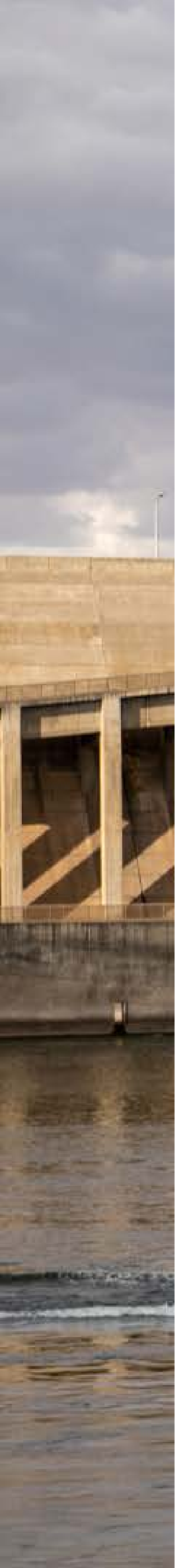


Pacific Northwest NATIONAL LABORATORY

State-of-the-Art Acoustic Telemetry for Fish Migration Studies: Current Capabilities and Future Advances

February 18, 2020

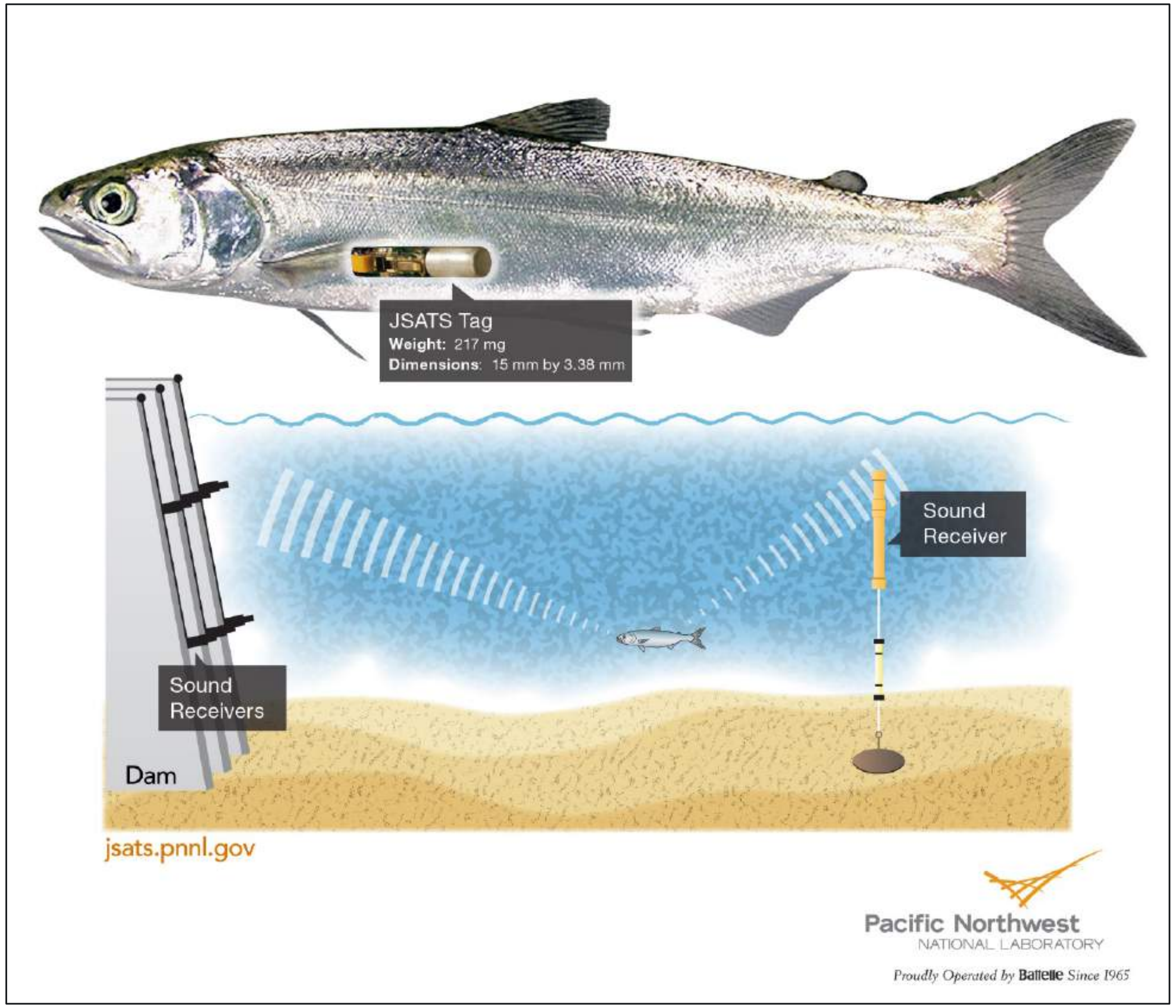
Daniel Deng and Stephanie Liss

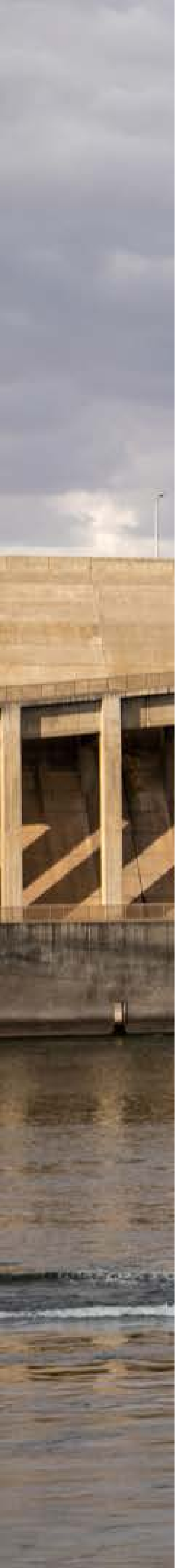
U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

Acoustic Telemetry Technology for Fish Behavior and Survival

- Sound source transmitting a signal containing information
- A receiver receiving the signal and decoding it to recover the transmitted information
- Encoding strategies
  - amplitude
  - frequency
  - phase of individual pulses
  - time between pulses

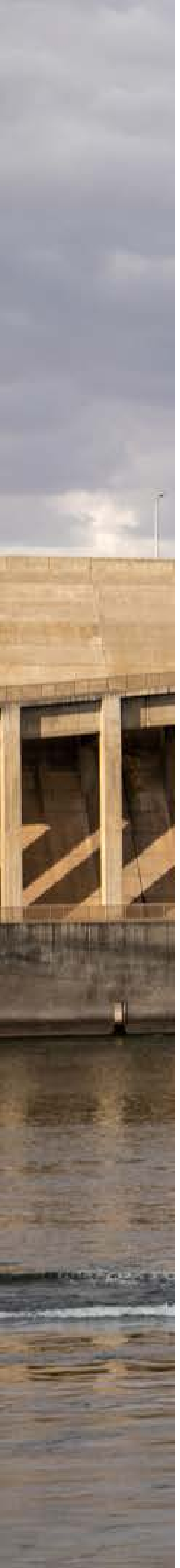




Pacific Northwest NATIONAL LABORATORY

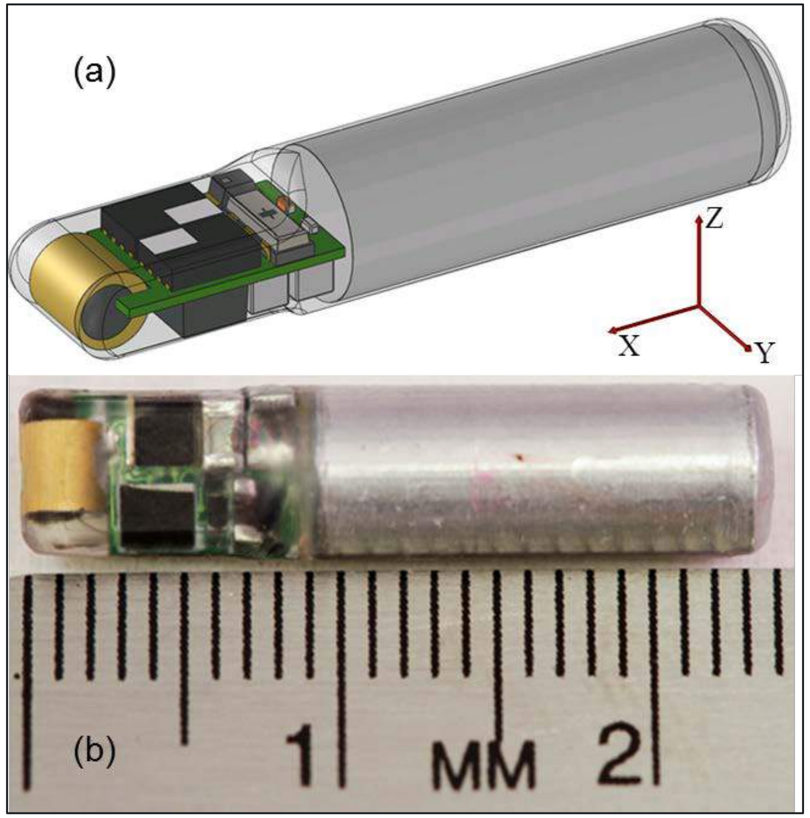
New Trends for Biotelemetry

- **More powerful transmitter**
- Long-lasting transmitter
- **Bio-logging**
- Flexible or stretchable transmitter
- **Cloud-based and real-time system to estimate behavior or survival of tagged aquatic animals**
- **Machine learning to improve 3D tracking accuracy and large data processing**
- **Smaller and lighter transmitter**



Long-Term Juvenile Sturgeon Tag Specifications*

- Dimension: 24.2 mm × 5.0 mm
- Dry Weight: 0.7 g
- Wet Weight: 0.2 g
- Source Level:
  - 161 or 163 dB at zero deg
- Configurable pulse rate interval & tag code
- Optional temperature, alternating, and hibernation mode
- Tag Life: 365 days at 161 dB and 15-s pulse rate interval



*Available for licensing; patented

Lu, J. et al. 2016. A small long-life acoustic transmitter for studying the behavior of aquatic animals. Review of Scientific Instruments, 87(11), 114902.

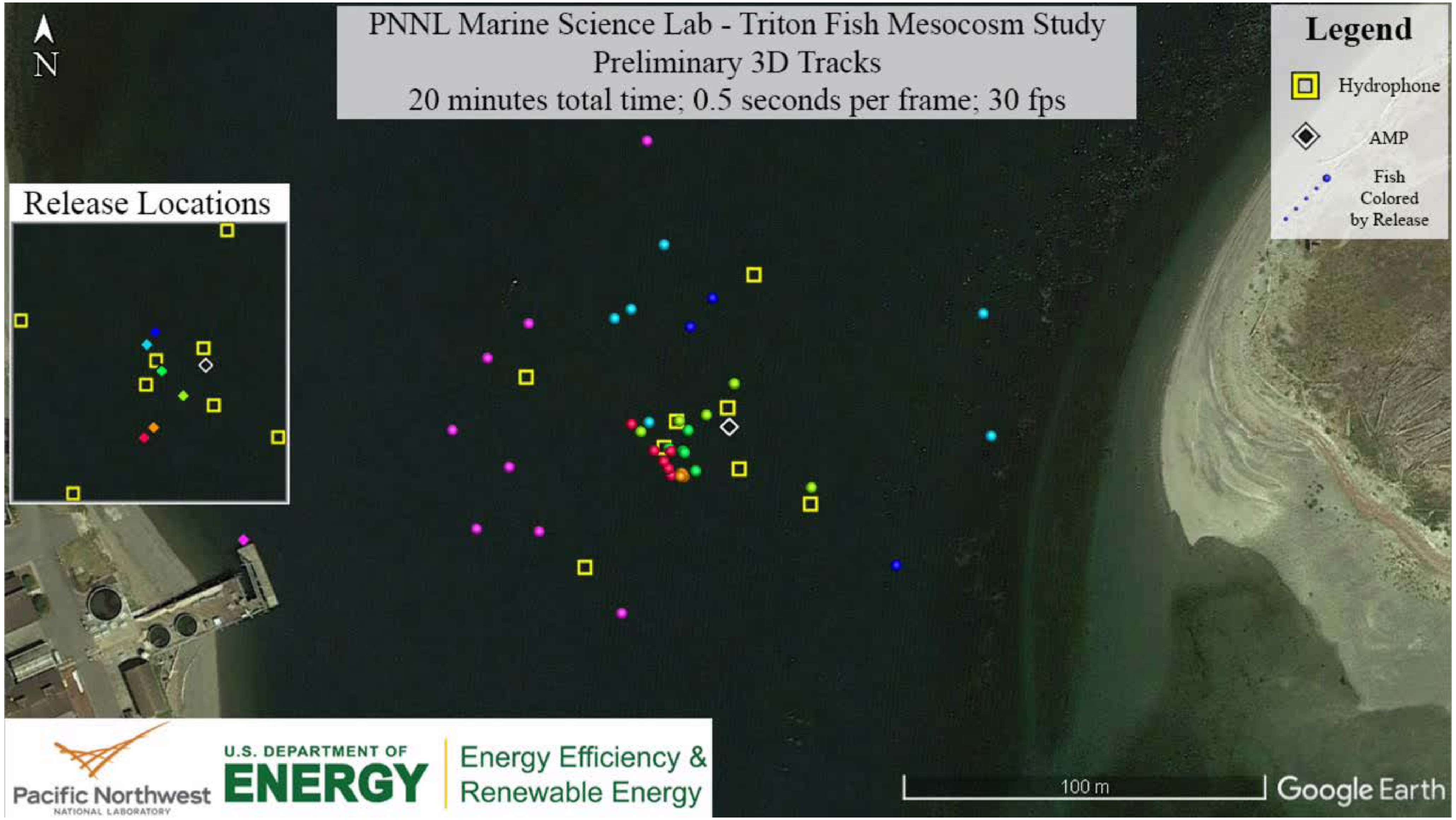
Sturgeon Tag Applications

- Small juvenile (< 1 year old) sturgeon
- Long term monitoring for adult fish such as adult lamprey and salmon
- Noisy environment such as immediate tailrace due to higher source level
- Mobile tracking due to longer detection range
- Marine environment

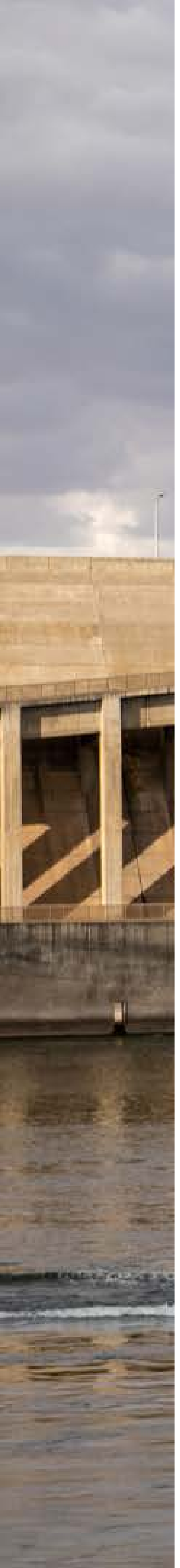
Juvenile lake sturgeon, ARL, PNNL

Juvenile white sturgeon, ARL, PNNL

Application of Sturgeon Tag: Triton Fish Mesocosm Study in Sequim Bay*



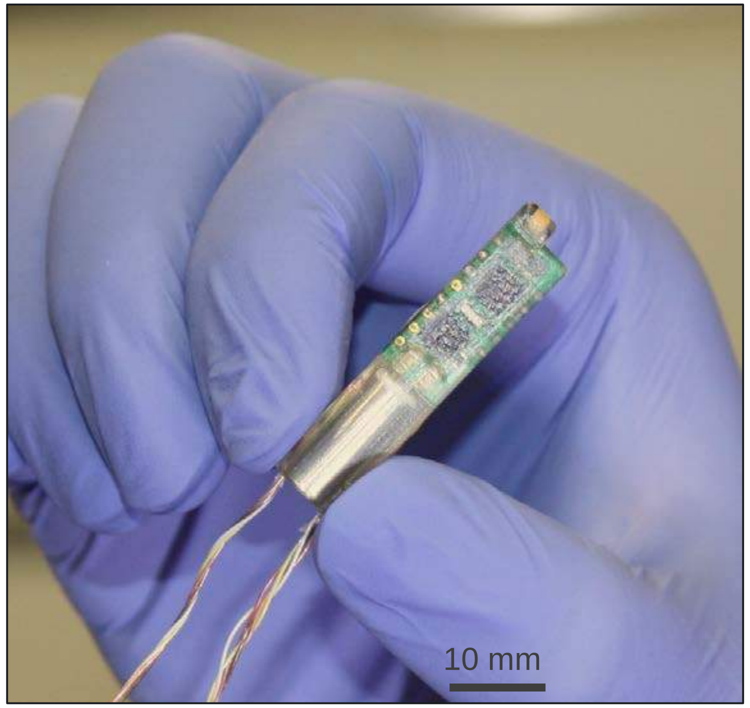
Staines et al. 2019. "Using acoustic telemetry for high resolution sablefish movement informing potential interactions with a tidal turbine." In Proceedings of OCEANS 2019 Seattle.

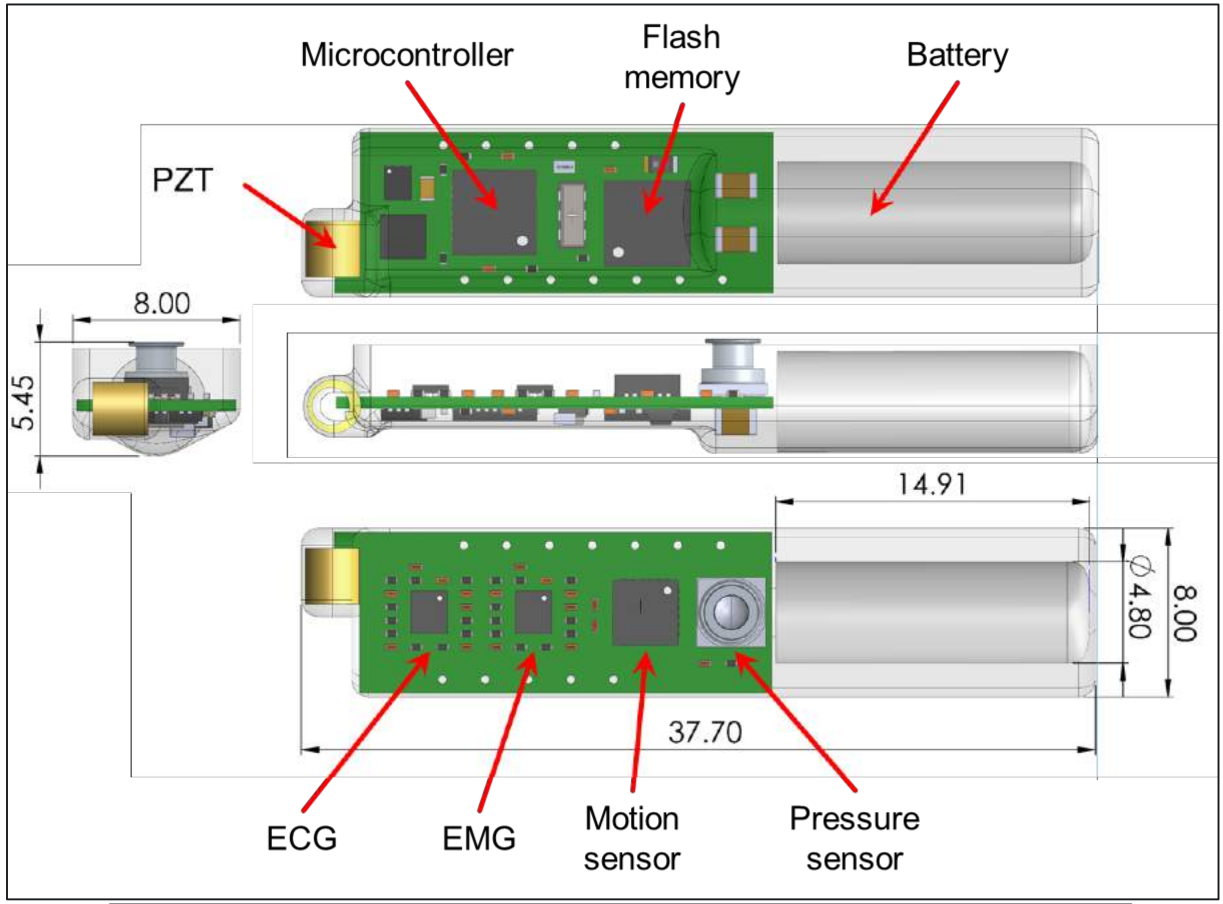


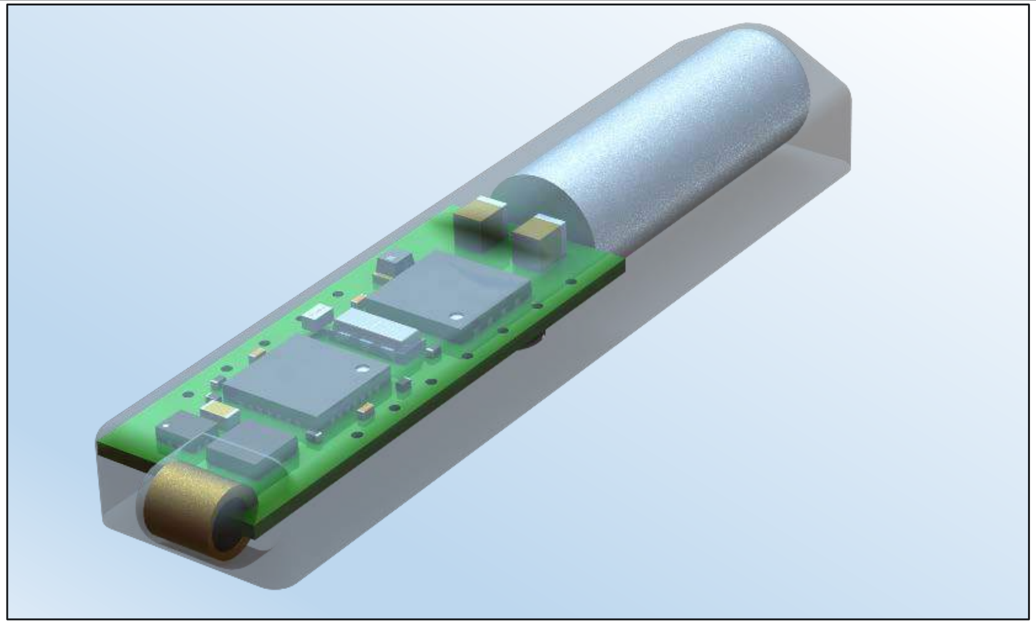
Pacific Northwest
NATIONAL LABORATORY

Lab-on-Fish Layout

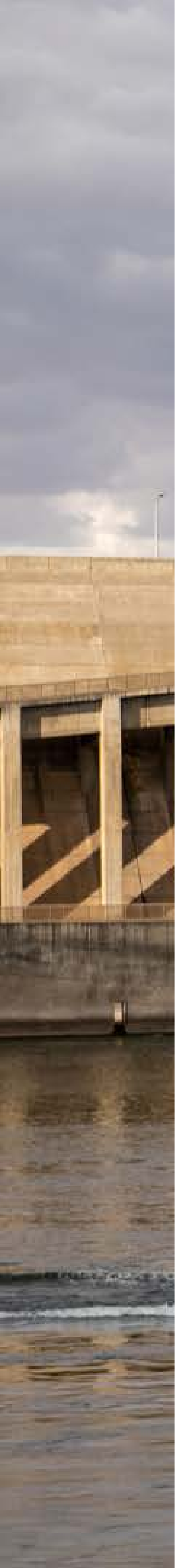
- Full Dimension: 5.5 mm × 8.0 mm × 37.7 mm
- Dry Weight: 2.4 g
- Wet Weight: 0.8 g
- Volume: 1608 mm^3
- PNNL-developed micro-battery





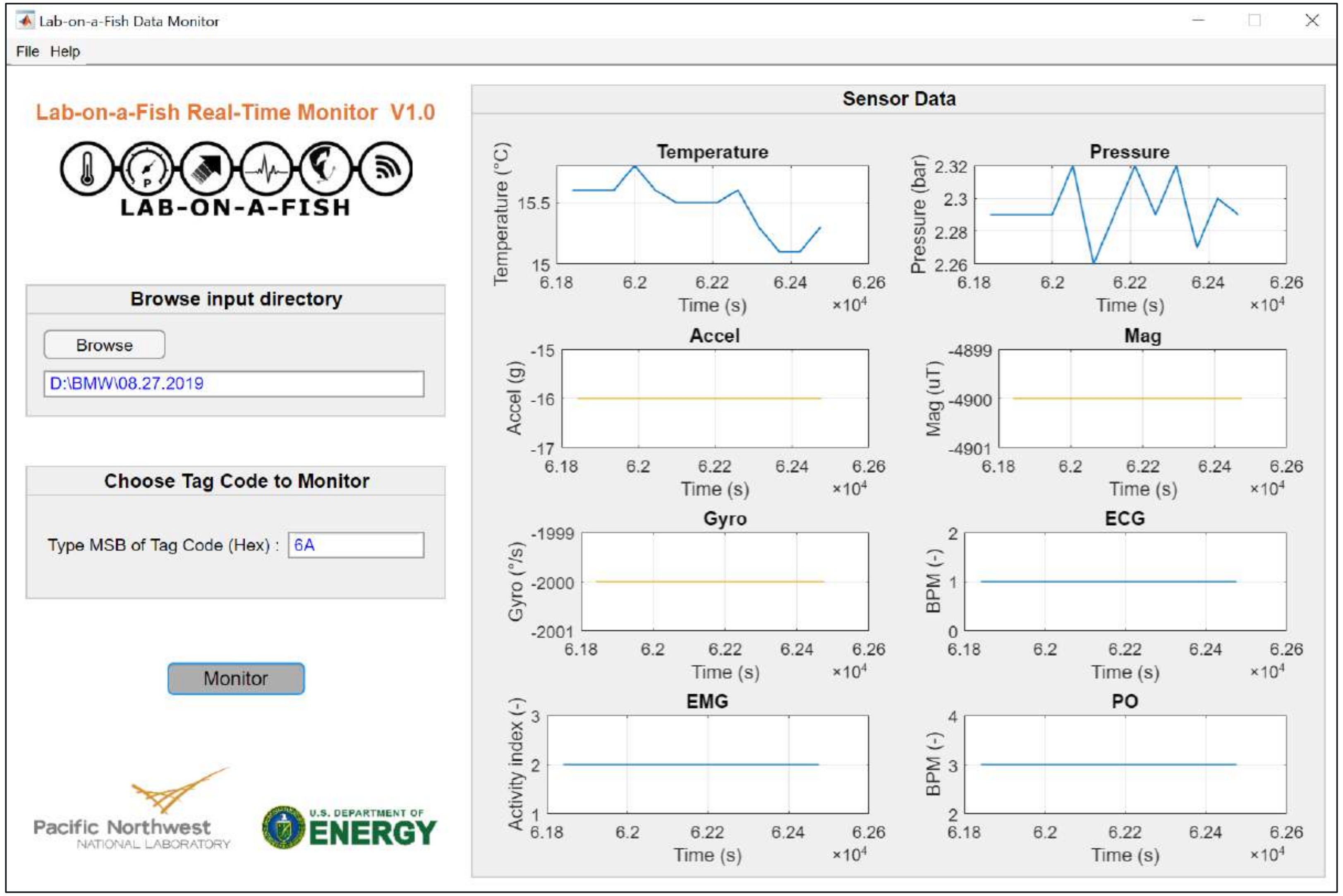


*Available for licensing; patent pending



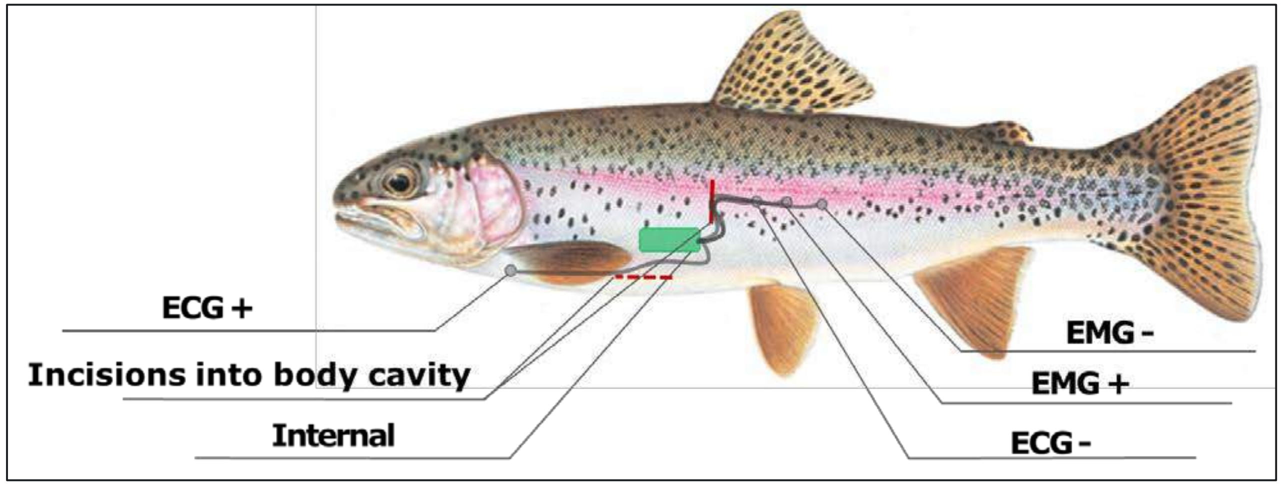
Bio-Logging: Lab-on-a-Fish

- Physiological
  - Electrocardiogram (ECG)
  - Electromyogram (EMG)
  - Pulse oximetry
- Environmental
  - Magnetic field
  - Temperature
  - Pressure
- Physical
  - Gyration
  - Acceleration

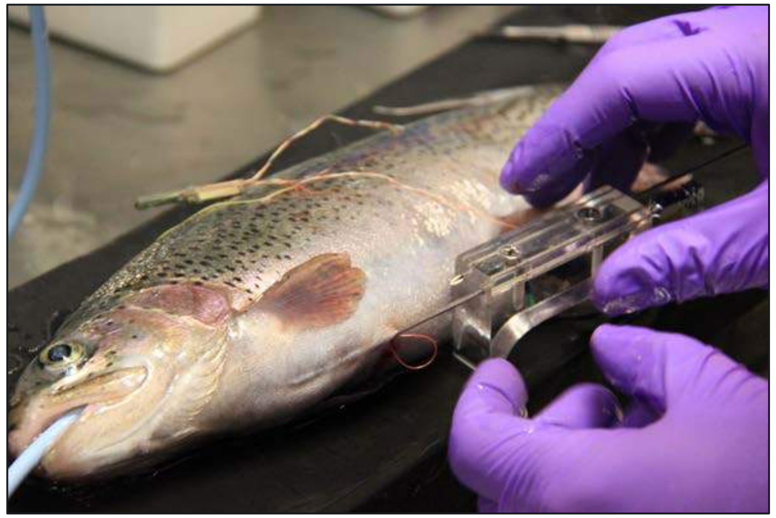


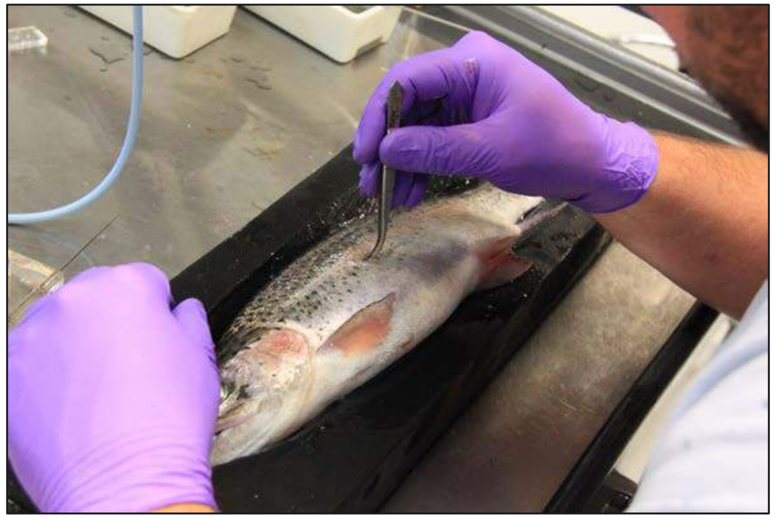
*Available for licensing; patent pending

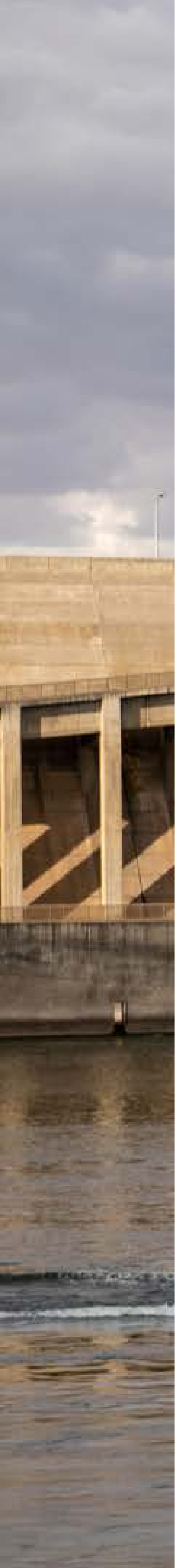
Lab-on-a-Fish Tagging Protocols



- Vertical incision into the body cavity for the main tag
- A second incision along the abdominal midline for ECG+
- ECG- and EMG+/- were embedded subdermally

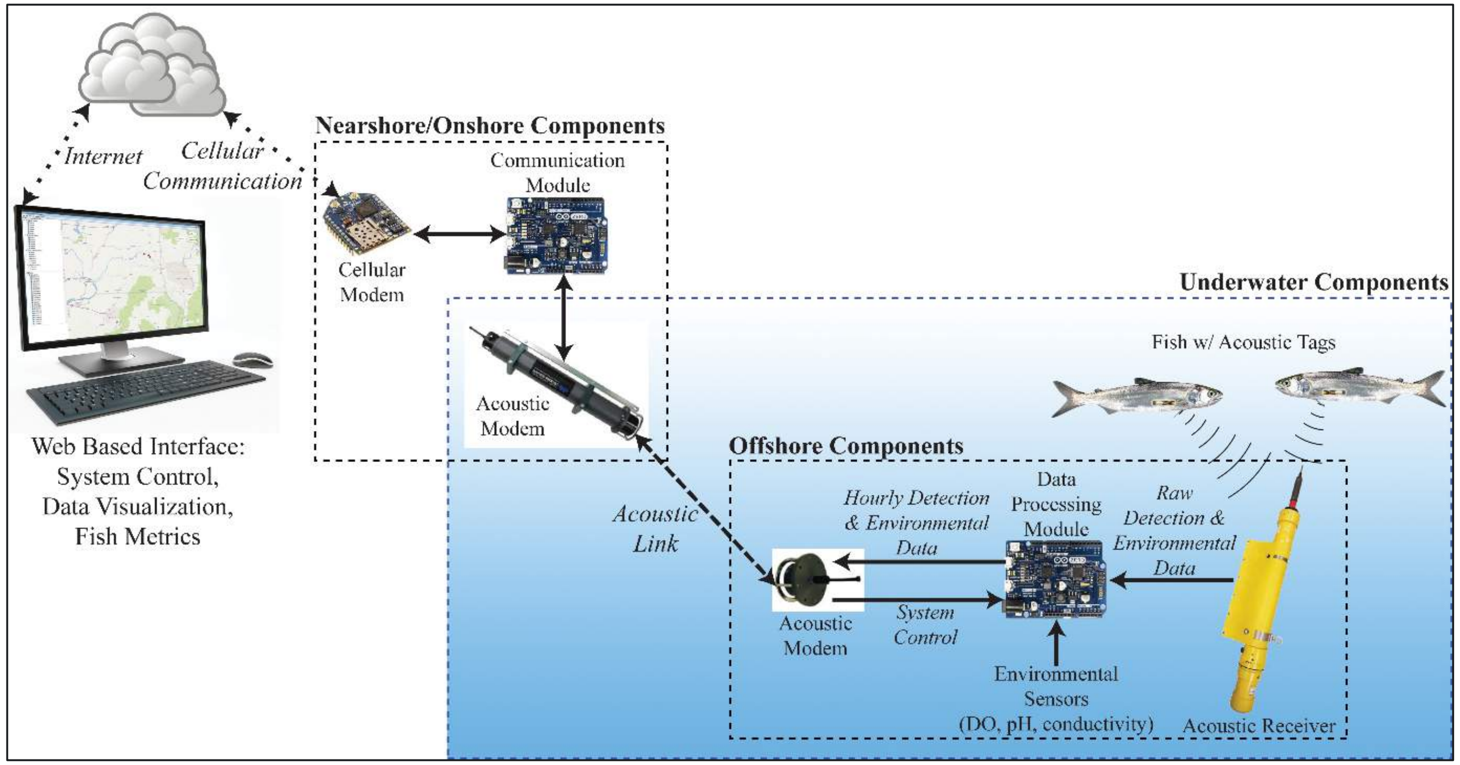


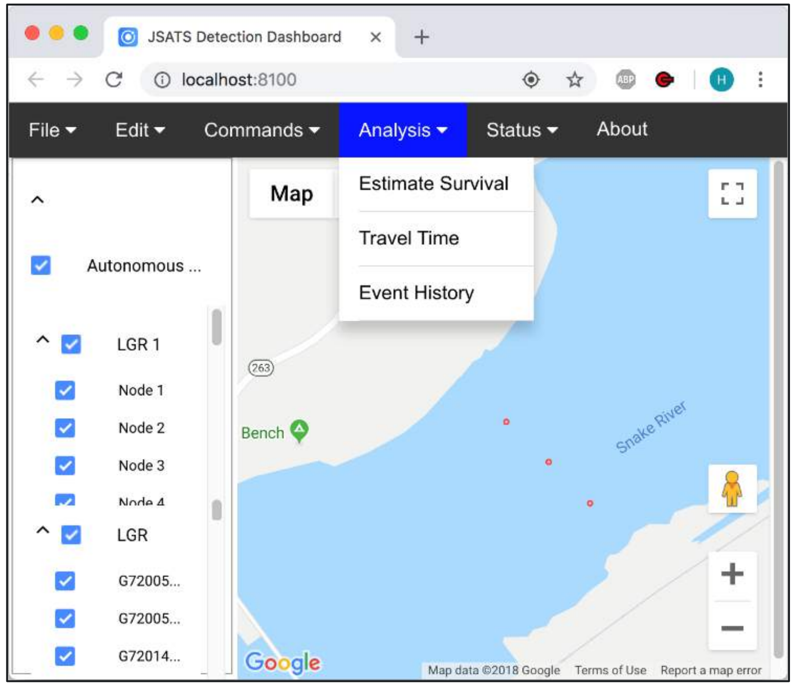




A Cloud-Based Autonomous Acoustic Receiver for Monitoring Real-Time Fish Survival

- Remote and real-time data acquisition
- Remote health monitoring of acoustic receivers
- Remote monitoring of environmental conditions
- User-friendly and real-time info on fish survival metrics



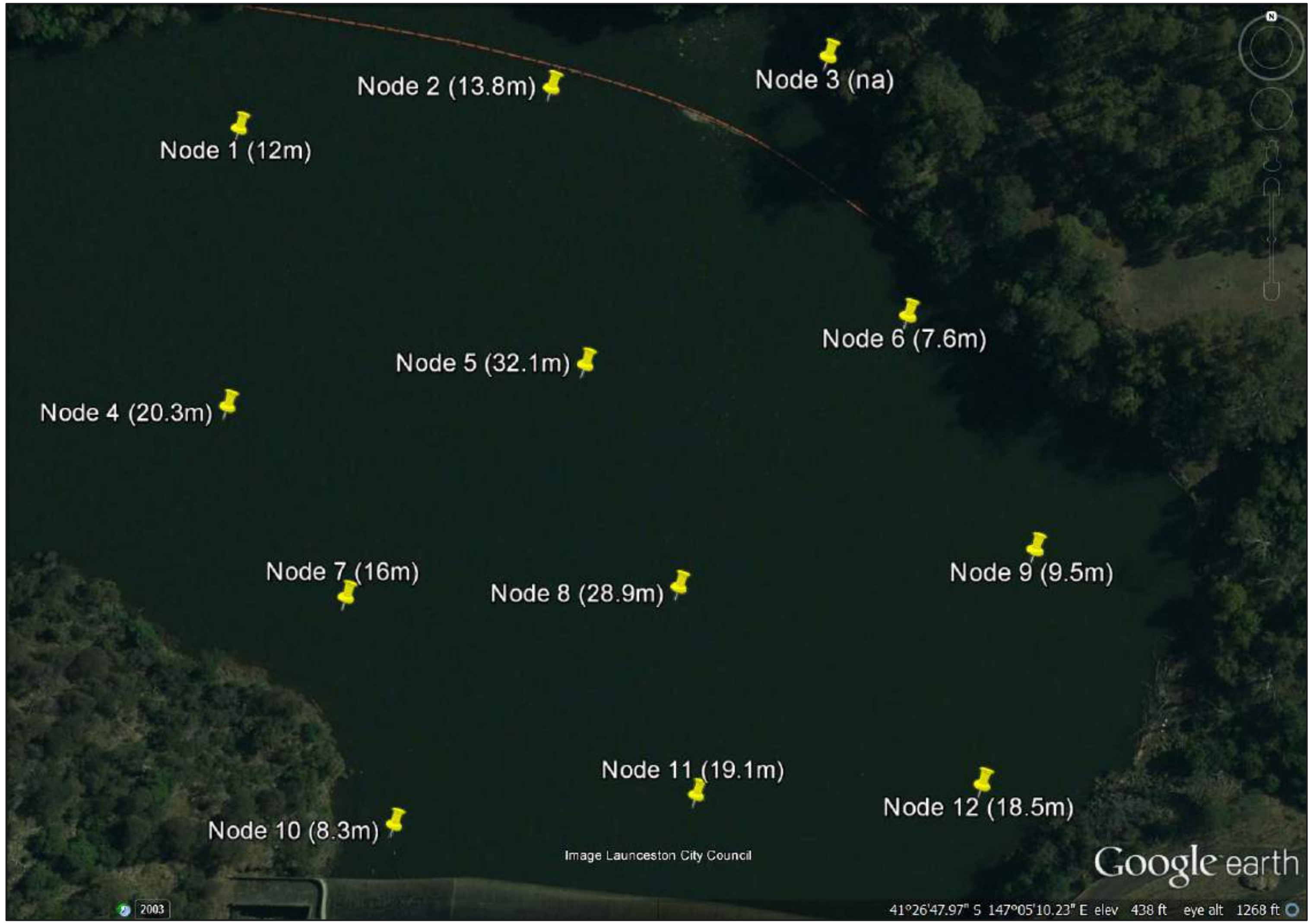


Yang et al. 2019. "Design and implementation of a real-time underwater acoustic telemetry system for fish behavior study and environmental sensing." In Proceedings of OCEANS 2019 Seattle.

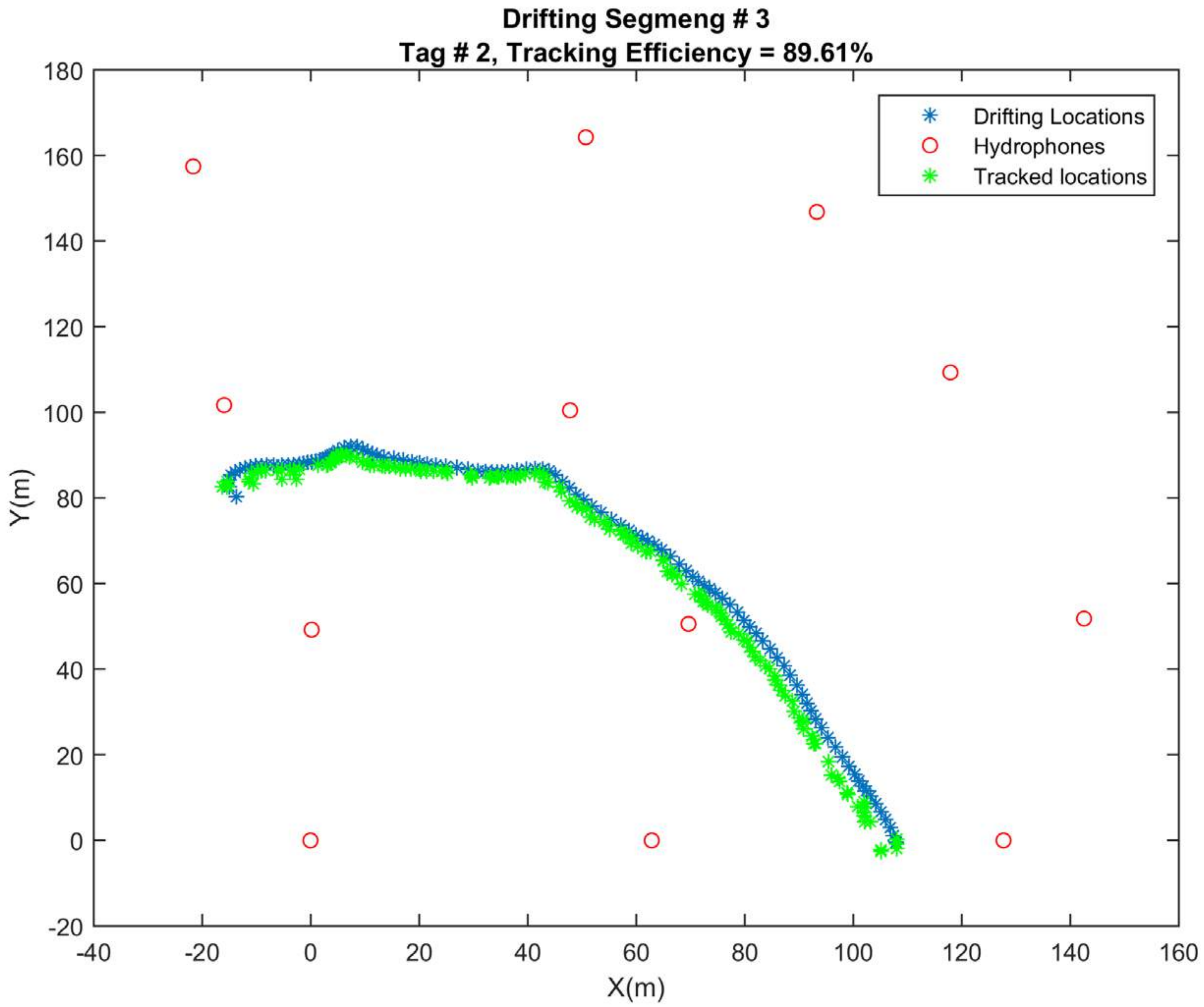
3D Tracking using Autonomous Receivers

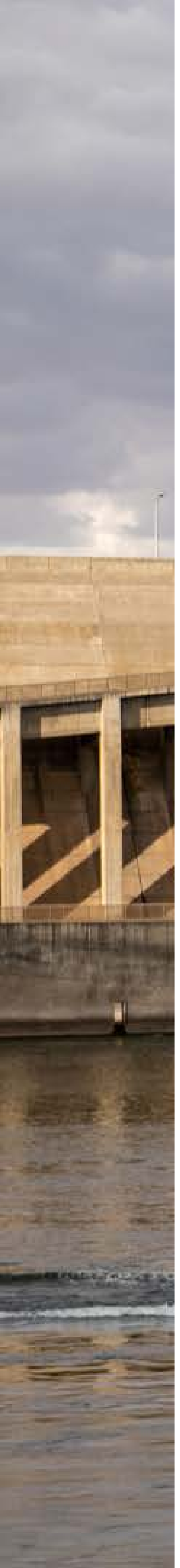
- Trevallyn Dam forebay at Tasmania, Australia
- Twelve JSATS autonomous receivers were deployed
- Feasible due to advances in underwater sensor network synchronization and 3D tracking algorithm

Courtesy of David Ikedife of Hydro Tasmania



Tracking Results: Drifting Target



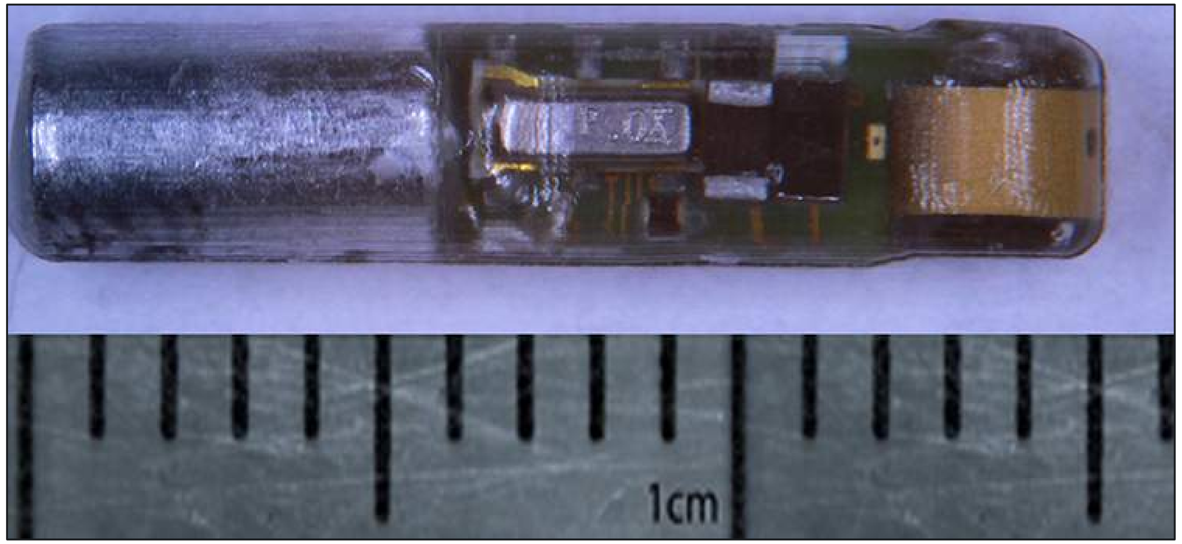


Pacific Northwest
NATIONAL LABORATORY

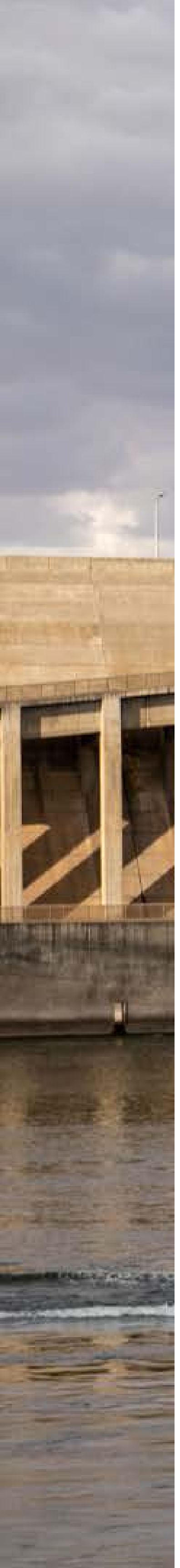
3D Tracking Results

Injectable Acoustic Transmitter

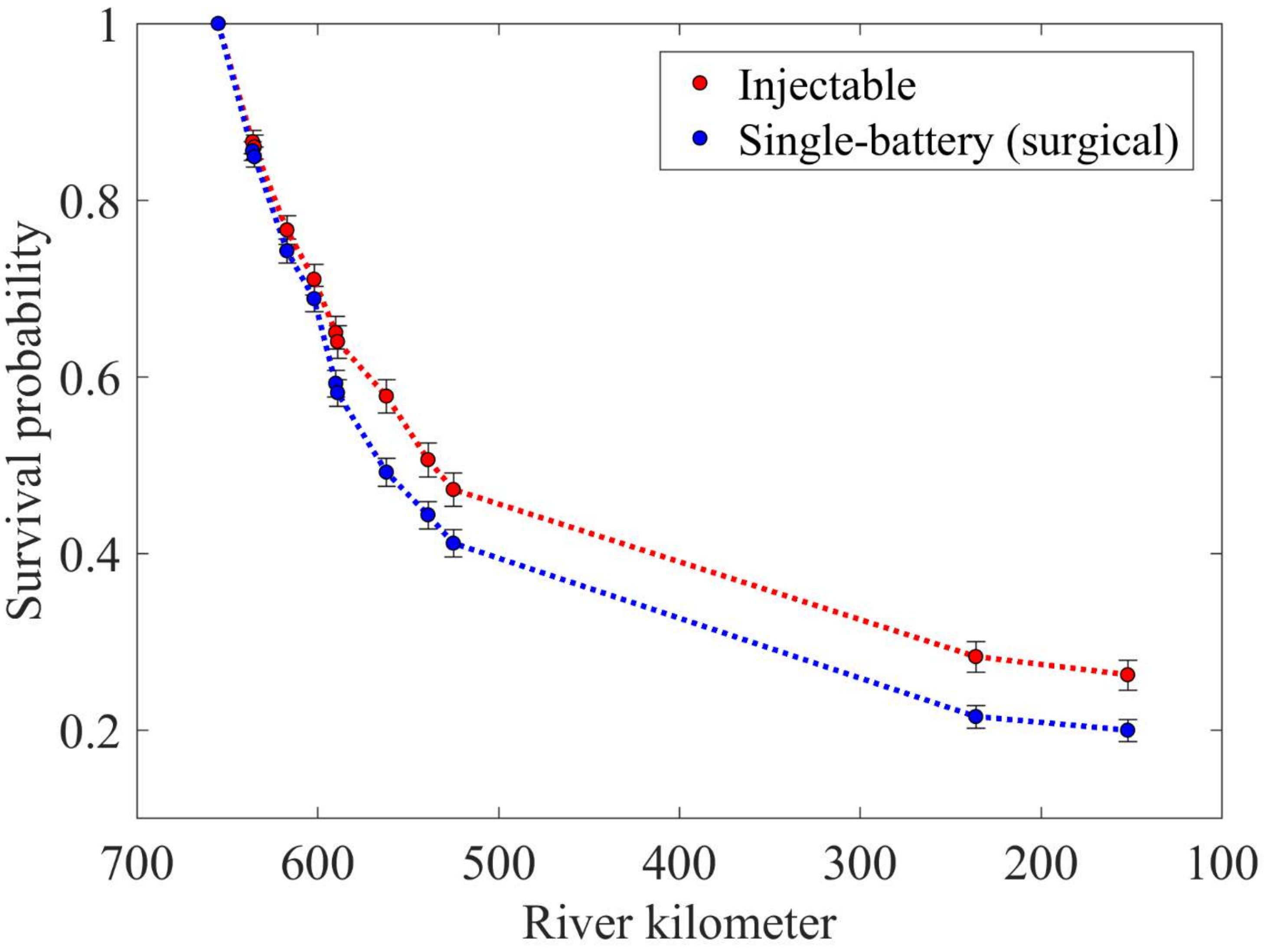
- Implantation by injection instead of surgery, leading to significant cost reduction in use and training
- Significantly reduced handling of fish
- Dimension: 15 mm × 3.3 mm
- Dry Weight: 0.2 g
- Wet Weight: 0.1 g
- Source Level:
  - 156 dB at zero deg
  - 155 dB average -90 to 90 deg
- Configurable pulse rate interval and tag code
- Optional temperature, alternating tag codes, and hibernation mode
- Tag life: > 120 days at 3-s pulse rate interval from prototype testing (Commercially available version has reduced tag life due to sponsors' need)



Deng ZD et al. 2015. "An injectable acoustic transmitter for juvenile salmon." Scientific Reports 5:8111



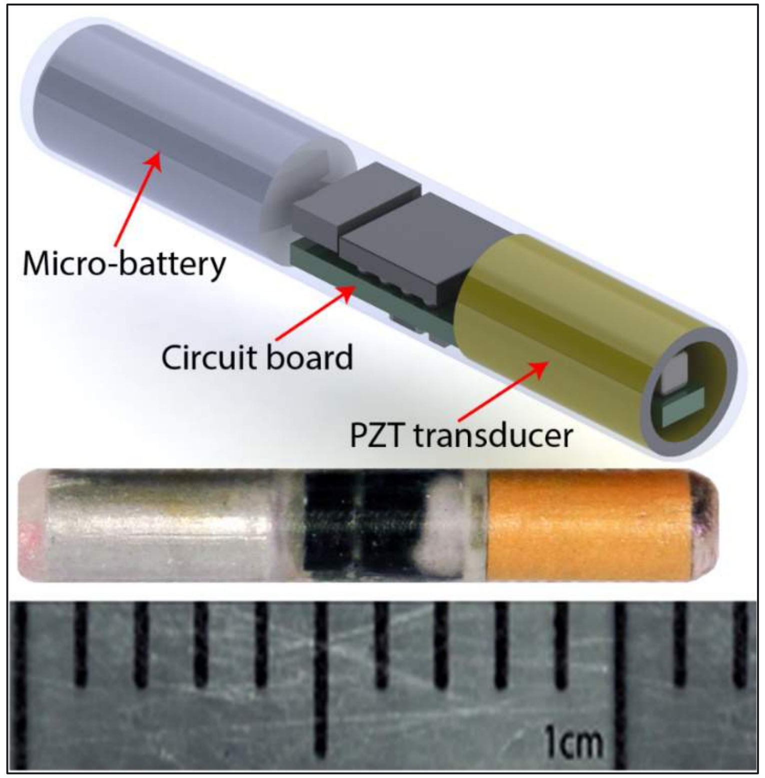
Survival Rate Comparison of Juvenile Chinook Salmon Using Injectable and Surgical Acoustic Transmitters



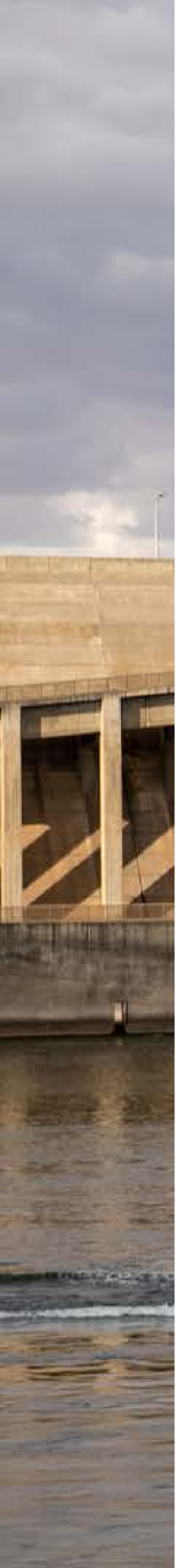
Deng ZD et al. 2017. "Comparing the survival rate of juvenile Chinook salmon migrating through hydropower systems using injectable and surgical acoustic transmitters." Scientific Reports 7:42999. doi:10.1038/srep42999

First Generation Juvenile Lamprey/Eel Acoustic Transmitter*

- Dimension: 12.0 mm × 2.0 mm
- Dry Weight: 0.08 g
- Wet Weight: 0.04 g
- Source Level: 148 dB
- Configurable pulse rate interval and tag code
- Optional temperature, alternating code, and hibernation mode
- Tag life: ~30 days at 5-s pulse rate interval
- Demonstrated feasibility in lab and field conditions

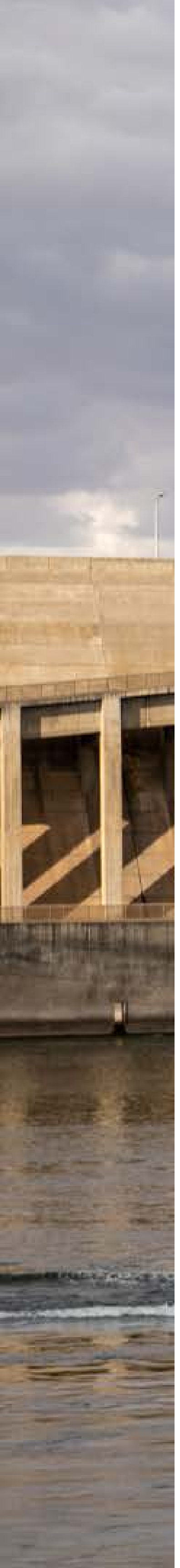


*Available for licensing; patented



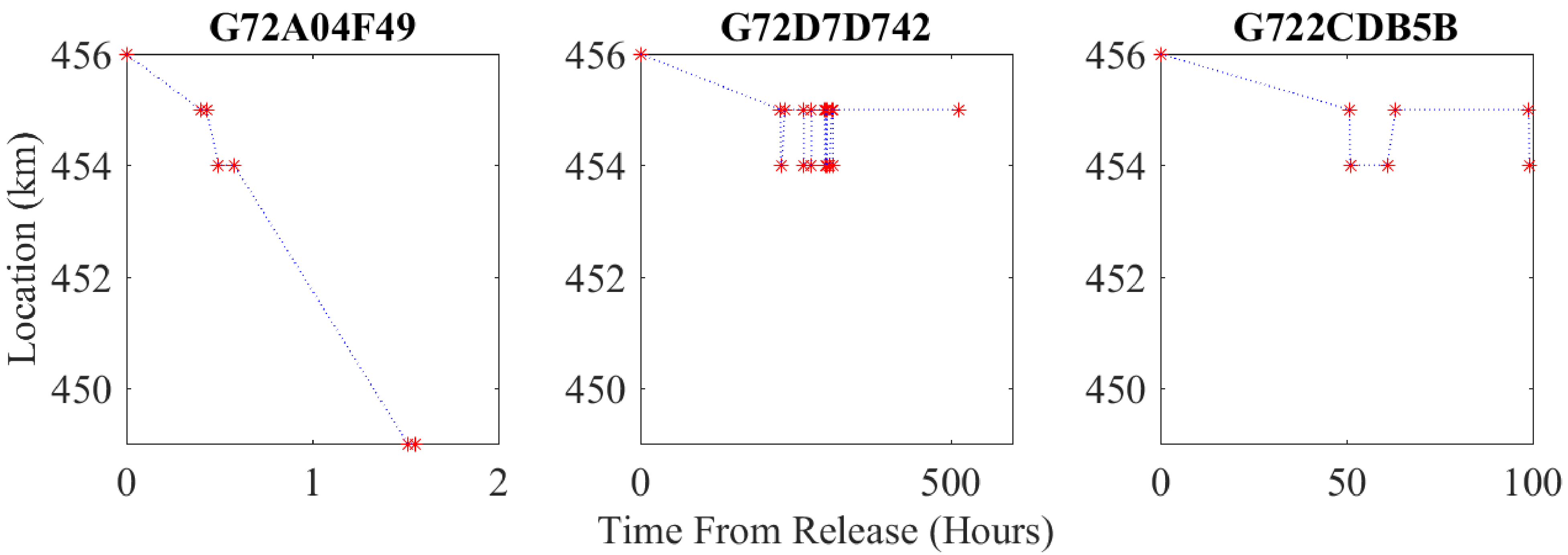
Pilot Field Trial with Juvenile Lamprey: Array Design

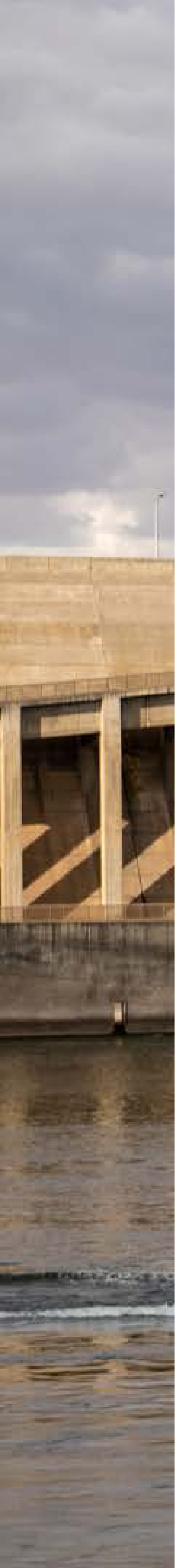
- A total of 41 JSATS autonomous receivers were deployed between McNary Dam and John Day Dam
  - 7 nodes at river km 449
  - 26 nodes at river km 454
  - 8 nodes at river km 455
- 100 tagged fish were released approximately 1 km upstream of the array at rkm 455 at three lateral locations across the river



Pilot Field Trial with Juvenile Lamprey: Detection Summary

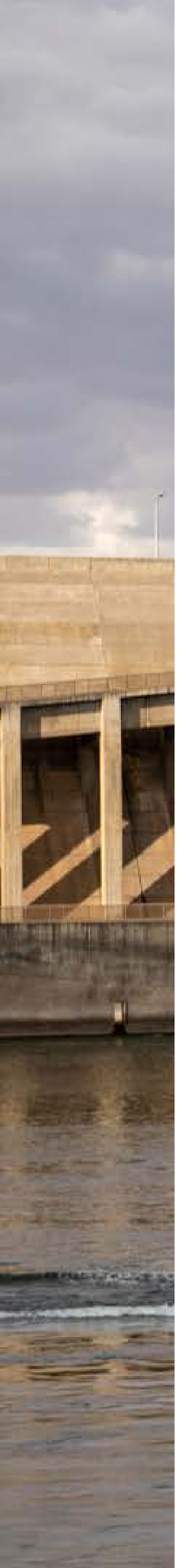
- Array at rkm 455
  - 98 out of 100 fish detected: Two tagged fish were never detected on any node
- Array at rkm 454
  - 98 out of 98 fish detected (100%)
- Array at rkm 449
  - 96 out of 98 fish detected: Two fish went back and forth between the 1st and 2nd array but never reached the 3rd array (shown below w/ a typical fish for comparison)





Next Frontiers

- Smaller, lighter, more powerful transmitter
- Long-lasting transmitter: self-powered platform
- Bio-logging sensors
- Flexible or stretchable sensors
- Cloud-based and real-time system to estimate behavior or survival of tagged aquatic animals
- Machine learning / deep learning for fish passage and hydro operations
- Only way to achieve these goals is multi-disciplinary approach and close collaboration between stakeholders nationally and internationally



Lamprey/Eel Acoustic Transmitter (ELAT): Previous Lab and Field Studies

Fisheries Research 195 (2017) 52–58

Contents lists available at ScienceDirect

Fisheries Research

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

ELSEVIER

Retention and effects of miniature transmitters in juvenile American eels

Robert P. Mueller[a,*], Jill Janak[a], Stephanie A. Liss[b], Richard S. Brown[a], Zhiqun Deng[c], Ryan A. Harnish[a]

[a] Pacific Northwest National Laboratory, Ecology Group, Richland, WA 99352, United States
[b] Pacific Northwest National Laboratory, Environmental Assessment Group, Richland, WA 99352, United States
[c] Pacific Northwest National Laboratory, Hydrology Group, Richland, WA 99352, United States

ENVIRONMENT AUTHOR PRODUCED

Implantation of a New Micro Acoustic Tag in Juvenile Pacific Lamprey and American Eel

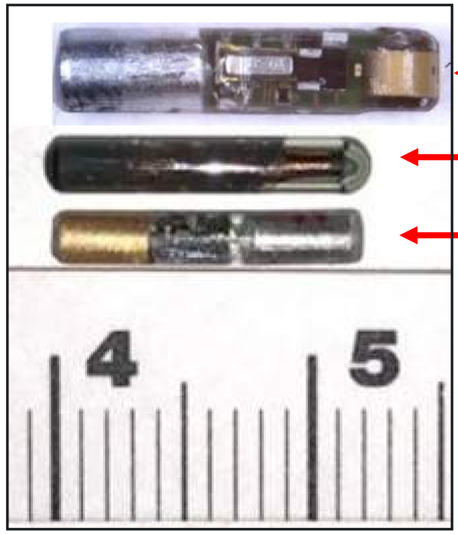
Robert Mueller[1], Stephanie Liss[1], Z. Daniel Deng[1]
[1]Earth Systems Science Division, Pacific Northwest National Laboratory

Protocols and Methods for Implantation of a New Micro Acoustic Tag in Juvenile Pacific Lamprey and American Eel

Robert Mueller, Stephanie Liss, and Z. Daniel Deng

Earth Systems Science Division,
Pacific Northwest National Laboratory
October 2018

jove



- 15.0 mm Injectable AT
- 12.5 mm PIT tag
- 12.0 mm ELAT

Pilot Field Trial of the Juvenile Lamprey/Eel Tag and RME Plan to Guide Future Juvenile Pacific Lamprey Acoustic Telemetry Studies

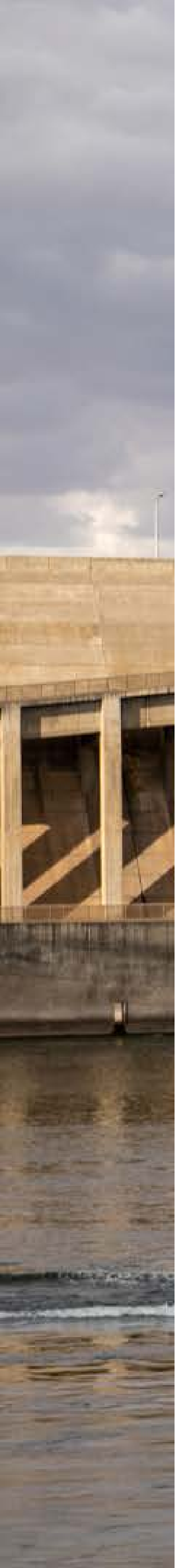
February 2018

ZD Deng
RP Mueller
JJ Martinez
H Li
KA Deters
AH Colotelo
PS Titzler
J Lu
T Fu
JS Cable
JM Hubbard

PNNL-27295

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

U.S. DEPARTMENT OF ENERGY
Prepared for the U.S. Department of Energy under Contract DE-AC05-76RL01830



Pacific Northwest
NATIONAL LABORATORY

ELAT Implantation in Juvenile Chinook Salmon

- Fischer et al. 2019
  - ELAT pilot lab study
    - ✓ Survival
    - ✓ Tag Retention
    - ✓ Growth

    } ELAT only
  - Results
    - ✓ 90% survival after 30 days
      - 62 mm fork length
      - 2.4–2.8 grams
      - 4.1% tag burden
    - ✓ Smallest survived fish: 54 mm (1.8 grams; 4.9% tag burden)
  - Recommendation: a follow-up tag effects lab study
    - ✓ Greater number of fish at smaller sizes
    - ✓ Evaluate additional tag effects metrics

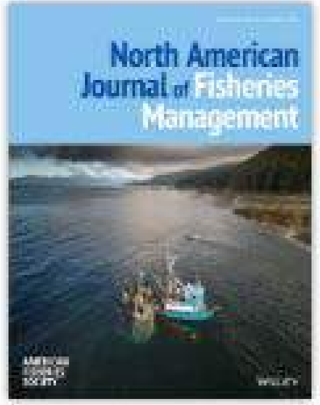
North American Journal of Fisheries Management

Management Brief

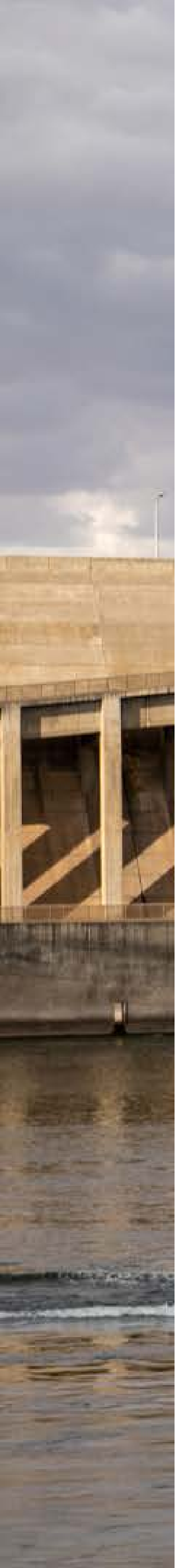
How Small Can We Go? Evaluating Survival, Tag Retention, and Growth of Juvenile Chinook Salmon Implanted with a New Acoustic Microtag

Eric S. Fischer, Shannon E. Blackburn, Stephanie A. Liss, James S. Hughes, Huidong Li, Zhiqun Daniel Deng

First published: 06 November 2019 | https://doi.org/10.1002/nafm.10367



Volume 39, Issue 6
December 2019
Pages 1329-1336

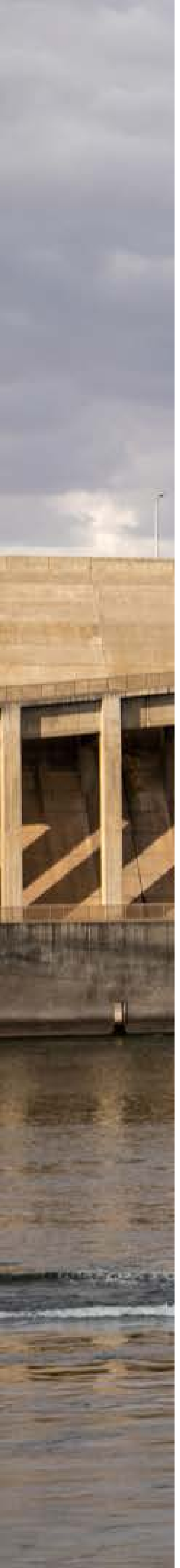


Recommendation:
Follow-up Tag Effects Lab Study

- Differences between the two studies

	Fischer et al. 2019	
Tag Effects Metric	Sample Size	Size Range (mm fork length)
Survival, tag retention, growth	97	52–99

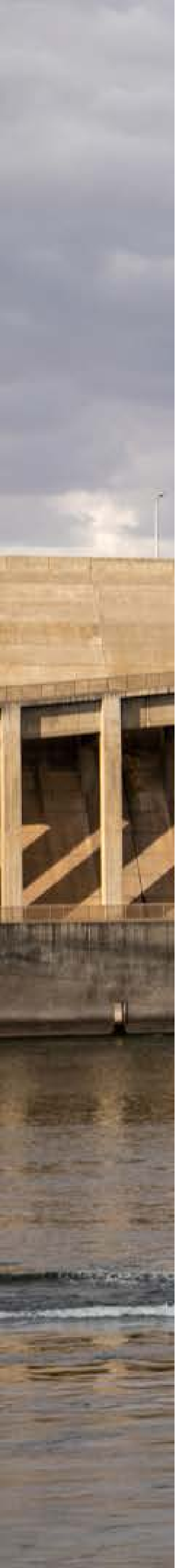
54 mm = smallest survived fish



Recommendation: Follow-up Tag Effects Lab Study

- Differences between the two studies

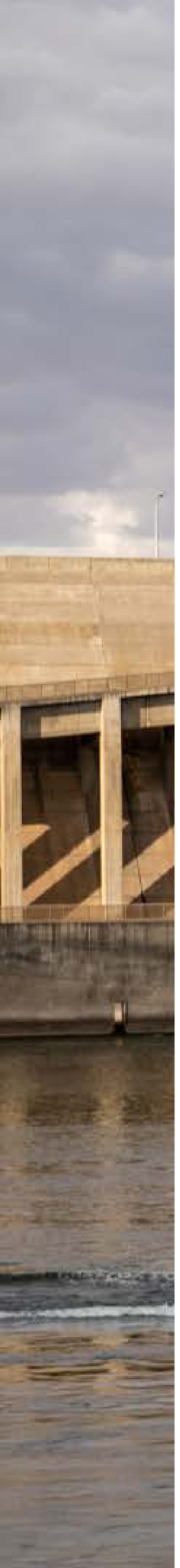
	Fischer et al. 2019		New Study	
Tag Effects Metric	Sample Size	Size Range (mm fork length)	Sample Size	Size Range (mm fork length)
Survival, tag retention, growth	97	52–99	519	36–99



Recommendation: Follow-up Tag Effects Lab Study

- Differences between the two studies

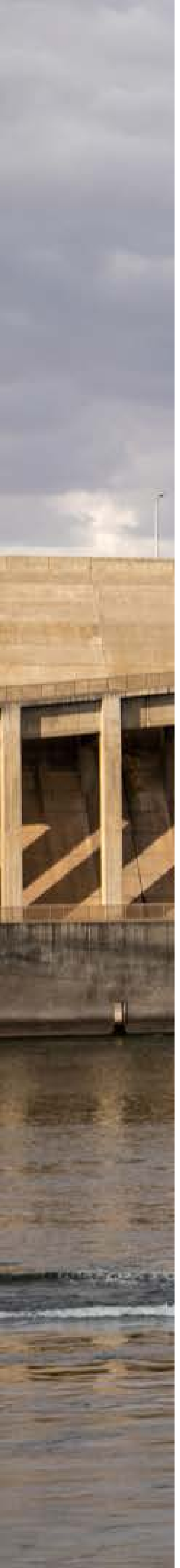
	Fischer et al. 2019		New Study	
Tag Effects Metric	Sample Size	Size Range (mm fork length)	Sample Size	Size Range (mm fork length)
Survival, tag retention, growth	97	52–99	519	36–99
Swimming performance	–	–	241	40–99



Recommendation:
Follow-up Tag Effects Lab Study

- Differences between the two studies

	Fischer et al. 2019		New Study	
Tag Effects Metric	Sample Size	Size Range (mm fork length)	Sample Size	Size Range (mm fork length)
Survival, tag retention, growth	97	52–99	519	36–99
Swimming performance	–	–	241	40–99
Total	97	52–99	760	36–99



What is the Minimum Size for Chinook Salmon that Can be Tagged with the ELAT?

Survival, tag retention, growth study

50-day holding period

- 12 °C
  - Tagged: *n*=130
  - Controls: *n*=131
- 17 °C
  - Tagged: *n*=128
  - Controls: *n*=130

N = 519

36–99 mm FL = size range of study fish

Swimming performance study

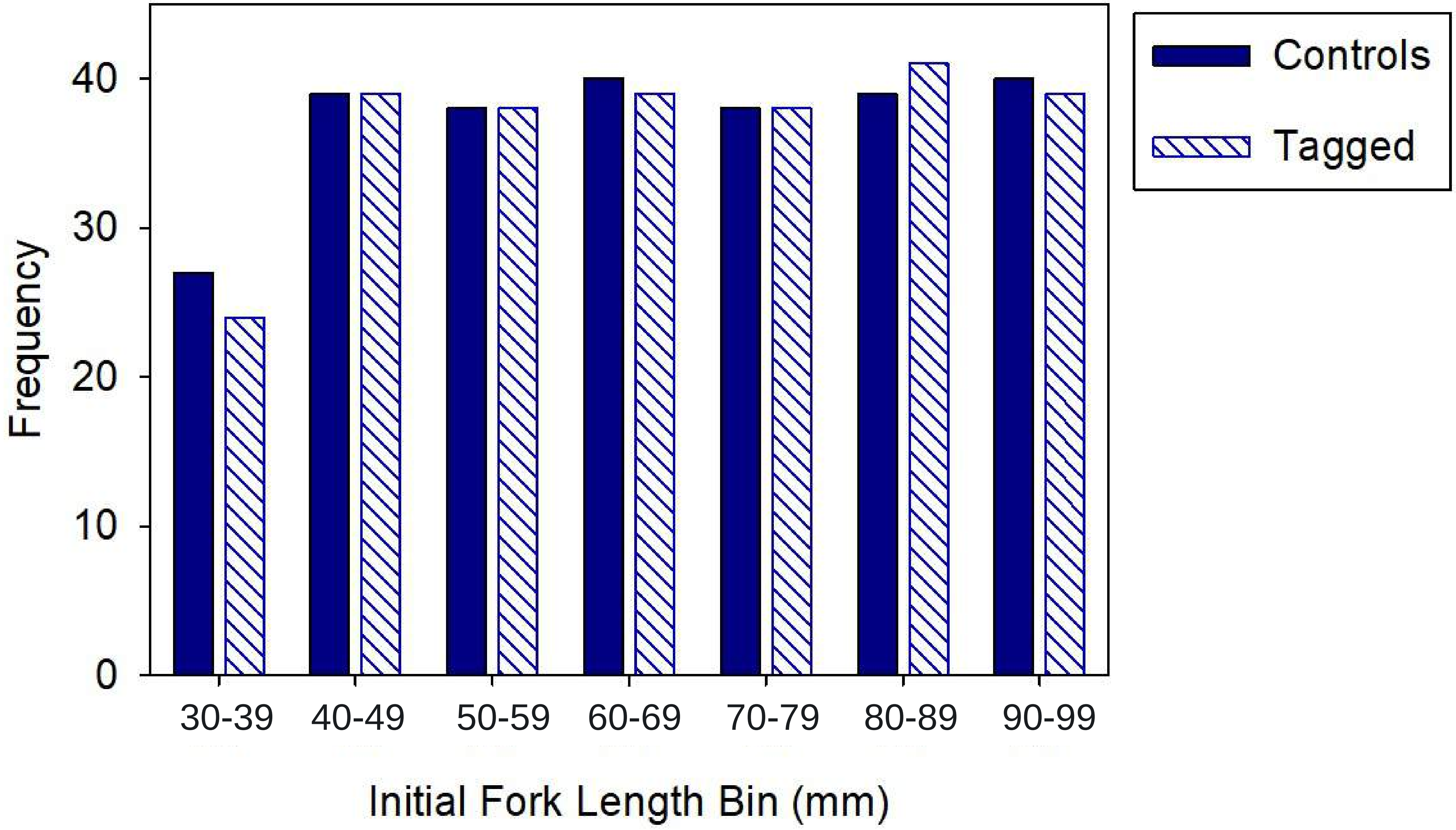
Critical swimming speed (U_{crit})

- 12 °C
  - Tagged: *n*=60
  - Controls: *n*=61
- 17 °C
  - Tagged: *n*=60
  - Controls: *n*=60

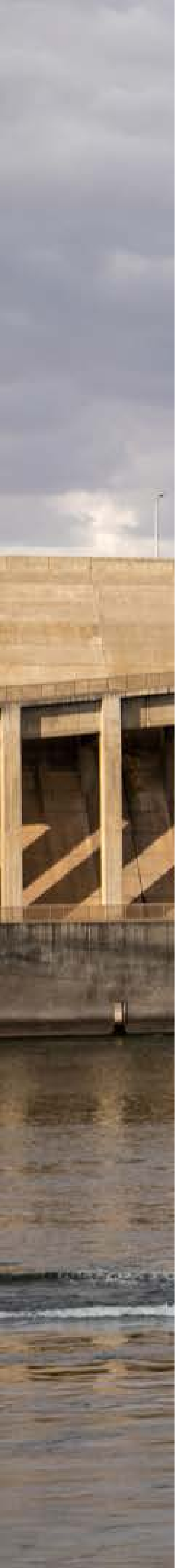
N = 241

40–99 mm FL = size range of study fish

Fish Evenly Distributed Across Size Range*

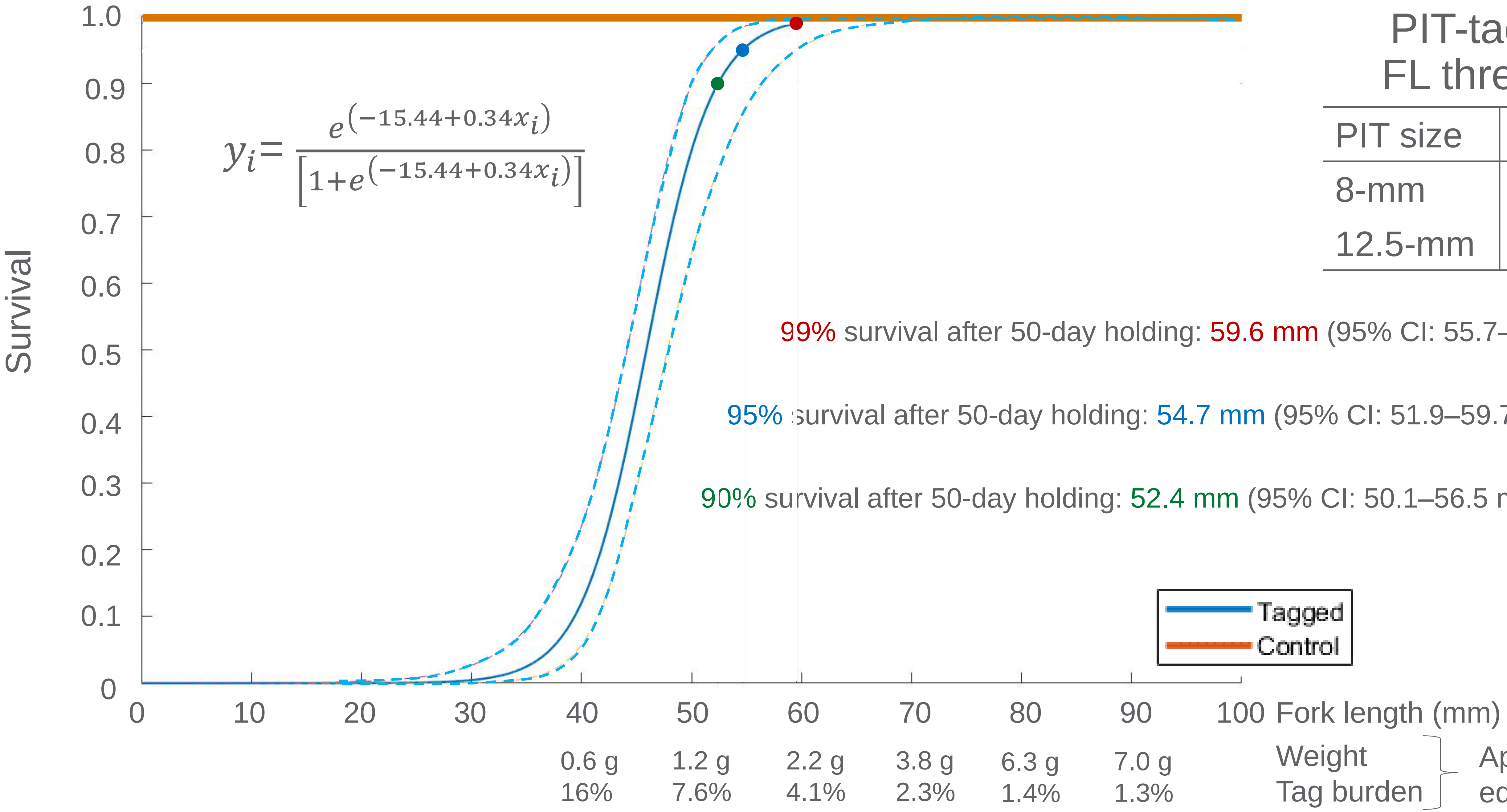


*No difference in temperatures: data combined.



Pacific Northwest NATIONAL LABORATORY

Statistical Results: Conservative Threshold = 60 mm

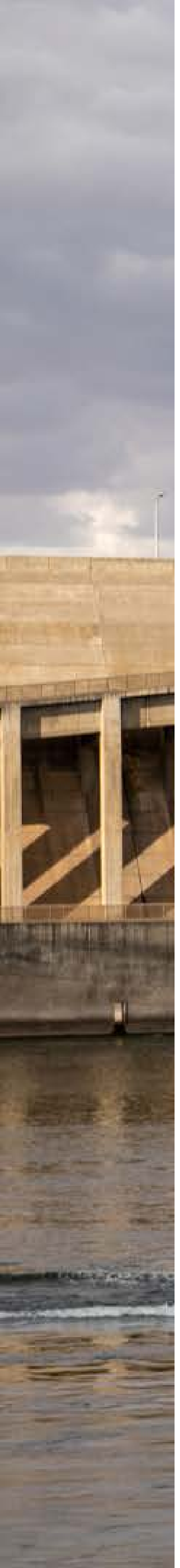


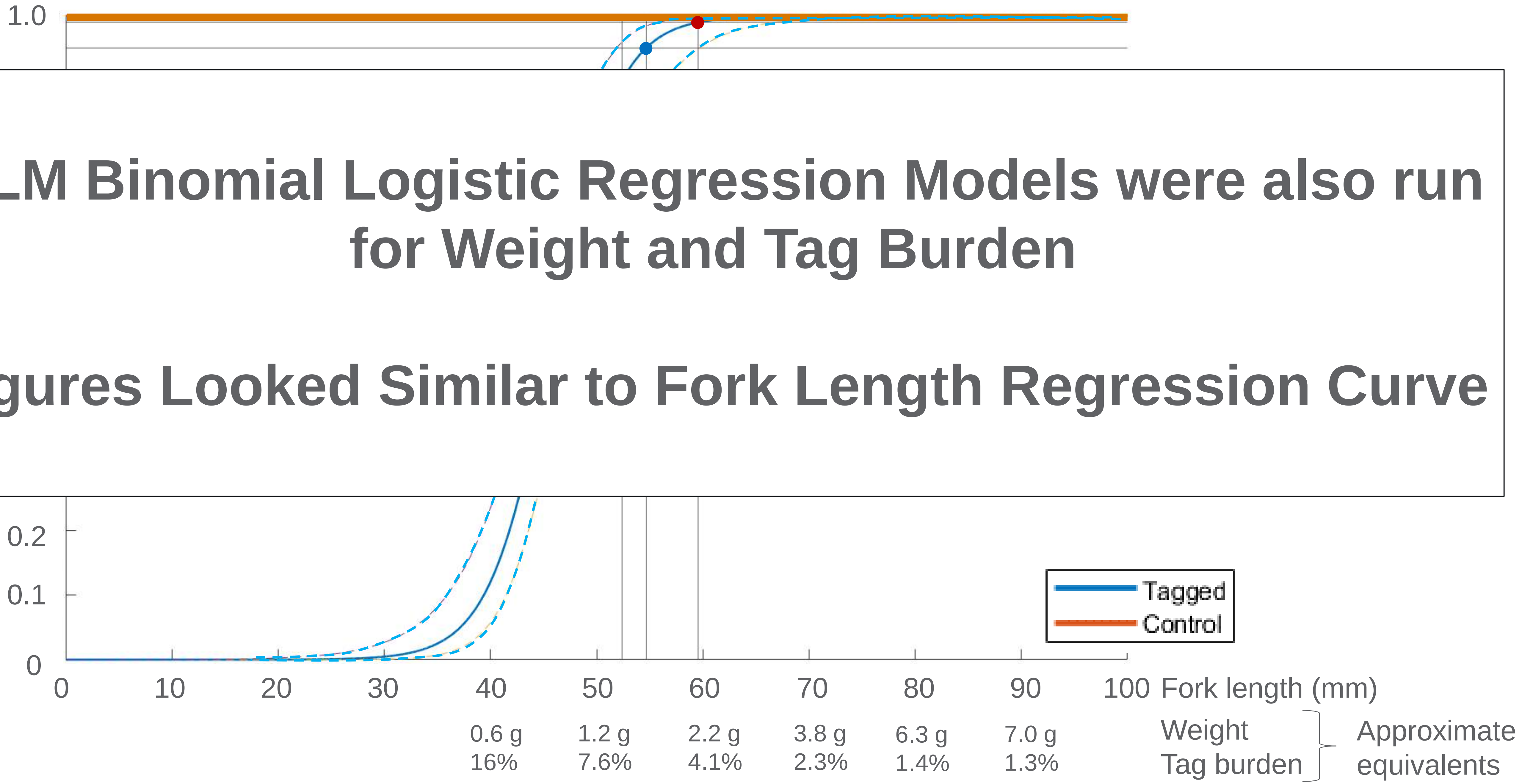
$$y_i = \frac{e^{(-15.44+0.34x_i)}}{\left[1+e^{(-15.44+0.34x_i)}\right]}$$

Recommended PIT-tagging FL threshold

PIT size	Fish size
8-mm	55 mm
12.5-mm	65 mm

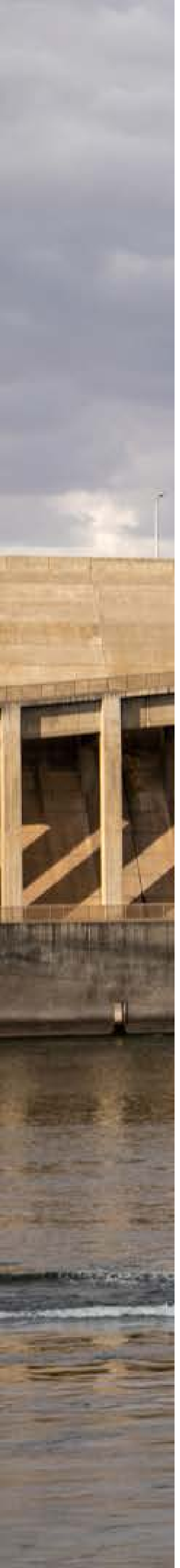
Statistical Results: Conservative Threshold = 60 mm





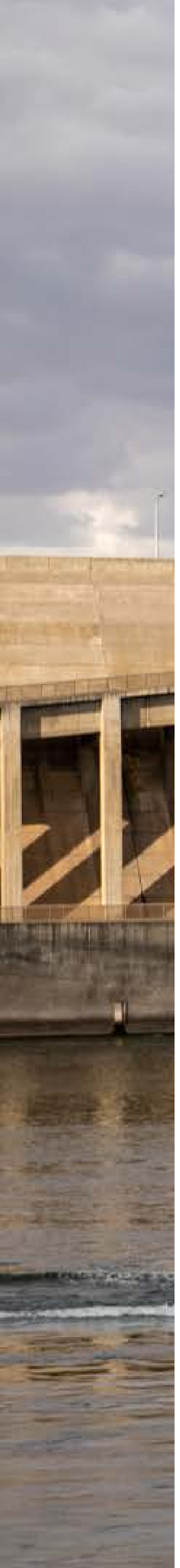
GLM Binomial Logistic Regression Models were also run for Weight and Tag Burden

Figures Looked Similar to Fork Length Regression Curve



Length, Weight and Tag Burden Results from GLMs to Fit a Variety of Study Objectives

Post-Tagging Survival (50 d)	Metric	95% CI
90%	53 mm FL	50–57 mm
	1.5 grams	1.3–1.9 g
	6.8% tag burden	5.2–7.9%
95%	55 mm FL	52–60 mm
	1.6 grams	1.4–2.1 g
	5.4% tag burden	3.4–6.7%
99%	60 mm FL	56–67 mm
	2.0 grams	1.7–2.8 g
	2.3% tag burden	0.0–4.1%

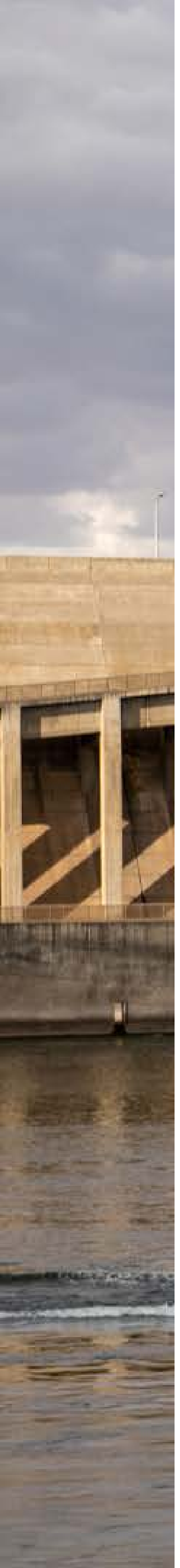


Survival Study

Biological Results:
All fish ≥ 58 mm survived and retained their ELAT

Initial (day 0) measurements of the five largest fish that died or expelled their ELAT in the survival study, and the number of days post-tagging it occurred.

Count	Day post-tagging	Fork length (mm)	Weight (g)	Tag burden (%)	Mechanism
1	6	51	1.5	5.9	Died
2	15	55	1.6	5.5	Died
3	18	51	1.4	6.3	Expelled ELAT
4	27	54	1.5	5.9	Expelled ELAT
5	29	57	1.7	5.2	Died



Pacific Northwest NATIONAL LABORATORY

Biological Results:
All fish ≥ 58 mm survived and retained their ELAT

Initial (day 0) measurements of the five largest fish that died or expelled their ELAT in the survival study, and the number of days post-tagging it occurred.

Count	Day post-tagging	Fork length (mm)	Weight (g)	Tag burden (%)	Mechanism
~~1~~	~~6~~	~~51~~	~~1.5~~	~~5.9~~	~~Died~~
2	15	55	1.6	5.5	Died
~~3~~	~~18~~	~~51~~	~~1.4~~	~~6.3~~	~~Expelled ELAT~~
~~4~~	~~27~~	~~54~~	~~1.5~~	~~5.9~~	~~Expelled ELAT~~
5	29	57	1.7	5.2	Died

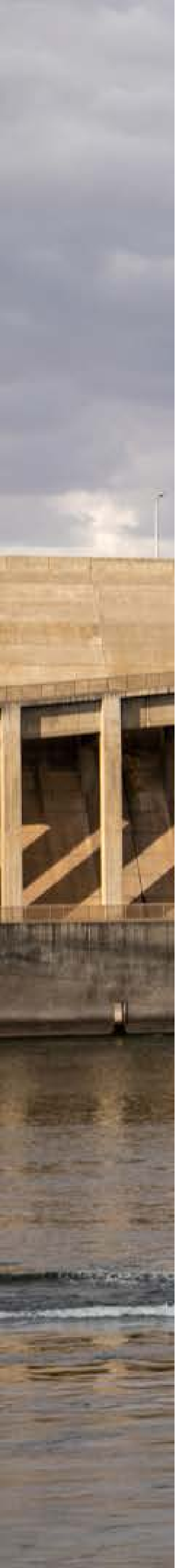
95% survival after 50-day holding threshold = 55 mm

55–59 mm { 31 out of 33 fish: **93.9%**

55–99 mm { 345 out of 347 fish: **99.4%**

Survival Study

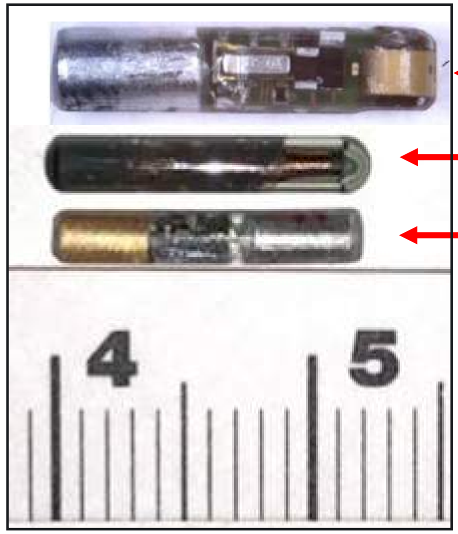
ELAT Allows for Active Monitoring of Small Chinook Salmon



Recommended PIT-tagging FL threshold

PIT size	Fish size
8-mm	55 mm
12.5-mm	65 mm

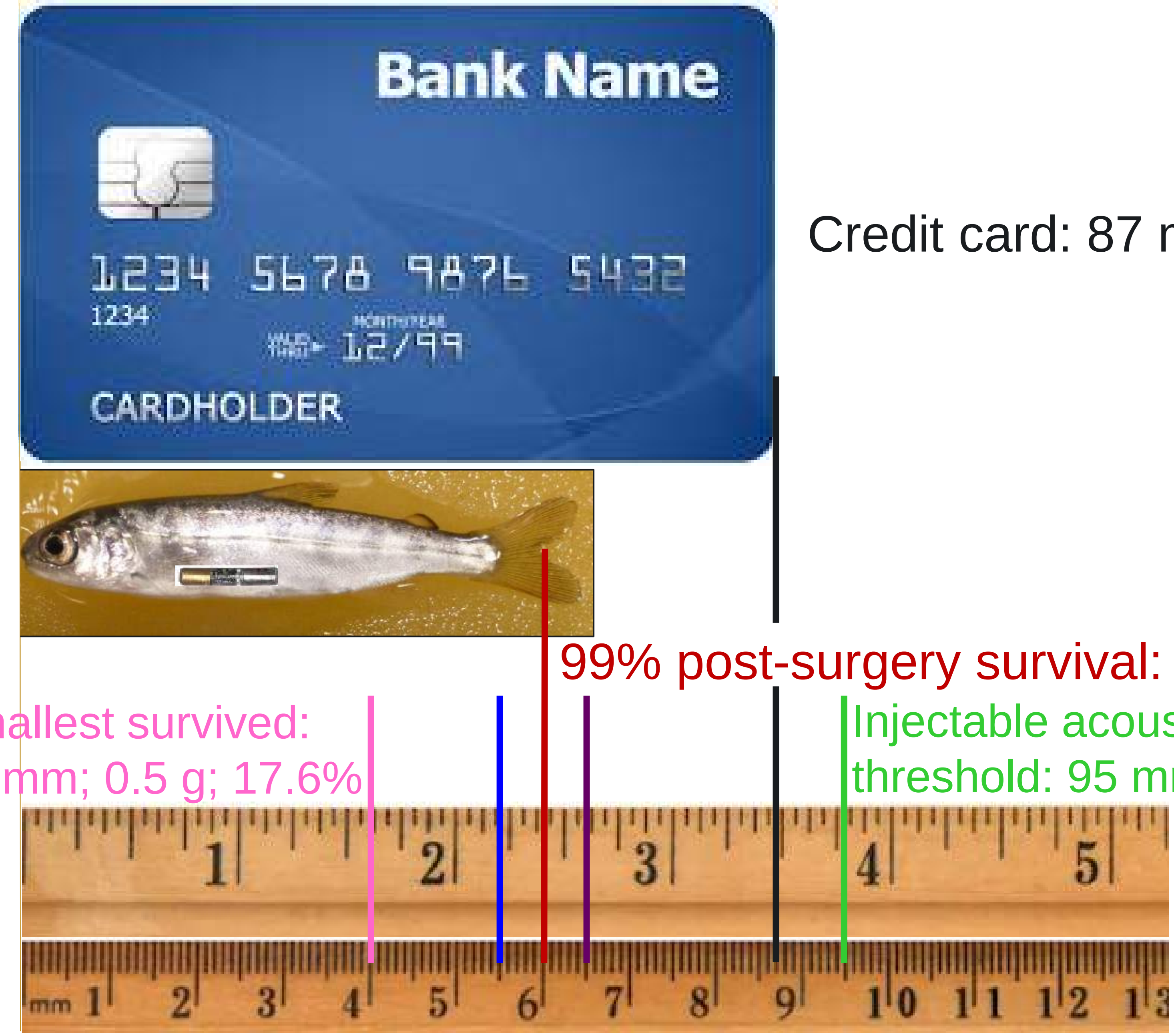
Same as our 95% 50-day post-surgery threshold



←15.0 mm Injectable

←12.5 mm PIT

←12.0 mm ELAT

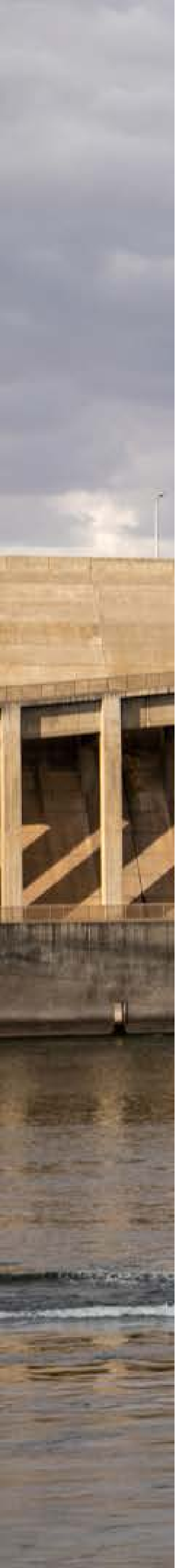


Credit card: 87 mm wide

99% post-surgery survival: 60 mm FL

Smallest survived: 40 mm; 0.5 g; 17.6%

Injectable acoustic transmitter threshold: 95 mm FL



Swimming Performance Study

Critical swimming speed (U_{crit})

Maximum speed at which a fish could swim as velocity increased over time

12 °C

Tagged	Controls
n=60	*n*=61

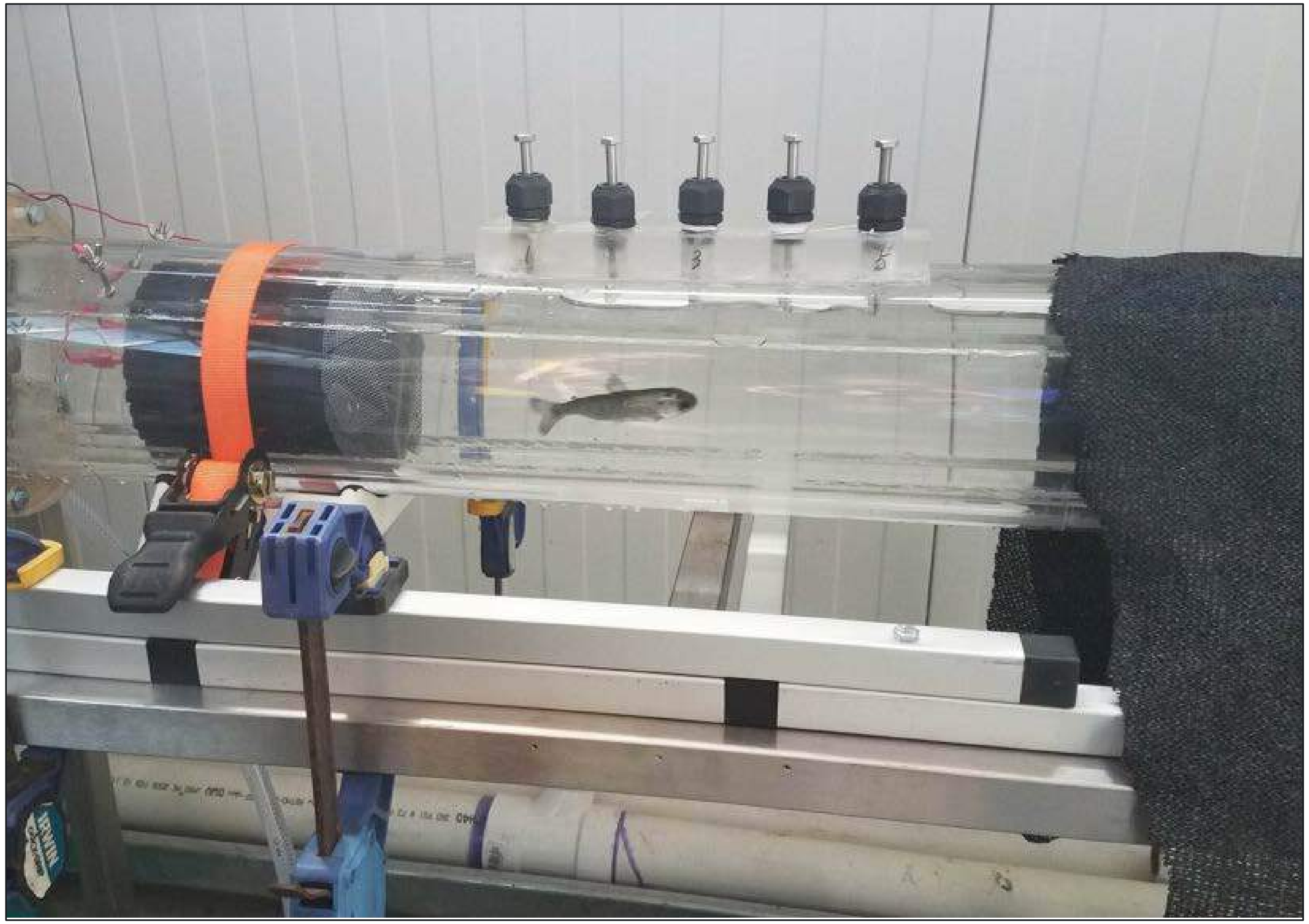
17 °C

Tagged	Controls
n=60	*n*=60

N = 241

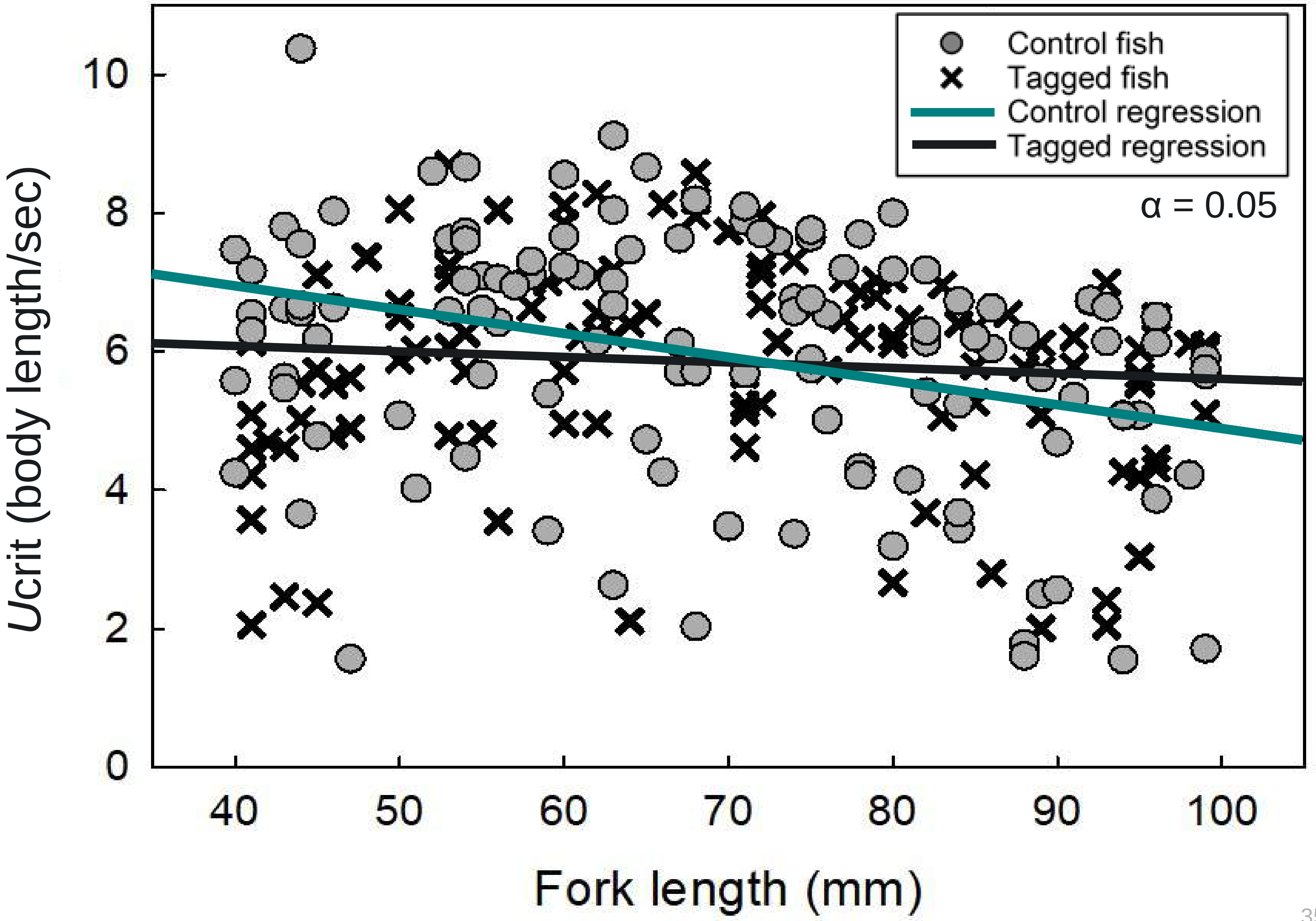
40–99 mm FL = size range of study fish

Fish evenly distributed across size range



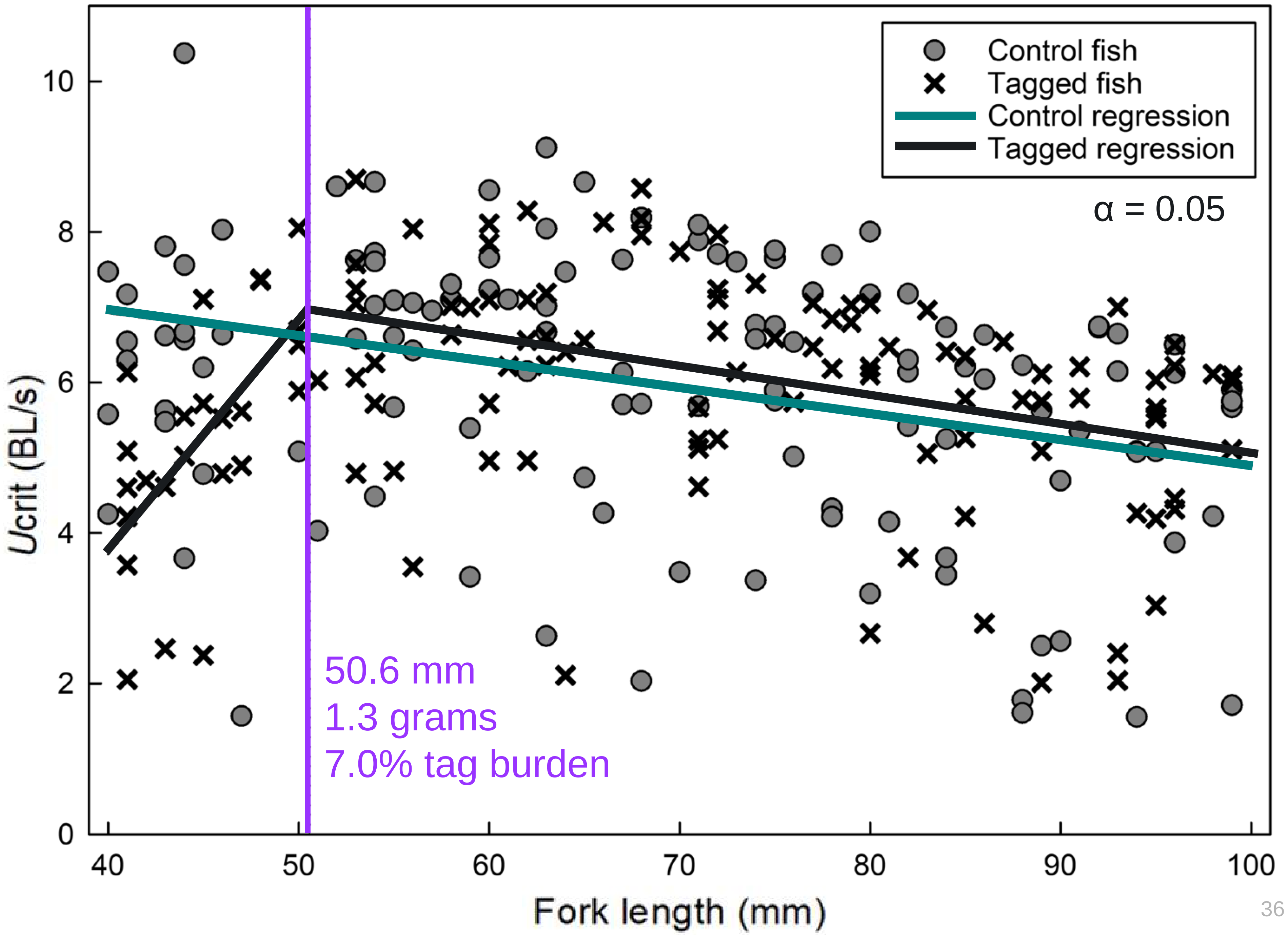
GLM Dependent on Fork Length and Treatment

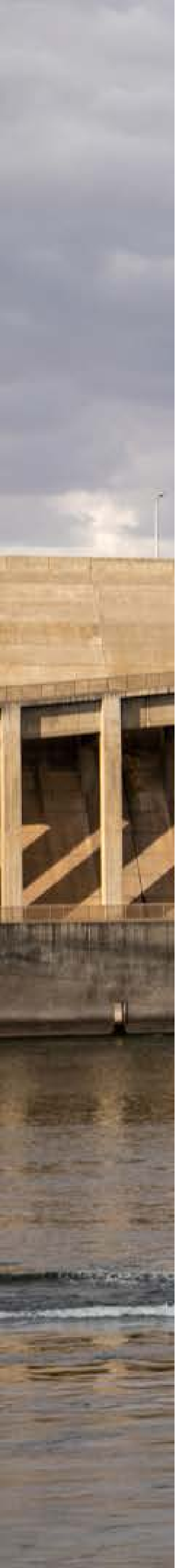
- No difference in temperature: data combined
- GLM performed
  - Dependent on fork length and treatment
- Tagged
  - y = -0.0072x + 6.35
  - R^2 = 0.072
- Control
  - y = -0.03x + 8.28
  - R^2 = 0.109



Significant threshold = 51 mm

- Smallest fish that could be tagged?
  - Spline regression better fit than linear
  - Spline point at 50.6 mm FL
- Swim performance decreased for tagged fish ≤ 50.6 mm FL





What is the Minimum Size for Chinook Salmon that Can be Tagged with the ELAT?

Survival, tag retention, growth study

90% 50-day survival = 53 mm FL

95% 50-day survival = 55 mm FL

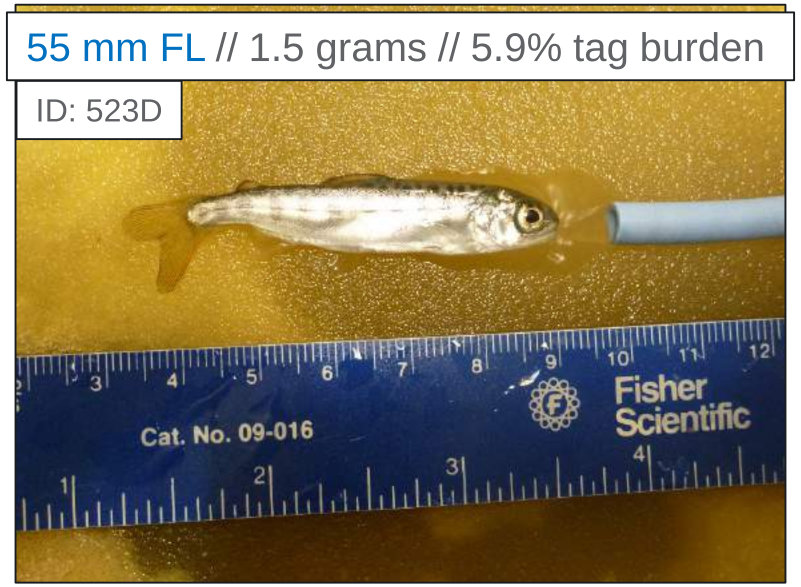
99% 50-day survival = 60 mm FL

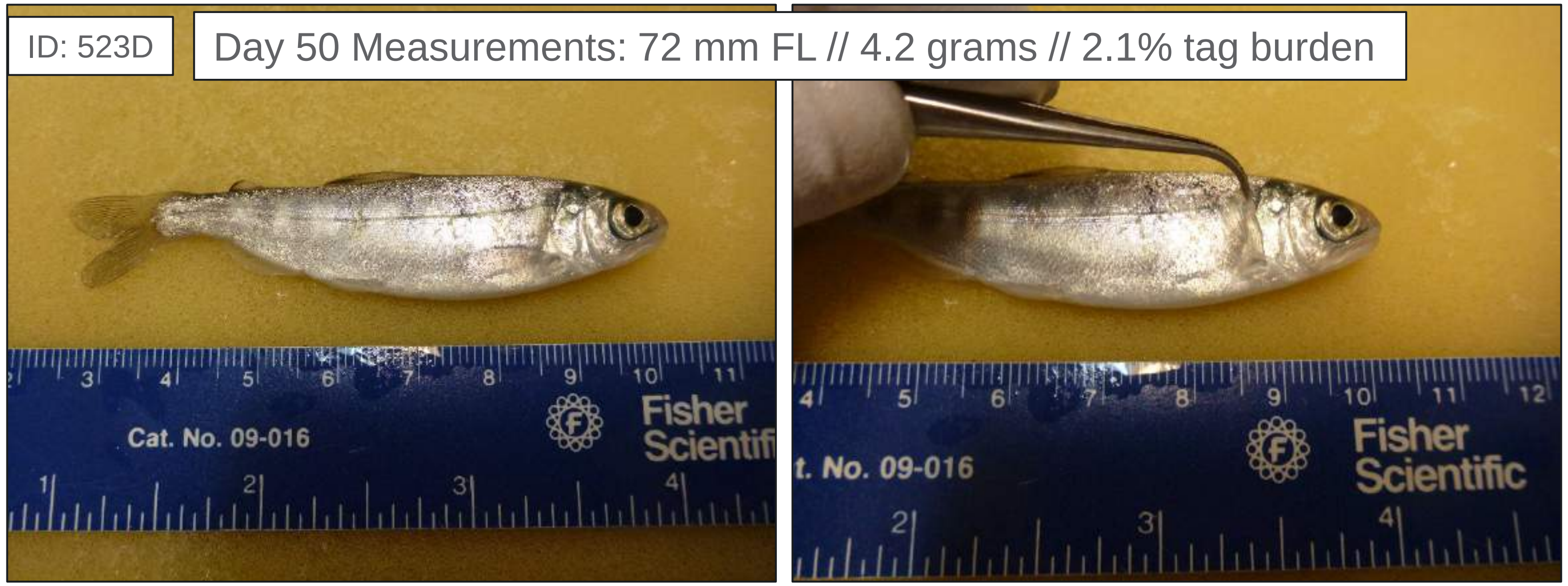
Swimming performance study

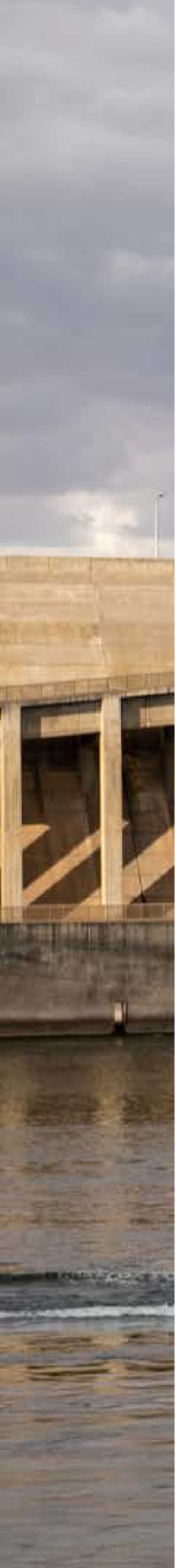
Spline point = 51 mm FL

Potentially less than 90% survival

55 mm fork length

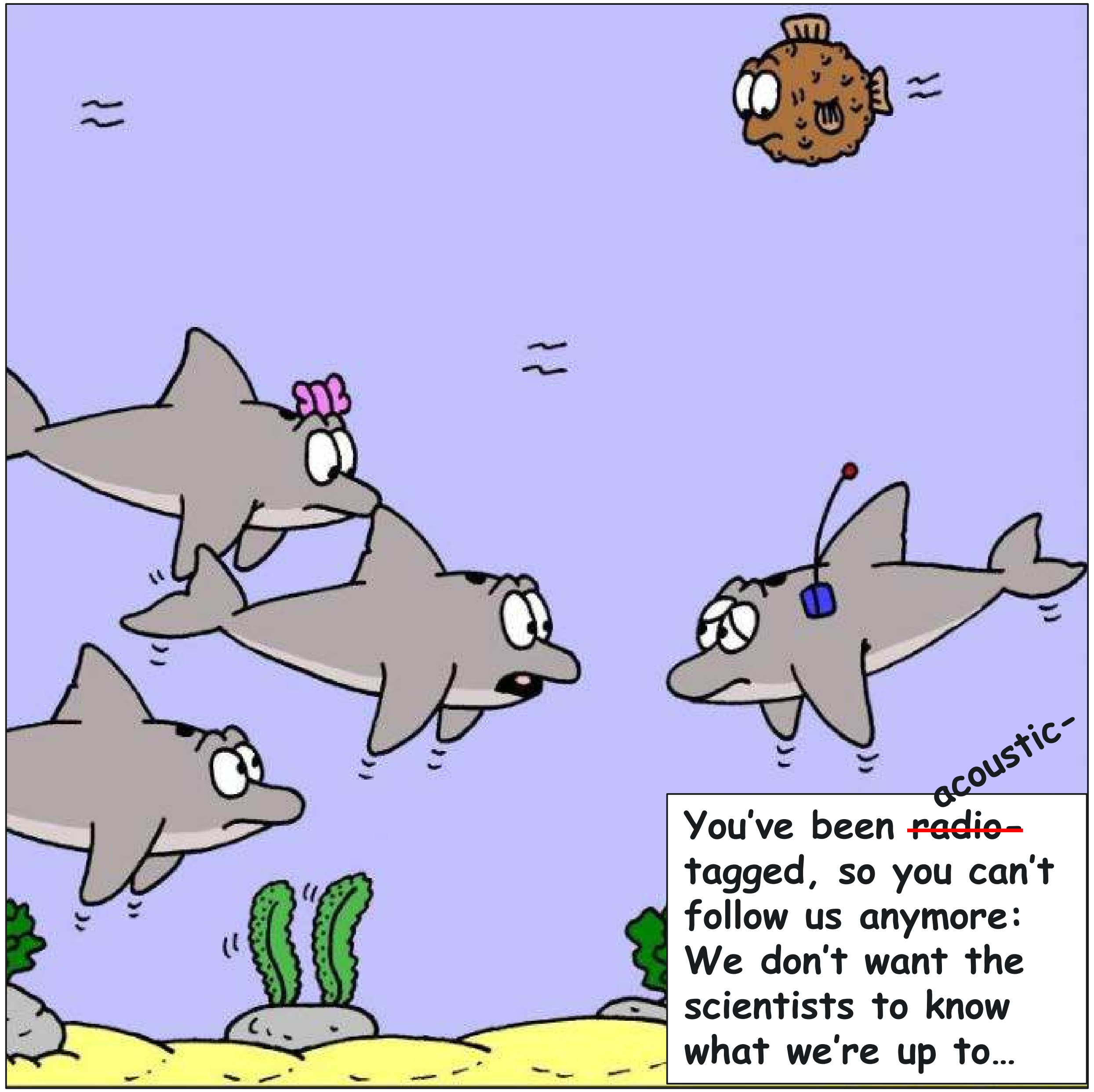


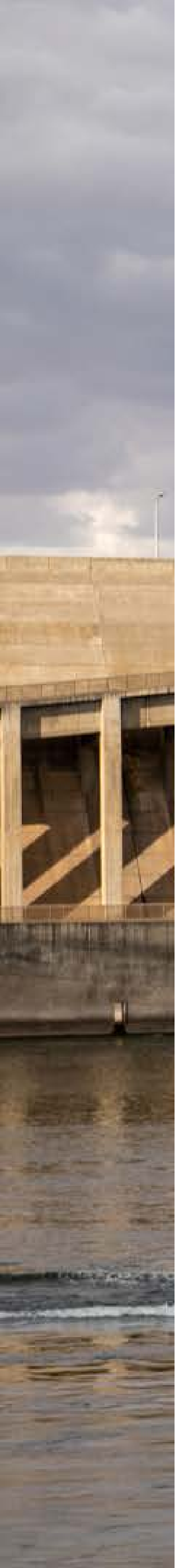




Where Do We Go From Here?

- Get the word out: publication in prep
- Potential field trials using lab study results
  - Variety of post-surgery survival thresholds to pick and choose what fits best for objectives
  - Tiny acoustic tag
    - ✓ Viable tool for use in the field
    - ✓ Actively track smaller Chinook Salmon
  - No suture = less cost
    - ✓ Fewer supplies
    - ✓ Faster surgery
- Other laboratory tag effects studies
  - Predator avoidance
  - Rapid decompression/barotrauma
  - Shear forces



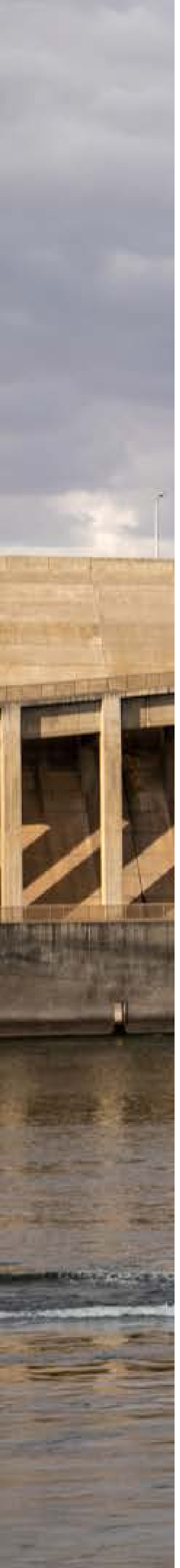


Pacific Northwest
NATIONAL LABORATORY

Acknowledgements

- Pacific Northwest National Laboratory
  - ELAT Study Funding
    - ✓ Laboratory Directed Research and Development
  - ELAT Study Co-Authors
    - ✓ Katherine Znotinas
    - ✓ Shannon Blackburn
    - ✓ Eric Fischer
    - ✓ James Hughes
    - ✓ Huidong Li
    - ✓ Daniel Deng
  - ELAT Study Support Staff
    - ✓ Kate Deters
    - ✓ Kristin Engbrecht
    - ✓ David Geist
    - ✓ Ryan Harnish
    - ✓ Cameron Holt
    - ✓ Jill Janak
    - ✓ Tim Linley
    - ✓ Erin McCann
    - ✓ Bob Mueller
    - ✓ Brett Pflugrath
    - ✓ John Stephenson
    - ✓ Yong Yuan
- U.S. Department of Energy Water Power Technologies Office
- U.S. Army Corps of Engineers
- Electric Power Research Institute
- Grant County Public Utilities District
- Idaho Power Company
- U.S. Bureau of Reclamation
- U.S. Fish and Wildlife Service
- Numerous additional DOE/USACE/PNNL Support Staff

Research for the ELAT study was conducted in compliance with a protocol approved by PNNL's Institutional Animal Care and Use Committee.



Pacific Northwest
NATIONAL LABORATORY

Questions?

http://JSATS.pnnl.gov/