Resource Guide and Literature Review for Addressing the Problem of Tag Predation in Salmonid Studies in the Central Valley of California

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TO: DELTA SCIENCE STEWARDSHIP COUNCIL

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Introduction

Acoustic telemetry is a powerful tool for studying movement and survival of fish in many different environments around the globe (Hussey et al. 2015; Crossin et al. 2017). An advantage of this technology is that study subjects do not need to be physically recaptured after their release and can instead be monitored remotely using acoustic hydrophones and receivers. However, the downside of relying on remote detection is that an acoustic tag may become dissociated from the study subject. One way this dissociation can occur is when a predator consumes the tagged study subject and the tag is transferred to the predator, a phenomenon we term *tag predation*. Tag predation is problematic when consumed tags continue to be detected and the movements of the predator are included in the detection history, providing misleading information regarding the state and behavior of the study subject (Gibson et al. 2015; Klinard and Matley 2020; Buchanan and Whitlock 2022). The severity of potential bias induced by tag predation depends on the biological and behavioral attributes of study subjects and predator species as well as on the study design and objectives. For example, studies of survival, movement, or behavior will be affected when the predator movement is on a comparable spatial scale as the study subject; behavioral and small-scale survival studies are likely to be affected by tag predation by resident predators with small home ranges, whereas larger-scale survival studies are likely to be affected by migratory predators or those with large home ranges (Klinard and Matley 2020). In such cases, removing detections of predators from the detection history is necessary to avoid biased study results. We use the term *predator filter* to refer to any formal approach for identifying and removing invalid portions of detection histories due to tag predation. This type of filtering follows and complements other data filters used to remove false positive detections due to technical mishaps such as tag collision (Heupel et al. 2006).

Tag predation is recognized as a significant impediment to studying anadromous salmonids in California's Central Valley, specifically Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss;* Buchanan et al. 2013). In one of the more dramatic examples of this issue, Buchanan et al. (2018) reported a 120% difference in estimated survival of fall-run Chinook Salmon in the San Joaquin Delta with and without a predator filter (filtered estimate 0.05; unfiltered estimate 0.11). A variety of filtering approaches have been developed for addressing this issue since acoustic telemetry studies began in the Central Valley over a decade ago (Vogel 2010; Buchanan and Whitlock 2022). However, there is a lack of guidance on when filtering is required and best practices for carrying it out. This has resulted in the development of multiple approaches to filtering and ambiguity in comparing results across different studies (Buchanan and Whitlock 2022). Much can be gained by considering past approaches to dealing with this issue, as well as examining past studies for information on movement capabilities and behavior of both salmonids and their predators in this region.

This document is a compilation and synthesis of the many references relevant to tag predation in salmonid studies in the Central Valley, as well as pertinent studies outside the region. Our aim is to provide researchers in the Central Valley with a set of resources that will help them contend with this issue in their investigations. This is the first product of a larger interagency research project devoted to developing a standard operating procedure for applying predator filters to acoustic telemetry data in the Central Valley. Additional objectives of the project include a metanalysis of past smolt and known predator telemetry data for the purpose of refining filtering approaches, and development of a software package that implements recommended filtering approaches and analysis tools.

How to Use This Document

This document is designed to save researchers time by organizing references using multiple formats to facilitate quick identification of relevant studies based on species, region in the Central Valley, or filtering approach. There are four main sections: (1) background, (2) categorization tables, (3) annotated bibliography, and (4) appendices.

The background section provides a framework for understanding the various types of filters and their usage and establishes a consistent terminology used throughout the document. This section also briefly outlines the history and types of acoustic telemetry studies undertaken in the recent past in the Sacramento River, San Joaquin River, and Delta (i.e., the transition zone between the freshwater regions of the Sacramento and San Joaquin rivers and the brackish and saltwater bays leading to the Pacific Ocean).

The categorization tables (Tables 1–3) that follow the background allow the reader to quickly identify references based on species, region, or predator filter type. Table 1 identifies acoustic telemetry studies on juvenile salmonids in the Central Valley of California that either describe the use of a predator filter or are explicitly focused on the problem of tag predation. Table 2 focuses on known predators of juvenile salmonids in the Central Valley of California; it identifies telemetry studies involving known predators and studies where predation of outmigrating salmonids was the focus of investigation (e.g., tethering studies). Table 3 identifies references for several methodological approaches that have been used to identify and address predated tags, both within and outside of the Central Valley of California. Methods are categorized based on type of analysis (statistics, machine learning, expert opinion) and key attributes of the approach. The intention behind these tables is that prospective researchers will be able to adapt filtering approaches from past studies for their purposes.

The annotated bibliography section contains citations and short summaries tailored to the tag predation issue, sorted alphabetically by author and divided between studies within and outside of the Central Valley. The within-Central Valley section provides a listing of acoustic telemetry studies that explicitly discussed and dealt with the problem of tag predation. The section containing references outside of the Central Valley is intended to provide additional information on approaches and technologies that are directly relevant to addressing tag predation problems and could be drawn upon for future investigations within the Central Valley. While tag predation is frequently acknowledged by studies in the Central Valley, the details of how it was handled in specific cases are often secondary to the main finding of the study (e.g., survival, migration rate, etc.). Our summaries in the annotated bibliography section delve into the decisions that researchers made in addressing the issue, saving researchers time that would otherwise be spent combing through the methods section and appendices of manuscripts and reports. Each resource is assigned keywords that characterize different attributes of the study (location, focal species, etc.); information on the type of predator filter used is also supplied where applicable.

The appendix includes a table of detection history *metrics* and a glossary of tag predation-related terms. A key step in developing a predator filter is selecting and defining metrics that characterize the apparent pattern of behavior of each tag in the study and that will be used to distinguish study subjects from predators. A table in the appendix aids prospective researchers in this task by providing an extensive list of metrics that others have used in the past. The metrics table lists those used by the bibliography references that addressed tag predation and provides the definition, spatiotemporal scale, and references for each metric. The glossary corresponds to concepts and filter types discussed in the background section and used in the keyword labels and summary text throughout the bibliography.

Background on Predator Filters

This section defines and discusses the various types of predator filters that have been used in the past, both within and outside of the Central Valley. Here, we establish the terminology that will be used throughout the rest of the document. Bolded text indicates keywords whose definitions can be quickly looked up in the Glossary section of the Appendix.

What is a predator filter?

A predator filter can be any formalized ruleset, statistical procedure, or algorithm used to identify whether, and optionally when, a tagged study subject was predated. Predator filters differ greatly in their complexity, subjectivity, and interpretability and in the effort required by the researcher. They are used on data sets that have already been screened for false positives that can arise from signal misreads and before statistical analysis focusing on the primary study objective(s). A predator filter can be applied in a manner that excludes only a portion of, or the entirety of, a tag's detection record from the analysis. We organize filtering methods based on the level at which tag histories are examined for suspicious behavior: ***tag-level*** filters involve summarization of the full detection history or track indicating predation at some point before the last detection, ***event-level*** filters identify time of tag predation between detection events, and ***track-level*** filters identify predation events using data sets containing time-indexed coordinate information (also known as multi-dimensional positioning array studies).

Different types of predator filters

We divide the types of filters into three main approaches as described by Buchanan and Whitlock (2022): (1) ***rule-based filters***, (2) ***pattern recognition filters***, and (3) ***hybrid filters***. Rule-based filters consist of a set of predefined thresholds for the capabilities or expected behavior of subjects that are used to flag suspicious detection events or full histories. Rule-based filters encompass a broad range of complexity, from a small set of rules with no tolerance for violations to a score-based and spatially explicit system applied at the level of detection events (Buchanan et al. 2018; Johnston et al. 2018). The thresholds (rules) themselves are defined by past research and expert judgement. Pattern recognition filters use automated statistical and machine learning procedures to identify outliers or clusters of aberrant tags or detections, which are then flagged as suspicious (Gibson et al. 2015; Daniels et al. 2018; Perry et al. 2018). There are many automated procedures for performing classification tasks. **Supervised learning** is a robust approach for creating a classification tool that is based on "training" an algorithm using labeled input data (e.g., using physical recapture of study subjects or confirmed predation events to classify what is and is not a smolt-like pattern of movement; Berry et al. 2019). It is uncommon for a researcher applying a pattern recognition filter to have a sufficient number of recaptured or recovered study subjects required for this type of procedure, and thus ***unsupervised learning*** approaches are often used instead. Unsupervised learning is a method for classifying subjects which partitions data sets into groups based on a multivariate dissimilarity measure. In a predator filter context, this means that a full data set of tag detection histories or tracks is assumed to contain a mixture of both valid study subjects and predators, and multivariate data describing tag movement are used to differentiate groups or identify aberrant data points.

Most of the procedures that have been used to filter out predated tags prior to analysis rely on two core assumptions: (1) that the behavior of study subjects and their predators are distinct, and (2) that differences in movement or residence pattern are detectable on the scale of the analysis. We describe these types of filters as being ***behavior-based***, and this category encompasses all the filtering approaches discussed above. An alternative approach to identifying compromised tags is to look for a change in the individual tag's signal after consumption occurs, which we term a ***signal-based*** type of filter. Conventional acoustic tags have not been shown to reliably produce a perceivably different signal once the study subject has been consumed (e.g., a reduction in signal strength or altered signal; Vogel 2010). However, there is a new type of acoustic tag, known as a ***predation tag***, that is specially designed to alter the signal output (e.g., change the tag ID) after a predation event. For example, one type of predation tag uses a polymer coating that dissolves after entering the acidic digestive tract of a predator, triggering a switch to the "predation" signal (acid-sensitive predation tag; Weinz et al. 2020). Another type of tag carries an accelerometer to detect loss of orientation during the predation event (Lennox et al. 2021). Predation tags hold great promise in facilitating robust classification approaches such as supervised learning but are not without issues. The "predation" signal may be triggered falsely or after a variable length of time following consumption depending on factors such as temperature, predator species, and amount of food in the gut, or tags may be too large for certain species and life stages (Weinz et al. 2020; Lennox et al. 2021). At the time of writing, some upcoming salmonid studies in the Central Valley have been designed to use acid-sensitive predation tags and so we include references to studies that have used or tested this technology. However, because most studies in the Central Valley have used conventional acoustic tags, we focus primarily on behavior-based approaches to diagnosing tag predation. We anticipate that further development of predation tags and tagging technology in general will contribute to advancement of predator filters in the future.

Acoustic Telemetry Studies and Predator Filters in the Central Valley

Chinook salmon and steelhead populations in California's Central Valley have been exposed to numerous threats related to human settlement including habitat loss and degradation, water diversion, and introduction of nonnative predators (Fisher 1994; Yoshiyama et al. 2000). These factors culminated in several populations being listed as endangered or threatened under the Endangered Species Act in the late 1990s and early 2000s (Williams 2006). Since that time there has been considerable interagency cooperation focused on balancing conservation objectives with human needs, specifically water exports used to provide water for municipal and agricultural needs for much of the state.

Since the mid-2000s, acoustic telemetry technology has been recognized as a valuable tool for studying important facets of salmonid management and conservation in the Sacramento-San Joaquin River system and the tidally influenced zone where the two rivers meet ("Delta" hereafter). Numerous acoustic telemetry studies have been performed that address survival, migration rate, route selection, and barrier effectiveness (e.g., Bowen et al. 2009; Perry et al. 2010, 2014; SJRGA 2013; Buchanan et al. 2021). Although the tag and receiver technologies employed have changed through time, these studies have developed a largely consistent spatial network of acoustic receiver stations and have produced important discoveries concerning the relationships between fish survival and migration and key environmental, biotic, and management factors (e.g., weather conditions, river flow, water chemistry, and pumping rates at water export facilities). While acoustic telemetry has provided many benefits, these studies have also been subject to the problem of tag predation, and the high incidence of predation necessitates that researchers filter their data prior to analysis. The multiple pathways and complex hydrodynamics in the Delta complicate the filtering process. For example, when water speed and direction are influenced by tides, a simple assessment of upstream movement may be inadequate to conclude that predation has occurred.

Diagnosing tag predation in a tidal environment is a challenge that researchers have contended with throughout the past decade and for which they have developed and applied various tools and approaches (see the previous section for a description of predator filter terminology). Vogel (2010) describes an event-level filtering approach which was largely signal-based and which also made use of tagged striped bass (*Morone saxatilis*). Johnston et al. (2018) used a simple example of a rule-based approach which disallowed any apparent upstream movement that was against the tide. SJGRA 2013 and Buchanan et al. (2018) applied a more complex rule-based, event-level filter with region-specific thresholds and which relied on a scoring system. Romine et al. (2014) provided an example of a pattern recognition filter being applied at the track-level, wherein a bivariate mixture model was successfully used to differentiate between smolts and predators. A survival study conducted by Perry et al. (2018) represents one example of a hybrid predator filter, in that a pattern recognition filter in the form of a cluster analysis was performed to look for predator-like movements at the tag level and was then followed by an event-level determination of when in the detection history the suspicious tags were transferred to predators based on expert judgement. Buchanan and Whitlock (2022) applied four different filtering approaches to the same data set, two rule-based filters and two pattern recognition filters.

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Table 1. Telemetry studies of juvenile salmonids in the Central Valley of California that address tag predation, categorized by river, region of the Delta, and species. Spatial extent describes the length of the study reach(s) considered in the investigation.

River	Focal species	Published work	Study aim(s)	Spatial extent
Sacramento River/North Delta	Chinook salmon (*Oncorhynchus tshawytscha*)	Johnston et al. 2018	Survival estimation	Coarse (> 50 km)
	Chinook salmon	Perry et al. 2018	Survival estimation	Coarse (> 50 km)
	Chinook salmon Steelhead (*Oncorhynchus mykiss*)	Romine et al. 2014	Predator filter methodology	Fine-scale 2-D[a] tracking (< 50 km),
San Joaquin River/South Delta	Steelhead	Buchanan 2018	Survival estimation	Coarse (> 50 km)
	Chinook salmon	Buchanan et al. 2018	Survival estimation	Coarse (> 50 km)
	Steelhead	Buchanan et al. 2021	Survival estimation	Coarse (> 50 km)
	Chinook salmon	Buchanan and Whitlock 2022	Predator filter methodology	Coarse (> 50 km)
	Chinook salmon	Hause 2020	Survival estimation	Coarse (> 50 km)
	Chinook salmon	SJGRA 2013	Survival estimation	Coarse (> 50 km)
	Chinook salmon Striped bass (*Morone saxatilis*)	Vogel 2010	Movement	Coarse (> 50 km) & Near-field tracking (< 50 km)
	Chinook salmon Striped bass Largemouth bass (*Micropterus salmoides*) White catfish (*Ameiurus catus*)	Vogel 2011	Predatory fish movement concurrent with survival estimation	Coarse (> 50 km)

[a] 2-D = 2-dimensional

Table 2. Studies that address, in some manner, predators and predation of anadromous salmonids in the California Central Valley categorized by species and study methodology.

Published work	**Predator species**	**Methodology**
Buchanan 2018	• Channel catfish (*Ictalurus punctatus*) • Largemouth bass (*Micropterus salmoides*) • Striped bass (*Morone saxatilis*) • White catfish (*Ameiurus catus*)	Acoustic telemetry; detection/non-detection
Buchanan and Whitlock 2022	• Channel catfish • Largemouth bass • Striped bass • White catfish	Acoustic telemetry; detection/non-detection
Cavallo et al. 2013	• 15 non-native taxonomic groups (*Alosa*, *Ameiurus*, *Lepomis*, *Micropterus*, and *Pomoxis* spp.)	Electrofishing surveys and removal
Cutter et al. 2017	• Unidentified predators	Acoustic sonar surveys
Loomis 2019	• Brown bullhead (*Ameiurus nebulosus*) • Black crappie (*Pomoxis nigromaculatus*) • Largemouth bass • Redear sunfish (*Lepomis microlophus*) • Sacramento pikeminnow (*Ptychocheilus grandis*) • Striped bass • White catfish	Acoustic sonar surveys
Michel et al. 2020a	• Unidentified predators	Tethering study
Michel et al. 2020b	• Brown bullhead • Black crappie • Channel catfish • Green sunfish (*Lepomis cyanellus*) • Largemouth bass • Smallmouth bass (*Micropterus dolomieu*) • Spotted bass (*Micropterus punctulatus*) • Striped bass • Warmouth (*Lepomis gulosus*) • White catfish	Tethering study; electrofishing surveys and removal

	• White crappie (*Pomoxis annularis*)	
Romine et al. 2014	• Smallmouth bass • Spotted bass • Striped bass	Acoustic telemetry; 2-D[a] tracking
Vogel 2011	• Striped bass • Largemouth bass • White Catfish	Acoustic telemetry; 2-D tracking

[a] 2-D = 2-dimensional

Table 3. Specification of predator filters in analyses including approach, quantitative method, classification scale, and data type.

Source	Filter type	Quantitative method	Classification scale	Data type	Description
Buchanan 2018	Rule-based	Score-based	Tag-level + event-level	Presence/absence	Spatially explicit rule set that also incorporated recaptures
Buchanan et al. 2018	Rule-based	Score-based	Tag-level + event-level	Presence/absence	Spatially explicit rule set
Buchanan et al. 2021	Rule-based	Score-based	Tag-level + event-level	Presence/absence	Spatially explicit rule set
Buchanan and Whitlock 2022	Pattern recognition (single species)	Multivariate, cluster analysis, ordination	Tag-level + event-level	Presence/absence	Ward Hierarchical clustering, Recursive ordination ellipse (ROE)
	Pattern recognition (multi-species)	Multivariate, cluster analysis, ordination	Tag-level + event-level	Presence/absence	Ward Hierarchical clustering, Recursive ordination ellipse (ROE)
	Rule-based (simple)	Binary rule set	Tag-level + event-level	Presence/absence	Zero tolerance for violation of any of five rules.
	Rule-based (complex)	Score-based	Tag-level + event-level	Presence/absence	Spatially explicit rule set
Daniels et al. 2018	Pattern recognition	Machine learning, random forest	Tag-level	Presence/absence	Supervised learning algorithm optimized by k-fold cross-validation
Gibson et al. 2015	Pattern recognition	Multivariate, Cluster analysis	Tag-level	Presence/absence	Ward Hierarchical clustering (minimum variance)
Hause 2020	Rule-based	Score-based	Tag-level	Presence/absence	Based on upstream movement
Johnston et al. 2018	Rule-based	Binary rule set	Tag-level	Presence/absence	Based on upstream movement against flow
Klinard et al. 2021	Pattern recognition	Multivariate, random forest	Tag-level	Presence/absence	Used to identify predator species, not to identify the predation event itself
Notte et al. 2022	Pattern recognition	Multivariate, cluster analysis	Tag-level	Presence/absence	k-means clustering

	Pattern recognition	Multivariate, random forest	Tag-level	Presence/absence	supervised
Perry et al. 2018	Pattern recognition	Cluster analysis	Tag-level	Presence/absence	Ward hierarchical clustering (minimum variance)
	Rule-based	Post hoc assessment	Event-Level	Presence/absence	Examined tag time-series to identify when predation occurred
Romine et al. 2014	Pattern recognition	Multivariate mixture model	Tag-level	2-D[a] tracks	Bivariate normal
Runde et al. 2020	Pattern recognition	Hidden Markov model	Tag-level	Acceleration and depth-use	Three-state hidden Markov model
SJGRA 2013	Rule-based	Score-based	Tag-level + event-level	Presence/absence	Spatially explicit rule set that also incorporated recaptures
Thorstad et al. 2012a	Rule-based	Post hoc assessment	Tag-level	Depth-use	Based on depth-use

[a] 2-D = 2-dimensional

Annotated Bibliography

Tag Predation Studies Within the Central Valley, California

Buchanan, R. A. 2018. **2016 six-year acoustic telemetry steelhead study: statistical methods and results**. Report. https://www.cbr.washington.edu/node/1282.

Keywords: steelhead, Central Valley, San Joaquin River, South Delta, tagged predators, striped bass, largemouth bass, white catfish, channel catfish, predator filter, rule-based, >50km

> *In this report, the authors used telemetry data in a multi-state release-recapture model to evaluate survival, migration route selection, and transition probabilities for juvenile steelhead in the San Joaquin River and Delta. The authors developed and applied a rule-based predator filter on the dataset prior to analyses. The criteria for the predator filter were constructed by comparing detections of tagged steelhead that were assumed to not be predated (isolated in a predator-free environment or physically recaptured at some point after release) and tagged predators. The predator filter criteria were spatially explicit, varying between receivers and/or transitions. They used various criteria that fit under several general categories, including fish speed, residence time, upstream transitions, travel time since release, and movements against flow, and they calibrated the criteria based on detection data for juvenile steelhead that were assumed to not be predated. They classified a tag track as having been consumed by a predator if at least two of the criteria failed to meet those required to be classified as a steelhead (noted as a predator score of at least 2). Overall, 11% of the 1,140 tagged juvenile steelhead were classified as being predated by the predator filter. The authors also evaluated tracks of 89 tagged predators via the predator filter to assess filter performance, and 79.8% were classified as predators. When considering tagged predators with at least five detection events, 98.5% were classified as predators.*

Buchanan, R. A., P. L. Brandes, and J. R. Skalski. 2018. **Survival of juvenile fall-run Chinook salmon through the San Joaquin River Delta, California, 2010–2015**. North American Journal of Fisheries Management 38(3):663–679. doi.org/10.1002/nafm.10063.

Keywords: Chinook salmon, San Joaquin River, South Delta, Central Valley, predator filter, rule-based, >50km

> *This study used acoustic telemetry data to estimate survival of out-migrating juvenile fall-run Chinook salmon in the San Joaquin River Delta from 2010 to 2015, and the authors found very low survival ranging from 0 to 0.05. They used a rule-based predator filter based on assumed behavioral differences between predators and smolts, including residence time near a receiver, travel rate between receivers, and movements against river flow. From this study, a minimum of 20% to 64% of tagged smolts were identified as predated upon via the predator filter.*

Buchanan, R. A., E. Buttermore, and J. Israel. 2021. **Outmigration survival of a threatened steelhead population through a tidal estuary**. Canadian Journal of Fisheries and Aquatic Sciences 78(12):1869–1886. doi.org/10.1139/cjfas-2020-0467.

Keywords: steelhead, Central Valley, San Joaquin River, South Delta, predator filter, rule-based, >50km

In this study, the authors estimated survival of outmigrating juvenile steelhead in the southern portion of the Sacramento–San Joaquin Delta using acoustic telemetry data. They used a rule-based predator filter to identify detections of predated smolts prior to survival estimation. The predator filter considered several metrics, including residence time near receivers, movements against river flow, and travel time between receivers. The filter assigned 7%–14% of tags as predated each year.

Buchanan, R. A., and J. R. Skalski. 2020. **Relating survival of fall-run Chinook salmon through the San Joaquin Delta to river flow**. Environmental Biology of Fishes 103:389–410. doi.org/10.1007/s10641-019-00918-y.

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, >50km

In this study, the authors evaluated the relationship between river flow and survival of migrating juvenile Chinook salmon in the South Delta using acoustic telemetry data. They found varied relationships among regions of the Delta, with survival through upstream riverine reaches correlated to San Joaquin River and interior Delta flows, and survival through the tidally influenced interior Delta correlated to Old River flows.

Buchanan, R. A., and S. L. Whitlock. 2022. **Diagnosing predated tags in telemetry survival studies of migratory fishes in river systems**. Animal Biotelemetry 10:13. doi.org/10.1186/s40317-022-00283-1.

Keywords: methodology, Chinook salmon, Central Valley, San Joaquin River, South Delta, tagged predators, largemouth bass, striped bass, channel catfish, white catfish, predator filter, rule-based, pattern recognition, multivariate, >50km,

In this study, the authors compared four methods for identifying predated acoustic tagged fish. Two methods were rule-based (one "simple" and one "complex") and two were pattern-recognition approaches (one with and one without tagged predator movement data included; "smolt-only" and "multispecies," respectively). The simple rule-based filter used five metrics for classifying predation, and tracks were classified as predated if at least one metric fit the predator conditions. The metrics included distance travelled upstream on a single trip, upstream movement velocity, upstream movement against the direction of flow, distance traveled per day, and time spent in the vicinity of a receiver station. The complex rule-based filter added additional metrics to those used in the simple filter and incorporated spatial components into the filter. The metrics fell into several general categories, including near-field residence time, mid-field residence time, far-field residence time, time since release, migration rate, scaled migration rate based on water velocity and fish body length, upstream transitions, movements against flow of water, and *regional movement patterns. The complex rule-based filter was similar to the filter used in Buchanan et al. 2018. The authors assigned a predation score where each metric that met predator conditions increased the score by one, and a score of at least two would result in predated classification. The smolt-only pattern recognition filter used hierarchical cluster analysis to flag suspicious behavior, and then a post hoc analysis to identify when tags started exhibiting behavior that could be classified as a predator. The authors used 20 explanatory variables in the cluster analysis, each being a summary statistic that may reflect differences in smolt and predator movements. From the results of the cluster analysis, they assigned predated groups based on behavior patterns expected to result from predation. The multispecies pattern recognition filter included data from tagged predatory fish and used similar methods as the smolt-only pattern recognition filter. For this, the groups from the cluster analysis were assigned as predated if >10% of tags were from known predators. For both pattern recognition filters, the authors used a principal components analysis with a recursive ordination ellipse method to classify at which detection an assigned predated smolt was first predated. The authors compared the four approaches by applying each method to a dataset of 648 tagged juvenile Chinook salmon in the San Joaquin River. Predation classification results varied among the methods, both in proportion (10%–21%) and composition of tags classified as predated. Results were more similar within related methods, with high overlap of predation classification between the two rule-based approaches (94% of tags flagged by simple filter were also flagged in complex filter) and the two pattern recognition approaches (100% of tags flagged in smolt-only filter were flagged in multispecies filter). There were spatial differences in where predation events were assigned between the rule-based and pattern recognition approaches, which was expected because the rule-based filter could assign predation events at the start or end of a detection event, whereas the pattern recognition filter assigned predation events in the reaches between telemetry stations. For all filters, there were some metrics that identified more predation events than others. Residence time metrics accounted for the majority of predation classifications for both rule-based models, with transition against flow and migration rate also contributing for the simple and complex filters, respectively. From the pattern recognition filters, predator groupings were characterized by upstream movement or long residence times, and smolt groupings were characterized by little upstream movement and higher migration rates.*

Cavallo, B., J. Merz, and J. Setka. 2013. **Effects of predator and flow manipulation on Chinook salmon (*Oncorhynchus tshawytscha*) survival in an imperiled estuary**. Environmental Biology of Fishes 96:393–403. doi.org/10.1007/s10641-012-9993-5.

Keywords: Chinook salmon, Central Valley, North Delta, <50km

In this study, the authors evaluated the effects of predator removal and flow on juvenile Chinook salmon migration speed and survival in the North Fork Mokelumne River, part of the Sacramento–San Joaquin Delta. They found that migration time decreased with increased flow, and this significantly increased survival. They also found that survival increased after initial predator removal efforts, but survival returned to pre-removal levels after the second predator removal.

Cutter, G. R., S. C. Manugian, J. Renfree, J. Smith, C. Michel, D. Huff, T. S. Sessions, B. E. Elliot, K. Stierhoff, S. Mau, D. Murfin, and D. A. Demer. 2017. **Mobile acoustic sampling to map bathymetry and quantify the densities and distributions of salmonid smolt predators in the San Joaquin River**. Report. doi.org/10.7289/V5/TM-SWFSC-575.

Keywords: Central Valley, San Joaquin River, <50km

In this study, the authors used acoustic sonar surveys to map bathymetry and assess the abundance and distribution of potential predators of salmon smolts in the San Joaquin River. They found that predators were associated with submerged vegetation and riverbed features along smolt migration paths.

Hause, C. 2020. **Outmigration survival of juvenile spring-run Chinook salmon in relation to physicochemical conditions in the San Joaquin River**. Master's Thesis. https://www.proquest.com/docview/2503429396.

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, predator filter, >50km

In this dissertation, the author evaluated survival of outmigration survival of juvenile Chinook salmon in the San Joaquin River relative to habitat conditions. The study revealed low survival in areas with high temperatures and low chlorophyll-alpha, fluorescent dissolved organic matter (fDOM), and turbidity. Prior to analyses, the author addressed potential predation in the smolt telemetry dataset by flagging any upstream movement greater than 16 km, and then manually inspecting flagged tracks to determine if/when a tag was predated.

Holleman, R. C., E. S. Gross, M. J. Thomas, A. L. Rypel, and N. A. Fangue. 2022. **Swimming behavior of emigrating Chinook salmon smolts**. PLoS ONE 17(3):e0263972. doi.org/10.1371/journal.pone.0263972.

Keywords: Chinook salmon, Central Valley, San Joaquin River, <50km

This study investigated swimming speed and behavior of Chinook salmon smolts using two-dimensional acoustic telemetry tracks and a three-dimensional hydrodynamic model at the junction of the San Joaquin River and Old River. The authors assumed tags that were in the study array (which was <400m of river) for longer than 60 minutes or that had a mean swimming speed over 0.5m/s were predators, and they removed data for such tags from analyses. They estimated smolt swimming speed to be 0.15–0.20 m/s, or 2.0–2.7 body-lengths/sec. They also found evidence that smolt swimming behavioral patterns include rheotaxis, lateral swimming that was more likely during daylight hours, and passive transport.

Johnston, M. E., A. E. Steel, M. Espe, T. Sommer, A. P. Klimley, P. Sandstrom, and D. Smith. 2018. **Survival of juvenile Chinook salmon in the Yolo Bypass and the Lower Sacramento River, California**. San Francisco Estuary and Watershed Science 16(2):4. doi.org/10.15447/sfews.2018v16iss2art4.

Keywords: Chinook salmon, Central Valley, Sacramento River, North Delta, predator filter, rule-based, >50km

In this study, the authors compared survival of juvenile Chinook salmon outmigrating via the Yolo Bypass system versus the combined other routes of the lower Sacramento River. They found no statistically significant differences in survival among routes during their two-year study. Before analyzing their acoustic telemetry dataset for survival, the authors identified predation events by using a single rule-based criterion: upstream movement that was not associated with tides and resulted in no further downstream movement indicated predation.

Loomis, C. M. 2019. **Density and distribution of piscivorous fishes in the Sacramento–San Joaquin Delta**. Master's Thesis. https://digitalcommons.humboldt.edu/etd/319/.

Keywords: Central Valley, San Joaquin River, South Delta, >50km

In this dissertation, the author used acoustic cameras to assess predator fish populations in the South Delta. He found predatory fish locations were mainly determined by spatial and structural components rather than temporal trends, and they were more likely to be found in shallow habitats with vegetation and man-made structures.

Michel, C. J., A. J. Ammann, E. D. Chapman, P. T. Sandstrom, H. E. Fish, M. J. Thomas, G. P. Singer, S. T. Lindley, A. P. Klimley, and R. B. MacFarlane. 2013. **The effects of environmental factors on the migratory movement patterns of Sacramento River yearling late-fall run Chinook salmon (*Oncorhynchus tshawytscha*)**. Environmental Biology of Fishes 96:257–271. doi.org/10.1007/s10641-012-9990-8.

Keywords: Chinook salmon, Central Valley, Sacramento River, North Delta, >50km

In this study, the authors used acoustic telemetry data to evaluate the effects of environmental factors on migration travel time for juvenile Chinook salmon in the Sacramento River. They found that river width to depth ratio, river flow, water turbidity, river flow to mean river flow ratio, and water velocity all improved model fit for time models of smolt migration, while water temperature did not.

Michel, C. J., A. J. Ammann, S. T. Lindley, P. T. Sandstrom, E. D. Chapman, M. J. Thomas, G. P. Singer, A. P. Klimley, and R. B. MacFarlane. 2015. **Chinook salmon outmigration survival in wet and dry years in California's Sacramento River**. Canadian Journal of Fisheries and Aquatic Sciences 72(11):1749–1760. doi.org/10.1139/cjfas-2014-0528.

Keywords: Chinook salmon, Central Valley, Sacramento River, North Delta, >50km

In this study, the authors used acoustic data to evaluate outmigration survival of juvenile Chinook salmon in the Sacramento River during wet and dry years. They found that outmigration survival was two to five times higher during a wet year compared to four dry years.

Michel, C. J., M. J. Henderson, C. M. Loomis, J. M. Smith, N. J. Demetras, I. S. Iglesias, B. M. Lehman, and D. D. Huff. 2020a. **Fish predation on a landscape scale**. Ecosphere 11(6):e03168. doi.org/10.1002/ecs2.3168.

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, >50km

In this study, the authors used predator event recorders (PERs, buoys with live juvenile Chinook salmon attached as bait for predators) to evaluate predation risk in the lower San Joaquin River and South Delta. The PERs were set up with GPS and timers that allowed data collection of exact time and location of predation. They used a mixed-effect Cox proportional hazard model to evaluate predation risk based on relevant covariates, and found that water temperature, time of day, mean predator distance, and river bottom roughness were the best predictors of predation occurrence.

Michel, C. J., J. M. Smith, B. M. Lehman, N. J. Demetras, D. D. Huff, P. L. Brandes, J. A. Israel, T. P. Quinn, and S. A. Hayes. 2020b. **Limitations of active removal to manage predatory fish populations**. North American Journal of Fisheries Management 40(1):3–16. doi.org/10.1002/nafm.10391.

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, <50km

In this study, the authors used predation event recorders (buoys with smolts attached) and acoustic telemetry data to assess predation on juvenile Chinook salmon in the San Joaquin River before and after predator removal efforts. They found no evidence of predator removal affecting either smolt survival or predation rates on smolts.

Perry, R. W., A. C. Pope, J. G. Romine, P. L. Brandes, J. R. Burau, A. R. Blake, A. J. Ammann, and C. J. Michel. 2018. **Flow-mediated effects on travel time, routing, and survival of juvenile Chinook salmon in a spatially complex, tidally forced river delta**. Canadian Journal of Fisheries and Aquatic Sciences 75(11):1886–1901. doi.org/10.1139/cjfas-2017-0310.

Keywords: Chinook salmon, Central Valley, Sacramento River, North Delta, South Delta, predator filter, pattern recognition, multivariate, >50km

In this study, the authors estimated travel time, migration routes, and survival of juvenile Chinook salmon through the Sacramento–San Joaquin River Delta using multi-state mark-recapture modeling on acoustic telemetry data. To filter out tags that may have been consumed by predators, the authors calculated five movement metrics to quantify differences in smolt-like behavior and predator-like behavior. The movement metrics included the mean rate of downstream movement, the number of consecutive detections at a single location, the total distance travelled divided by the number of days in the study area, the number of transitions between telemetry stations that were likely to only be possible by a predator (upstream against the flow), and the total time in the receiver array. They used a hierarchical cluster analysis to group each tag by the multivariate characteristics of the five movement metrics and then examined the group with movement characteristics that resembled predator behavior (upstream movement against flow, long residence time near receivers, low distance travelled per day). For each tag in *this group, the authors looked at the time series of movement metrics to decide when the tag transitioned from smolt-like behavior to predator-like behavior and then removed detections identified as occurring after predation. They found that 17% of tags were identified for review based on movement metrics and that 11% of tags had predator-like behavior that required removing part of their detection histories.*

Perry, R. W., J. R. Skalski, P. L. Brandes, P. T. Sandstrom, A. P. Klimley, A. Ammann, and B. MacFarlane. 2010. **Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta**. North American Journal of Fisheries Management 30:142–156. doi.org/10.1577/M08-200.1.

Keywords: Chinook salmon, Central Valley, Sacramento River, North Delta, >50km

This study developed a mark-recapture model for estimating survival and migration route for outmigrating juvenile Chinook salmon in the Sacramento River and applied the model to the first smolt acoustic telemetry data available in the Sacramento–San Joaquin Delta. The authors truncated detection histories for five fish due to directed long distance upstream movement against the flow that indicated predation.

Romine, J. G., R. W. Perry, S. V. Johnston, C. W. Fitzer, S. W. Pagliughi, and A. R. Blake. 2014. **Identifying when tagged fishes have been consumed by piscivorous predators: Application of multivariate mixture models to movement parameters of telemetered fishes**. Animal Biotelemetry 2(1):3. doi.org/10.1186/2050-3385-2-3.

Keywords: methodology, Chinook salmon, steelhead, striped bass, smallmouth bass, spotted bass, tagged predators, Central Valley, Sacramento River, predator filter, pattern recognition, parametric, multivariate mixture models, <50km

In this study, the authors applied multivariate mixture models to classify telemetered fish as smolts (Chinook salmon and steelhead) or predators (striped bass, smallmouth bass, and spotted bass) in the Sacramento River. Both smolts and predators were tracked with acoustic tags, and the authors used two movement statistics estimated from two-dimensional tracks in a bivariate normal mixture model — the Lévy exponent (b) and tortuosity (τ). They hypothesized that smolts would exhibit directed movement with shallow turn angles and relatively constant swimming speeds, which would be consistent with a smolt migrating to the ocean (τ closer to one, lower b), and that predators would exhibit nonlinear movement trajectories with steep turn angles associated with prey-searching (τ closer to 0.5, higher b). The model results were in line with the authors' hypothesized relationships for Lévy exponent and tortuosity, and accurately classified ~80% of predator tracks as predators. About 26% of tagged smolt tracks were classified as predators, but the authors could not evaluate tagged smolt classification accuracy because the predation fate of smolts could not be verified without recapture data. The approach presented by the authors provides an objective statistical method to address predation in telemetry studies that can also be combined with behavior and rule-based criteria for assessing predation. Additional statistics could also be added to the mixture model to improve classification accuracy.

Singer, G. P., A. R. Hearn, E. D. Chapman, M. L. Peterson, P. E. Lacivita, W. N. Brostoff, A. Bremner, and A. P. Klimley. 2013. **Interannual variation of reach specific migratory success for Sacramento River hatchery yearling late-fall run Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead trout (*Oncorhynchus mykiss*)**. Environmental Biology of Fishes 96:363–379. doi.org/10.1007/s10641-012-0037-y.

Keywords: Chinook salmon, steelhead, Central Valley, Sacramento River, North Delta, >50km

In this study, the authors used acoustic telemetry data to estimate migration success (apparent survival between sites) for juvenile Chinook salmon and steelhead in the Sacramento River. They found overall migration success to the Pacific Ocean to be less than 25% for both species.

San Joaquin River Group Authority (SJRGA) 2013. **2011 annual technical report: on implementation and monitoring of the San Joaquin River agreement and the Vernalis Adaptive Management Plan**. SJRGA, Report to the California Water Resources Control Board, Davis, California. http://tuolumnerivertac.com/Documents/SJRGA2013_2011AnnualTechnicalReport_compressed.pdf

Keywords: Chinook salmon, complex rule-based filter, Central Valley, San Joaquin River, South Delta, >50km

This report describes the twelfth and final year of the initial series of Vernalis Adaptive Management Plan (VAMP) studies initiated as part of the State Water Resources Control Board Decision 1641. The document contains eight chapters, each describing separate investigations conducted in 2011 with summaries of earlier work conducted by the group. The focus of these investigations concern delta hydrology, juvenile Chinook salmon survival and route selection, and the effectiveness of a bio-acoustic fish fence placed at the head of Old River in the San Joaquin River, among others.

There were key improvements to the 2011 study design relative to previous studies and the placement of additional monitoring stations. Both of these modifications have persisted over time, and the 2011 study represented a shift to a newer, higher resolution monitoring effort that has since continued. The most notable difference between 2011 and previous years was the addition of receivers for the purpose of understanding route selection probabilities. The route-selection and survival study in 2011 was further exceptional compared to past acoustic investigations because delta inflow during the study period was very high and coincided with high survival. Flows were too high for a barrier to be safely installed at the head of Old River.

Chapter five represented the most relevant chapter in the report in relation to survival and migration studies in the South Delta and in developing procedures to address the tag predation problem. Criteria considered when creating the complex rule-based filter are discussed in depth, complete with region specific thresholds. There were a set of six criteria used in justifying rule-sets for eliminating nonrepresentative portions of tag histories: (1) fish speed measured by migration rate and adjusted for daily fluctuations flow direction and velocity (e.g., tidal cycles); (2) residence time including near-, mid-, and far-field metrics (see Glossary for definitions); (3) upstream transitions, including forays of substantial duration in upstream regions; (4) unexpected *transitions (e.g., from inside CVP holding tanks to other receivers nearby); (5) travel time since release (e.g., no more than 15 days); (6) movement against flow (e.g., no movement from a station against relatively strong flow).*

Vogel, D. A. 2010. **Evaluation of acoustic-tagged juvenile Chinook salmon movements in the Sacramento–San Joaquin Delta during the 2009 Vernalis Adaptive Management Program**. Report. https://www.waterboards.ca.gov/waterrights/water_issues/programs/bay_delta/bay_delta_plan/water_quality_control_planning/docs/sjrf_spprtinfo/vogel_2010.pdf

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, tag recovery, >50km

This is a report on an acoustic telemetry study of juvenile Chinook salmon in the San Joaquin River. The report included detailed assessments of fish movements from acoustic data. They also used mobile telemetry surveys and tag recovery to identify predated tags, and they used acoustic telemetry of striped bass to characterize predator movements. The results of the study suggested high predation rates on tagged smolts.

Vogel, D. A. 2011. **Evaluation of acoustic-tagged juvenile Chinook salmon and predatory fish movements in the Sacramento–San Joaquin Delta during the 2010 Vernalis Adaptive Management Program**. Report. http://www.nativefishlab.net/library/internalpdf/21297.pdf

Keywords: Chinook salmon, Central Valley, San Joaquin River, South Delta, tag recovery, tagged predators, largemouth bass, striped bass, white catfish, >50km

Acoustic telemetry tracking of smolts and several predator species was conducted to examine prey movement and the home range sizes of several predators, primarily focused on striped bass. This research was conducted in response to the high tag predation rate observed in previous years. Main findings of this work were that tag predation appears to be a significant impediment to reliably estimating survival primarily because striped bass are particularly wide ranging.

Young, M. J., F. V. Feyrer, D. D. Colombano, J. L. Conrad, and A. Sih. 2018. **Fish-habitat relationships along the estuarine gradient of the Sacramento–San Joaquin Delta, California: Implications for habitat restoration**. Estuaries and Coasts 41:2389–2409. doi.org/10.1007/s12237-018-0417-4.

Keywords: Central Valley, <50km

In this study, the authors evaluated relationships between fish abundances and water quality and habitat features using ordination and generalized linear mixed models with data collected from four tidal lakes in the Sacramento–San Joaquin Delta. They found that species assemblage composition was associated with salinity, turbidity, elevation, and submerged aquatic vegetation density.

Tag Predation Studies Outside of the Central Valley, California

Daniels, J., G. Chaput, and J. Carr. 2018. **Estimating consumption rate of Atlantic salmon smolts (*Salmo salar*) by striped bass (*Morone saxatilis*) in the Miramichi River estuary using acoustic telemetry**. Canadian Journal of Fisheries and Aquatic Sciences 75(11):1811–1822. https://doi.org/10.1139/cjfas-2017-0373.

Keywords: methodology, Atlantic salmon, striped bass, tagged predators, predator filter, pattern recognition, multivariate, >50km

This study developed a random forests classification model to differentiate movement patterns of acoustic tagged Atlantic salmon smolts and striped bass. Unlike other studies, this study used telemetry data from known-smolts (not potentially predated) and striped bass as training data in the model. The model used eight movement variables, including average speed, time between first and last detection during the study period, count of switches in upstream and downstream movement, cumulative upstream distance between detections, cumulative distance between detections, time at striped bass spawning grounds, time between first and last detections at striped bass spawning grounds, and count of visits and transitions between the northwest and southwest portions of the river. The dataset of known-smolts and striped bass movement variables were used to train the random forests model, and the model was optimized by using k-fold cross validation. The random forests model was then applied to smolt telemetry data to determine the probability of each tag track being more similar to smolt behavior or striped bass behavior. The authors used three different classification methods for a smolt being predated based on the random forests model: (1) binary classification based on a bass probability cutoff of 0.5, as in tag tracks less than 0.5 were classified as smolts and greater than 0.5 were classified as striped bass, (2) a scaled estimate calculated by summing the bass classification probabilities for each tagged smolt and dividing by the total number of tagged smolts, and (3) a three-level classification where <0.20 was classified as smolt, >0.80 was classified as striped bass, and values in between were classified as "unknown." Then, the authors used those classification data to estimate the proportion of smolts predated by striped bass based on stock and year. They found that smolts were characterized by unidirectional downstream movement, whereas striped bass movement detection histories contained more frequent upstream and downstream reversals. Most bass-probability values for tagged smolts from the application of the random forests model were close to 0 or 1, indicating the model was reliable at classifying a tagged smolt as predated or not. All classification methods yielded similar results, and they found 1.9%–19.9% of smolt tracks were classified as predated by striped bass depending on stock and year. By using a supervised learning method (known-smolt tracks for training data), this study was able to assess model performance. Their model only incorrectly classified one fish (a smolt classified as a striped bass) out of 63 tracks, for an incorrect classification rate of 1.6%.

Daniels, J., S. Sutton, D. Webber, and J. Carr. 2019. **Extent of predation bias present in migration survival and timing of Atlantic salmon smolt (*Salmo salar*) as suggested by a novel acoustic tag**. Animal Biotelemetry 7:16. doi.org/10.1186/s40317-019-0178-2.

Keywords: Atlantic salmon, predation tag, >50km, signal-based

In this study, the authors used predation detection acoustic transmitters to evaluate how predation may bias survival estimates for outmigrating Atlantic salmon smolts. They found that 24 of 50 predation tags signaled as predated, and there was a positive bias of up to 11.6% in survival estimates when predation was not accounted for.

Gibson, A. J. F., E. A. Halfyard, R. G. Bradford, M. J. W. Stokesbury, and A. M. Redden. 2015. **Effects of predation on telemetry-based survival estimates: Insights from a study on endangered Atlantic salmon smolts**. Canadian Journal of Fisheries and Aquatic Sciences 72(5):728–741. doi.org/10.1139/cjfas-2014-0245.

Keywords: methodology, Atlantic salmon, striped bass, tagged predators, predator filter, pattern recognition, multivariate, >50km

This study used cluster analyses of 11 migration summary variables to compare movements between acoustic tagged Atlantic salmon smolts and striped bass for identification of striped bass predation on tagged smolts, and then compared smolt survival estimates with and without accounting for predation. The summary variables included: total number of detections, total days with detections, total time between first and last detection, total distance travelled, mean upstream velocity, maximum upstream velocity, mean downstream velocity, maximum downstream velocity, total number of migration reversals, total time at spawning grounds for striped bass, and total detections at an upstream river before confluence with another river. The authors used hierarchical clustering with Ward's minimum variance method to identify behavioral groupings for two years of data. The smolt tags that clustered with striped bass tags were assumed to be potentially predated, and post hoc examination of mean summary variables for each group was used for final classification of potentially predated smolts. From their interpretation of the clustering results, the authors estimated 2.4% and 13.6% of tags were predated each year. For the first year, the clustering resulted in two groups that were easily identifiable as salmon smolts or striped bass. However, the clustering of the second year's data was less conclusive and required some subjective interpretation. Based on predation classification results, smolt survival estimates were reduced from 43.5% to 41.1% and 32.6% to 19.0% by incorporating predation.

Halfyard, E. A., D. Webber, J. Del Papa, T. Leadley, S. T. Kessel, S. F. Colborne, and A. T. Fisk. 2017. **Evaluation of an acoustic telemetry transmitter designed to identify predation events**. Methods in Ecology and Evolution 8(9):1063–1071. doi.org/10.1111/2041-210X.12726.

Keywords: methodology, predation tag, yellow perch, rainbow trout, largemouth bass, signal-based

In this study, the authors conducted a laboratory study to evaluate various metrics relating to performance of two generations of prototype acoustic predation tags, including the rate at which tags correctly identified predation events, the time after predation until detection of predation, tag retention time in the predator's gut, and false-positive rates for both live and dead prey fish. They found predation events were successfully detected in >90% of trials and signal lag time was

1–29 hours. They found no false positives in generation 1 tags but a rate of over 20% false-positives for generation 2 tags.

Jepsen, N., S. Pedersen, and E. Thorstad. 2000. **Behavioural interactions between prey (trout smolts) and predators (pike and pikeperch) in an impounded river**. Regulated Rivers: Research and Management 16(2):189–198. doi.org/10.1002/(SICI)1099-1646(200003/04)16:2<189::AID-RRR570>3.0.CO;2-N.

Keywords: brown trout, northern pike, pikeperch, tagged predators, <50km

In this study, the authors radio tagged migrating trout smolts and two predatory fishes (pike and pikeperch) to evaluate predator-prey interactions. They found that most smolts were consumed by pike or pikeperch, and that pike and pikeperch likely altered their behavior to predate on migrating smolts.

Klinard, N. V., and J. K. Matley. 2020. **Living until proven dead: Addressing mortality in acoustic telemetry research**. Reviews in Fish Biology and Fisheries 30:485–499. doi.org/10.1007/s11160-020-09613-z.

Keywords: review, methodology,

This study was a review to assess mortality consideration in acoustic telemetry studies published from 2015 to 2019. The authors reviewed 640 articles — for each article, they determined whether mortality was considered, and if so, they summarized general methods used to address mortality based on study type groupings (ecology/behavior, survival/mortality, tagging effects). They found that mortality was considered or discussed in 61% of articles, with ecology/behavior studies having the lowest mortality consideration rate (50%). Some common methods used to address mortality included the number of detections or cease in detections, changes in movement patterns, harvest information or observed fate, and predation evidence. The authors suggested that addressing possible mortality of study organisms should become standard practice in acoustic telemetry studies.

Klinard N. V., J. K. Matley, S. V. Ivanova, S. M. Larocque, A. T. Fisk, and T. B. Johnson. 2021. **Application of machine learning to identify predators of stocked fish in Lake Ontario: Using acoustic telemetry predation tags to inform management**. Journal of Fish Biology 98:237–250. doi.org/10.1111/jfb.14574.

Keywords: bloater (prey), Atlantic salmon , brown trout (predator) , Chinook salmon , coho salmon (predator) , rainbow trout (predator) , lake trout (predator) , predation tag, tagged predators, pattern recognition, machine learning, >50km

In this study, the authors evaluated survival and predation of bloater (a prey fish species) in Lake Ontario using acoustic telemetry with predation tags (tags that change signal when predated). In addition to summarizing post-stocking survival and identifying predation events via the predation tags, the authors sought to identify which predator species consumed the study subjects. To do so, they developed a random forests model to identify predators based on movement patterns. The authors tagged potential predators to obtain movement data, including Atlantic salmon, brown *trout, Chinook salmon, coho salmon, rainbow trout, and lake trout. They used ten movement metrics in their analyses to distinguish among predator species: proportion of days detected, maximum distance moved, average distance detected from release site, standard deviation of distance detected from the release site, average time between detections, standard deviation of time between detections, count of transitions between east and west sides of the lake, average distance moved in consecutive days, proportion of detection days that were consecutive, and average number of days between detections. To establish the random forests model, they used 70% of the tagged predator data as training data and the other 30% as test data to evaluate model accuracy. Their model correctly classified 55.9% of the test data set, with varied classification accuracy among species (0-89% accuracy). Then they applied the model to data from 20 bloater that were classified as predated via their predation tags and had sufficient post-predation contact data. The model predicted that lake trout and brown trout were the primary predators of bloater, consuming 10 and 8 fish, respectively.*

Notte D. V., R. J. Lennox, D. C. Hardie, and G. T. Crossin. 2022. **Application of machine learning and acoustic predation tags to classify migration fate of Atlantic salmon smolts**. Oecologia 198:605–618. doi.org/10.1007/s00442-022-05138-3.

Keywords: Atlantic salmon, predation tag, predator filter, Methodology, pattern recognition, machine learning, >50km,

In this study, the authors used several approaches to classify fates (successful migration, mortality of unknown cause, or predation) of outmigrating Atlantic salmon smolts tracked with acoustic predation tags. Fate classifications for predation tags were based on the tag technology of switching codes via a pH sensor when digested by a predator. However, previous studies showed that the predation tags are not 100% reliable for identifying predation and have the potential to produce both false-positives (switches to predation code even when not predated) and false-negatives (failing to switch codes when predated). Therefore, the authors also applied two machine learning approaches to identify predation, one that was completely independent of predation tag data and another that was informed by predation tag data. The three approaches used by the authors to assign fates included (1) using just the predation tags themselves, (2) unsupervised k-means clustering, and (3) supervised random forest informed with predation tag data. For their machine learning approaches, the authors used movement metrics from telemetry data that were expected to be different between smolts and predators. The metrics included: total number of detections, maximum and minimum number of detections at a single receiver, number of days with detections, time between first and last detections, total distance travelled, mean and maximum upstream velocity between sites, mean and maximum downstream velocity between sites, count of route reversals, total time at striped bass spawning sites, count of detections above confluence with another river, cumulative upstream distance travelled, mean and maximum distance travelled in a single upstream directed series of detections, migration rate, and maximum velocity in freshwater and tidal water. The clustering method relied solely on movement metrics for fate classification, while the random forests model used movement metrics for fate classification but was informed by the predation information given by predation tags. The clustering method resulted in a 3.5%–30% reduction in predation estimates compared to the *predation tags alone, whereas the random forest model resulted in a 9%–32% increase in predation estimates compared to predation tags. Prediction accuracy was generally better for the random forest method (81.6%–94.4%) than the clustering method (38.2%–82.4%).*

Runde, B. J., T. Michelot, N. M. Bacheler, K. W. Shertzer, and J. A. Buckel. 2020. **Assigning fates in telemetry studies using hidden Markov models: an application to deepwater groupers released with descender devices**. North American Journal of Fisheries Management 40:1417–1434. doi.org/10.1002/nafm.10504.

Keywords: deepwater grouper, predator filter, pattern recognition, hidden Markov model, <50km marine

In this study, the authors used acoustic telemetry to evaluate survival of groupers that were either surface-released or deep-released with descender devices. They used a three-state hidden Markov model to assign a fate to each fish, where two states characterized movement of live groupers and the third state was assumed to represent behaviors of grouper predators. The acoustic tags used in this study included sensors that collected data on acceleration and depth. The authors pooled sensor data into 30-minute bins and used three metrics in the hidden Markov model to distinguish between predated tags and live groupers. The metrics included mean acceleration, mean normalized depth (depth as a proportion of release depth), and standard deviation of depth. The two states that were identified as live groupers were characterized by low acceleration, depth near the sea floor, and low to moderate depth changes, whereas the state identified as predators was characterized by higher acceleration, a wide range of depth use, and more rapid depth changes. The authors used two approaches for fate determination — one that relied more on the hidden Markov model, and another that supplemented the model with additional expert judgements. For each approach, 22 and 11 of 40 deep-released grouper were classified as dead/predated. There was no way for the authors to directly evaluate the validity of predation classification without known fates of tagged fish (recaptures).

Seitz, A. C., M. B. Courtney, M. D. Evans, and K. Manishin. 2019. **Pop-up satellite archival tags reveal evidence of intense predation on large immature Chinook salmon (*Oncorhynchus tshawytscha*) in the North Pacific Ocean**. Canadian Journal of Fisheries and Aquatic Sciences. doi.org/10.1139/cjfas-2018-0490.

Keywords: Chinook salmon, marine, >50km

In this study, the authors used depth, temperature, and light data from pop-up satellite tags to evaluate predation on large immature Chinook salmon in the Pacific Ocean. They found evidence that 24 of 33 tagged fish were predated upon.

Thorstad, E. B., I. Uglem, B. Finstad, C.M. Chittenden, R. Nilsen, F. Økland, and P.A. Bjørn. 2012. **Stocking location and predation by marine fishes affect survival of hatchery-reared Atlantic salmon smolts**. Fisheries Management and Ecology 19(5):400–409. doi.org/10.1111/j.1365-2400.2012.00854.x.

Keywords: Atlantic salmon, predator filter, Atlantic cod, saithe, tagged predators, marine, <50km

In this study, the authors used acoustic telemetry with depth recorders to assess Atlantic salmon smolt survival upon entering the marine environment. In addition to tagging Atlantic salmon, they also tagged and tracked predatory fish, including Atlantic cod and saithe. They inferred predation of tagged smolts by comparing depth-use behavior between smolts and predators. Predatory fish moved up and down the water column frequently and used much greater depths than smolts. They classified predation occurrence in 14 of 57 smolts that entered the marine portion of their study site.

Weinz, A. A., J. K. Matley, N. V. Klinard, A. T. Fisk, and S. F. Colborne. 2020. **Identification of predation events in wild fish using novel acoustic transmitters**. Animal Biotelemetry 8(1):28. doi.org/10.1186/s40317-020-00215-x.

Keywords: methodology, predation tag, yellow perch, <50km

In this study, the authors implanted predation acoustic tags, which change signal upon digestion by a predator, into yellow perch in the Detroit River. The objective of the study was to evaluate the performance of predation tags in a field setting by assessing predation fate based on detection data for fish that emitted a predation signal. They used several space-use metrics to assess behavior and movement before and after the switch in tag signal that indicated predation, including roaming index values, movement pathways, and step lengths of movement distances. Based on movement patterns, the authors inferred that 15 of 19 individuals with tag codes that switched to the predation signal were indeed predated, and the remaining four individuals were classified as unclear fate.

Appendix

Table of Metrics

The following table lists derived variables (metrics) used to identify individual tags or portions of tag detection histories in which the tag from the intended study subject was inside the gut of a predator. Metrics reflect hypotheses regarding what a tagged study subject would be expected to do versus one of its predators. All listed metrics were used as part of a predator filter in a telemetry study on anadromous salmonids in the Central Valley of California or were part of an analysis with the same or similar aims outside of the region. Categories of these metrics include time between detections (in general); residence time (i.e., instances of repeated detection at the same station); distance traveled; apparent migration rate; movement pattern; environmental conditions; and a combination of these factors.

Category	Metric	Source
Time	Time between first and last detection	Daniels et al. 2018 Gibson et al. 2015 Notte et al. 2022
	Time since release	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Total days with detections	Gibson et al. 2015 Notte et al. 2022
	Proportion of days with detections	Klinard et al. 2021
	Proportion of detection days that were consecutive	Klinard et al. 2021
	Time since last detection event at station	Buchanan and Whitlock 2022 SJRGA 2013
	Time between detections	Klinard et al. 2021
Residence time	Near-field (within detection event)	Buchanan and Whitlock 2022 SJRGA 2013
	Mid-field (within uninterrupted series of stationary detection events)	Buchanan and Whitlock 2022 Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Far-field (region-specific) - San Joaquin River (SJR) to upstream of head of Old River (HOR) - SJR from the HOR through the Stockton receivers - SJR from the Turner Cut junction through Medford Island - Old River from its head to the Middle River junction - Old River from the head of Middle River to Highway 4 (including the water export facilities) - Middle River from its head to Highway 4, and San Joaquin or Sacramento River from Threemile Slough to Chipps Island, including Jersey Point and False River	Buchanan and Whitlock 2022 Buchanan and Whitlock 2022 Buchanan et al. 2021 SJRGA 2013

	Cumulative near field	Buchanan et al. 2021 Buchanan and Whitlock 2022 Perry et al. 2018
	Maximum near field at any station	Buchanan and Whitlock 2022
	Time spent downstream before entering alternative river upstream	Buchanan et al. 2021 Buchanan and Whitlock 2022
	Time in high-risk zones / known predator spawning areas or aggregation sites	Buchanan and Whitlock 2022 Daniels et al. 2018 Gibson et al. 2015 Notte et al. 2022
Distance	Cumulative upstream distance between detections	Buchanan and Whitlock 2022 Daniels et al. 2018 Notte et al. 2022
	Distance traveled upstream on single transition	Buchanan and Whitlock 2022 Hause 2020 Notte et al. 2022
	Maximum distance traveled upstream on single transition	Buchanan and Whitlock 2022 Notte et al. 2022
	Cumulative distance between detections	Buchanan and Whitlock 2022 Daniels et al. 2018
	Total distance traveled	Gibson et al. 2015 Klinard et al. 2021 Notte et al. 2022
	Step lengths of movement distance	Weinz et al. 2020
	Distance from release site	Klinard et al. 2021
Migration rate	Average speed (distance over days)	Buchanan and Whitlock 2022 Daniels et al. 2018 Perry et al. 2018
	Minimum migration rate for upstream-directed transitions	SJRGA 2013
	Maximum cumulative distance over days	Buchanan and Whitlock 2022
	Mean upstream velocity	Gibson et al. 2015 Notte et al. 2022
	Mean upstream velocity on single transition	Buchanan and Whitlock 2022
	Maximum upstream velocity	Buchanan and Whitlock 2022 Gibson et al. 2015 Notte et al. 2022
	Mean downstream velocity	Gibson et al. 2015 Notte et al. 2022 Perry et al. 2018
	Maximum downstream velocity	Buchanan and Whitlock 2022 Notte et al. 2022 Gibson et al. 2015

	Mean speed during transition	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Mean speed during transition (std. dev)	Buchanan and Whitlock 2022
	Body lengths per second during transition	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Body lengths per second (maximum)	Buchanan and Whitlock 2022
Movement pattern	Count of route reversals	Buchanan and Whitlock 2022 Daniels et al. 2018 Notte et al. 2022
	Count of switches from downstream to upstream movement (=subset of route reversals)	Buchanan et al. 2021 Buchanan and Whitlock 2022
	Proportion upstream transitions	Buchanan and Whitlock 2022
	Proportion visits in high-risk zones	Buchanan and Whitlock 2022
	Count of visits	Daniels et al. 2018
	Count of detections	Gibson et al. 2015 Notte et al. 2022
	Count of visits at station	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Maximum visits at any station	Buchanan and Whitlock 2022 SJRGA 2013
	Count of consecutive visits at any station	Perry et al. 2018
	Count of transitions between different portions of river/lake	Buchanan et al. 2021 Buchanan and Whitlock 2022 Daniels et al. 2018 Klinard et al. 2021 SJRGA 2013
	Count of detections at upstream river before confluence with another river	Gibson et al. 2015 Notte et al. 2022
	Roaming index	Weinz et al. 2020
	Movement pathways	Weinz et al. 2020
	Next transition directed downstream (T/F)	Buchanan et al. 2021 Buchanan and Whitlock 2022
	Lévy exponent (b)	Romine et al. 2014
	tortuosity (τ)	Romine et al. 2014
	Upstream movement not associated with tides and with no further downstream movement	Johnston et al. 2018
	No more than 3 upstream forays detected	SJRGA 2013

	Transitions from the CVP holding tank to nearby sites	SJRGA 2013
	Depth use	Thorstad et al. 2012 Runde et al. 2020
	Acceleration	Runde et al. 2020
Environmental conditions	Flow conditions at start of transition (discharge, velocity, river stage)	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Flow conditions at end of transition (flow, velocity, river stage)	Buchanan et al. 2021 Buchanan and Whitlock 2022 SJRGA 2013
	Exports rate at start of transition	Buchanan et al. 2021 SJRGA 2013
	Reservoir inflow at start of transition	Buchanan et al. 2021 SJRGA 2013
	Barrier status	Buchanan et al. 2021
	Flow during residence	Buchanan and Whitlock 2022
Combination	Time spent in regions after specific movement patterns	Buchanan et al. 2021
	Movement against flow	Buchanan et al. 2021 Buchanan and Whitlock 2022 Perry et al. 2018 SJRGA 2013
	Proportion transitions against flow	Buchanan and Whitlock 2022
	Maximum speed in freshwater and tidewater	Notte et al. 2022

Glossary

Behavior-based Filter: A methodological approach for identifying tag predation that relies on contrast in movement capability, habitat use, or other tendencies between study subjects and predators.

Detection Event: Aggregation of acoustic signal detections from an individual tag on one or more receivers uninterrupted by detections of the tag elsewhere or (optionally) by time gaps beyond a specified maximum duration (event time threshold); individual events are identified by the tag, spatial scale, and timing, where spatial scale may range from a single receiver to full telemetry station, and timing is indicated by the first and last detection times or alternatively by the time of peak signal strength.

Dual/multi-line Station: A station with multiple receiver lines treated independently for the purpose of estimating detection probability or direction of movement.

Event-level: Classification of a study subject's status as predated or not predated based on a summarization of attributes or apparent movements of a tag between discrete detection events; indicates timing of predation event in relation to tag's sequence of detection events.

Event Time Threshold: Gap in time between detections at a station that distinguishes one detection event from another.

Far-field: Relating to acoustic detection data of a single tag interpreted in the context of a regional or study-wide collection of stations.

Far-field Residence Time: Time lag from first detection of tag at specified collection of stations (“region”) to first, or alternatively last, detection of tag in current detection event at station in the same region.

Hybrid Filter: An approach for diagnosing tag predation that combines elements used by both rule-based and pattern recognition filters.

Hydrophone: Underwater licensing device typically contained within or connected to a receiver; assumed to be stationary for the purpose of this document.

Lévy exponent (b): The exponent of a power function defining the relationship between step length and the frequency of occurrence of a step length.

Metric: Features used to diagnose tag predation events within a predator filter. These may be continuous, ordinal, or categorical and are based directly on measured variables, including summarizations, transformations, and/or combinations of measured variables.

Mid-field: Relating to acoustic detections of a single tag at a station interpreted in the context of detections of the same tag at neighboring stations.

Mid-field Residence Time: Entire time lag between first and last detections of tag at a station without intervening detections elsewhere.

Near-field: Relating to acoustic signal data of a single tag obtained in the vicinity of a single receiver or station. May also refer to detections uninterrupted by time gaps beyond a specified maximum duration (event time threshold).

Near-field Residence Time: Time lag between first and last detections of tag at a station without intervening detections elsewhere or time gaps beyond a specified maximum duration.

Pattern Recognition Filter: Approach for diagnosing tag predation that involves application of one or more statistical or machine learning procedures. Though automated, these approaches still require subjectivity in the selection of metrics, transformations, and tuning parameters. Pattern recognition generally requires some amount “labelled” data – meaning a set of metrics which are identified *a priori* as either predator or non-predator.

Predation Tag: An electronic tag that transmits a uniquely identifiable acoustic signal that switches to an alternative signal version upon predation of the tag, such as when a coating is dissolved within the gut of a predator or when loss of equilibrium is detected by an accelerometer.

Predator Filter: Any formal approach for identifying and removing invalid portions of acoustic tag detection histories due to tag predation, applied after removal of false positives caused by signal misreads and prior to the primary data analysis. This term encompasses rulesets, statistical procedures, and algorithms used to identify whether, and optionally when, a tagged study subject was predated.

Presence/absence Data: Detection data indicating the presence of a unique tag in the detection range of one or more receivers and the timing of detection.

Receiver: Device that records the timing and transmitter identifier of acoustic signals detected by an associated hydrophone; assumed to be stationary for the purpose of this document.

Receiver-level Event: Acoustic detection event aggregated at the level of an individual receiver.

Receiver Line: Collection of one or more receivers or hydrophones arranged in parallel across a river channel; combined detection range assumed to be the cross-section of the channel. Also referred to as "line" or "gate".

Rule-based Filter: Approach for diagnosing tag predation that involves the application of a predefined set of rules based on past research or expert judgement.

Signal-based Filter: An approach for identifying tag predation that relies entirely on data sent from the tag, such as temperature, depth, or predation signal triggered by the predation or digestive process (see "predation tag"), or else relies on interpreting temporal patterns in signal strength.

Station: Location that may contain one or more receivers or hydrophones in one or more lines, whose purpose is defined by the study design.

Supervised Learning: An algorithm that bases its knowledge acquisition on the attributes of subjects with known labels (e.g., fate classification) and seeks to generalize to a new set of unlabeled subjects (see also unsupervised learning). For example, a model or classification tool intended to identify ("label") smolt tags that have been consumed by a predator can be "trained" using a data set where the fate (retained by smolt vs. tag predation) of all tags is known.

Tag: Acoustic transmitter attached to or implanted in a study subject (e.g., fish) that transmits uniquely identifiable acoustic signal at regular intervals.

Tag-level: Classification of a tag as representing the original study subject or a predator based on a summary of the full detection history; indicates whether the tag is or has been in a predator by the end of its detection history but not when the predation event occurred.

Tag Predation: Consumption of tagged study subject and transfer of the active tag to the consuming predator.

Tag Signal: An individual recording of a specific frequency or coded message indicating that a uniquely identifiable tag is within the detection range of a receiver (e.g., "ping" or "hit"); this record may represent a misreading or a false positive.

Tortuosity (τ): A measure characterizing the extremity of changes to the turn angle of a track (see Romine et al. 2014).

Track-level: Classification of a study subject's status as predated or not predated based on a change that occurs while the study subject's position is effectively being continuously monitored.

This type of classification requires a sufficient number of receivers in close enough range and configured in such a way that they generate a sequence of time-indexed positions (coordinates; i.e., a multi-dimensional positioning array).

Unsupervised Learning: An algorithm that seeks to combine (cluster) unlabeled subjects into groups based on similarities in their characteristics (see also supervised learning). In this case, a data set is thought to contain a mixture of two or more classes of individuals, none of whose identities are known. These approaches search for the latent grouping based on multivariate measures of dissimilarity.

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