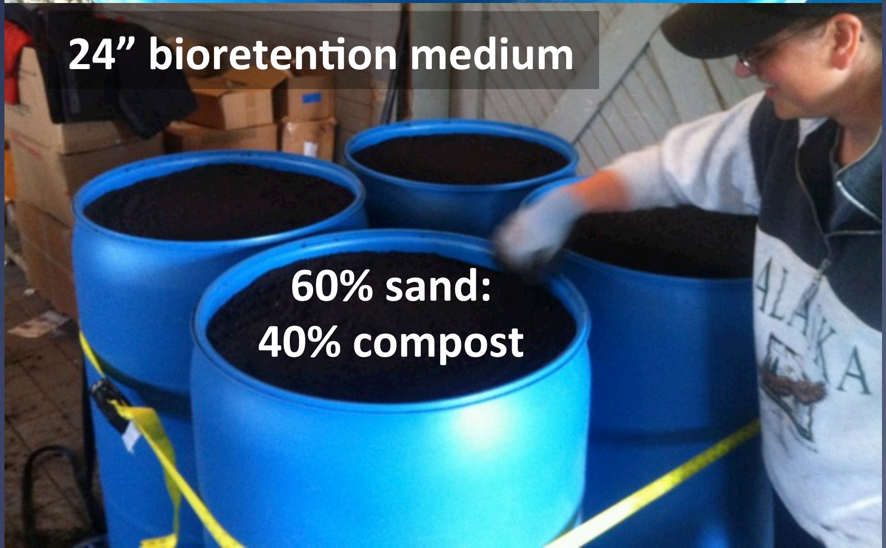
Chemosphere

Soil bioretention protects juvenile salmon and their prey from the toxic impacts of urban stormwater runoff

J.K. McIntyre [a,*], J.W. Davis [b], C. Hinman [a], K.H. Macneale [c], B.F. Anulacion [c], N.L. Scholz [c], J.D. Stark [a]

[a] *Washington State University, Puyallup Research and Extension Center, Puyallup, WA, USA*
[b] *U.S. Fish & Wildlife Service, Washington Fish and Wildlife Office, Lacey, WA, USA*
[c] *National Ocean and Atmospheric Administration, National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, WA, USA*

Scaling up the bioretention experiments: can we rescue the adult coho spawners?

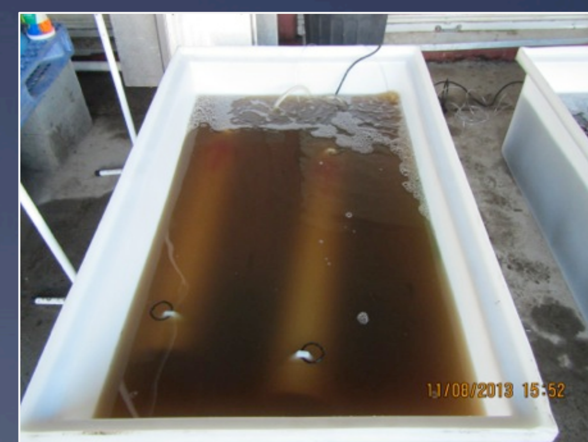


Adult spawner exposures

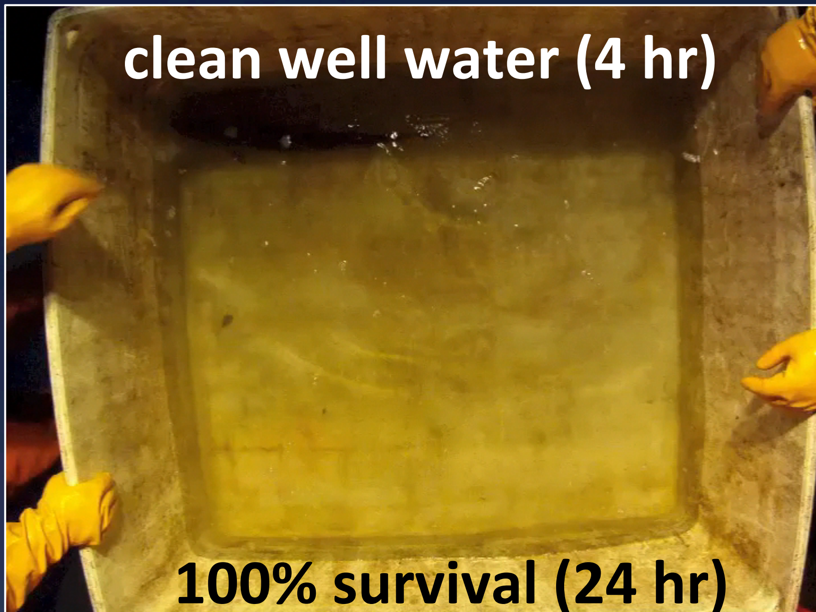
clean well water

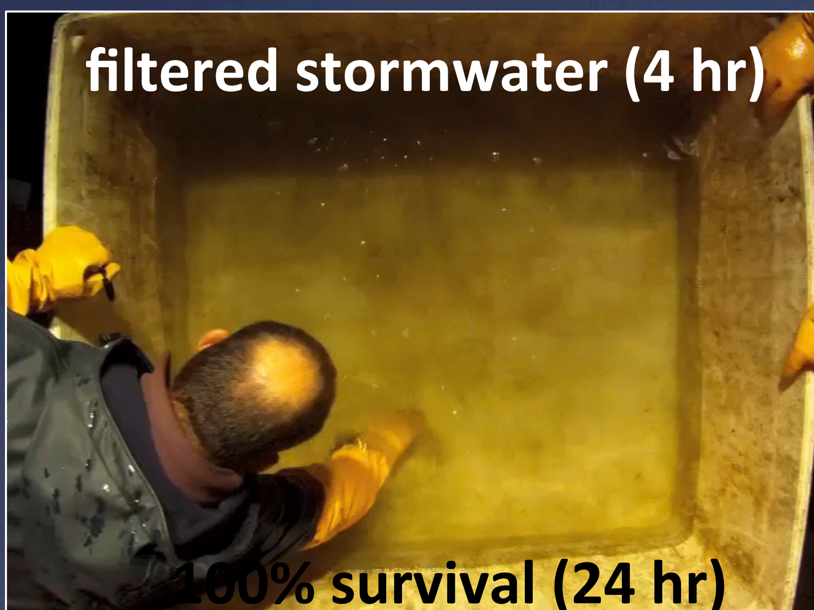
untreated stormwater

filtered stormwater



Stormwater runoff exposures, 2013-14





Seven distinct storm events.
In all cases:

100% mortality (or symptomatic)
vs.
100% survival

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U.S. FISH & WILDLIFE SERVICE · DEPARTMENT OF THE INTERIOR