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MANAGEMENT BRIEF

Retention of T-bar anchor tags by adult steelhead during their upstream migration

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Abstract

Objective: T-bar anchor tags can be used to obtain recapture data from anglers, directly estimate exploitation, and evaluate population dynamics. However, their use by biologists to study anadromous salmonid fisheries is limited. Two hurdles to adoption include the functional difficulty of tagging large anadromous salmonids using conventional tagging equipment and a lack of information on tag loss by large anadromous salmonids and how it changes over time. As such, our objectives were to (1) describe a T-bar anchor tagging system modified to study adult steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) and (2) present an instantaneous tag loss model for steelhead that allows estimation of tag loss over time.

Methods: First, we developed a modified tagging system by tagging hatchery-obtained steelhead carcasses and live, resident Rainbow Trout larger than 500 mm using a variety of hardware and tag dimensions. Next, we double-tagged adult steelhead captured at the Lower Granite Dam adult fish trap, Washington, United States. We then used data from 182 recaptured steelhead to fit an instantaneous tag loss model. Last, we investigated whether steelhead tag loss was related to body length.

Result: Tag loss was generally low within the time period under study (i.e., up to 221 days between release and recapture). The estimated probability of tag loss was 0.034 at release, 0.044 at 1 month, and 0.113 at 8 months. We failed to detect significant differences in tag loss parameters between two data subsets consisting of small (<720-mm) and large (≥720-mm) steelhead.

Conclusion: T-bar anchor tags are useful external tags for studying adult steelhead during their upstream migration. Because anglers can be used to provide recapture data, T-bar anchor tags may be particularly useful where angler effort is high or direct estimation of fishery exploitation is desired.

KEYWORDS
fisheries, survey methods, tags and tagging, threatened and endangered species

INTRODUCTION

The marking and recapture of individuals allows for the collection of information on the abundance, movement, growth, mortality, and exploitation of fishes (Pine et al. 2012). Physical tags are widely used because they can allow fisheries professionals to identify individual fish and track them across capture events. Among physical tags, internal tags (i.e., tags placed fully inside the body and detected remotely) typically have higher retention rates compared to external tags (i.e., tags attached to the outside of the body and detected visually) but are more expensive (Buzby and Deegan 1999; Bodine and Fleming 2014; Zentner et al. 2021). Detecting internal tags also requires expensive, specialized equipment that is not generally available to anglers (Pine et al. 2012). Consequently, external tags are preferred when budgets are limited or when anglers are used to provide recapture data—a practice widely used to study exploited fish populations (e.g., Meyer and Schill 2014).

A critical consideration of mark–recapture studies is tag loss, or the probability that a given fish loses its tag during the study. Failure to account for tag loss can result in underestimated recapture rates that bias subsequent estimates of exploitation, harvest, abundance, and demographic rates (Miranda et al. 2002; Koenigs et al. 2013; Zentner et al. 2021). The proportion of tags lost during a mark–recapture study depends on characteristics of the tag (e.g., type, size, and placement), the fish being tagged (e.g., species, size, behavior, life stage, health), the habitat used by the tagged fish, the method of recapture (e.g., angling versus gill net), and the time elapsed since tagging occurred (Smith and McPherson 1981; Walsh and Winkelman 2004; Pine et al. 2012; Zentner et al. 2021). Directly estimating tag loss during the study is ideal, but sometimes logistically infeasible (e.g., Williamson 1999; Skilbrei and Jørgensen 2010; Null et al. 2013). Consequently, a lack of published tag loss estimates for a given species or setting can inhibit tag adoption even if retention is high (Pine et al. 2012).

Information on tag loss is typically obtained by double-tagging fish, a technique that allows individuals that shed one tag to be distinguished from untagged individuals (Pine et al. 2012). When double-tagged fish are recaptured, tag loss can be modeled using one of two analytical approaches. The most common approach is to compute the ratio of double-tagged fish that retained both tags to the ratio of fish that retained only one tag at a discrete point in time (i.e., discrete tag loss; Wetherall 1982). Although accurate (McCormick and Meyer 2018), discrete tag loss models cannot account for changes in the probability of tag loss over time. Consequently, borrowing discrete tag loss estimates from published literature introduces bias if any individuals under study remain tagged for a different amount of time (t) than was originally used to create the estimate. Discrete tag loss estimates are also not suitable for long-term mark–recapture studies because t may vary considerably among individuals (e.g., when anglers are used to recapture fish). In contrast, instantaneous tag loss models quantify the relationship between tag loss and t, which allows the probability of tag loss to vary among individuals that remain tagged for different periods of time (Barrowman and Myers 1996). As such, instantaneous tag loss models offer additional insight and are more readily transferable to other studies than discrete tag loss models, which are only transferable when t is identical among all individuals in both studies.

Impact Statement

We developed a modified T-bar anchor tag to study anadromous salmonids, double-tagged adult steelhead during their upstream migration, and modeled the probability of tag loss through time. The rate of tag loss was low, indicating that modified T-bar anchor tags are suitable for studying steelhead during their upstream migration.

One of the most widely used external fish tags is the T-bar anchor tag (Pine et al. 2012). T-bar anchor tags contain unique fish identifiers, are easy to attach, and are visible to anglers. In addition, reporting information (e.g., a phone number) can be printed on the exterior portion of the tag. As such, T-bar anchor tags are ideal for studies that use angler reporting to provide recapture data over extended periods of time, a practice frequently used to study fisheries and exploited fish populations (Pine et al. 2012).

Steelhead *Oncorhynchus mykiss* (anadromous Rainbow Trout) is an ecologically, economically, and culturally important fish that is often the focus of intensive fisheries (Busby et al. 1996; Thorpe 1998). Declines in the distribution and abundance of wild populations have resulted in federal protections and a multitude of research focused on the movement, population dynamics, and exploitation of steelhead (Busby et al. 1996; Thorpe 1998). High angler effort in most steelhead fisheries makes angler reporting a promising avenue for data collection and makes T-bar anchor tags a promising tool for obtaining angler reports over the months-long steelhead season (Pine et al. 2012). Information gained from such reports could then be used to directly quantify angler behavior and effects on the population under study (e.g., angler encounter rate, harvest, and catch-and-release mortality).

The use of T-bar anchor tags to study adult steelhead was previously limited by two methodological hurdles. First, the size and musculature of adult steelhead makes them challenging to properly tag (i.e., positioning the anchor between the dorsal pterygiophores) using conventional tagging systems. Second, information on the retention of T-bar anchor tags in large salmonids, particularly adult anadromous salmonids migrating through freshwater habitat, is surprisingly limited. In fact, we are aware of only two instances in which loss of T-bar anchor tags was estimated for any anadromous salmonid species during its upstream migration, and neither study provided estimates of tag loss over time (i.e., Smith and McPherson 1981; Lubenau et al. 2024). Furthermore, every published estimate of time-specific tag loss by *O. mykiss* of which we are aware solely used freshwater-resident, hatchery-reared Rainbow Trout no larger than 366 mm (McAllister et al. 1992; Mourning et al. 1994; Nuhfer et al. 1996; Walsh and Winkelman 2004; McCormick and Meyer 2018). Consequently, the use of T-bar anchor tags on adult steelhead (500–1000 mm fork length [FL] in the Snake River; Copeland et al. 2017) has been limited relative to their value as a research tool. Here, we qualitatively evaluate the effectiveness of a standard T-bar anchor tagging system designed for resident salmonids, present a modified T-bar anchor tagging system designed specifically for adult steelhead, and estimate tag loss over time during their upstream migration through a popular freshwater fishery.

METHODS

Tag development

The Idaho Department of Fish and Game (IDFG) has extensively used T-bar anchor tags to estimate demographic rates and angler exploitation rates for resident sport fishes (Meyer and Schill 2014), but not for steelhead. Consequently, we first investigated the effectiveness of "standard" Floy FD-94 T-bar anchor tags (Floy Tag and Manufacturing) by tagging adult steelhead carcasses obtained from IDFG hatcheries. Standard tags were 77 mm long and consisted of a 17-mm monofilament leader followed by a 60-mm rubber streamer intended to rest outside of the fish, upon which a unique identification code and IDFG contact information were printed. We inserted tags between the dorsal pterygiophores under the base of the dorsal fin (Smith and McPherson 1981; Zentner et al. 2021) using a Mark III Regular Pistol Grip Tagging Gun (Avery Dennison) equipped with a Regular Needle, which allowed a maximum insertion depth of 16 mm. We then dissected tagged carcasses to evaluate whether tags were properly affixed. This investigation identified two inadequacies of the tagging system. First, the short insertion depth of Regular Needles made it difficult to properly affix tags between the dorsal pterygiophores, particularly in 675-mm-FL and larger steelhead. Second, proper insertion between the pterygiophores of large steelhead often resulted in the streamer becoming partially embedded in the dorsal musculature, thereby preventing anglers from easily reading information printed on the streamers. Because both inadequacies inhibit the ability of T-bar anchor tags to provide recapture data, a new tagging system was developed. We used a Mark II Long Pistol Grip Tagging Gun (Avery Dennison) equipped with a Super Heavy-Duty Needle (allowing a maximum insertion depth of 29 mm) to inject custom-ordered "modified" Floy FD-94 T-bar anchor tags. Modified tags were also 77 mm long (a manufacturer requirement), but the monofilament leader was extended from 17 to 32 mm and the streamer was shortened from 60 to 45 mm (Figure 1). These new dimensions were chosen to maximize the length of the leader while retaining enough streamer length to print reporting information (e.g., agency and phone number). We assessed this modified tagging system first by tagging additional steelhead carcasses and later by tagging live, resident Rainbow Trout larger than 500 mm, which were angled from a broodstock pond located at the Clearwater Fish Hatchery (Ahsahka, Idaho). The longer insertion depth of Super Heavy-Duty Needles resulted in more consistent affixation to dorsal pterygiophores, and the streamer of modified tags did not become embedded in the dorsal musculature of Rainbow Trout or steelhead of any size. Consequently, modified T-bar anchor tags paired with Mark II Long Pistol Grip Tagging Guns and Super Heavy-Duty Needles were adopted for tagging adult steelhead.

Fish sampling

We double-tagged adult steelhead captured by the adult fish trap at Lower Granite Dam (Harmon 2003), a run-of-the-river hydroelectric dam operated by the U.S. Army Corps of Engineers on the Snake River in southeast Washington. The adult fish trap is used by IDFG and other agencies to obtain systematic random samples from the steelhead run for monitoring and research (Harmon 2003; Camacho et al. 2018). For the duration of the 2019 and 2020 steelhead runs, approximately 20% of captured steelhead were randomly selected for double-tagging. We selected 216

FIGURE 1 Photograph of standard (A) and modified (B) Floy FD-94 T-bar anchor tags. Modified T-bar anchor tags were used to tag adult Snake River steelhead during their upstream migration.

steelhead captured between July 9, 2019, and March 23, 2020, and an additional 401 steelhead captured between July 7, 2020, and April 29, 2021. All selected steelhead were anesthetized in accordance with standard IDFG procedures (Camacho et al. 2018), measured, and tagged with two modified nonreward T-bar anchor tags. All fish were tagged by IDFG and National Oceanic and Atmospheric Administration staff at Lower Granite Dam. Staff had previous experience in tagging adult steelhead and were provided detailed instruction on proper use of the new tagging system. All fish were tagged using new tagging equipment, and used needles were readily replaced with new needles at the discretion of individual taggers. The first tag was inserted just ventral to the posterior edge of the dorsal fin on the left side. The second tag was also inserted on the left side of the fish but approximately 3 cm in front of the first tag to ensure independent tag loss and avoid disturbing the anchor of the first tag when injecting the second. We chose to place both tags on the same side of each fish to ensure that the injection of the second tag would not interfere with the anchor of the first and because placing both tags on the left side considerably reduced out-of-water handling time at the Lower Granite Dam adult tagging station. Prior to fish release, both tags were gently pulled away from the insertion point to ensure proper affixation to dorsal pterygiophores (Smith and McPherson 1981). Steelhead were then released into a recovery tank from which they could volitionally resume their upstream migration.

Tag reporting

Angler-encountered tags were reported using a toll-free telephone number printed on the streamer (1-866-258-0338), the IDFG "Tag You're It!" reporting Web page (https://idfg.idaho.gov/fish/tag/add), and by mail or drop-off at IDFG regional offices (Meyer and Schill 2014). Tags were also reported by agency-operated broodstock traps and weirs that encountered tagged steelhead. Anglers were asked to report the date of capture and number of intact tags visible on the fish. Data from all recaptured steelhead were pooled prior to analysis.

Data analysis

We estimated tag loss using the Barrowman and Myers (1996) instantaneous tag loss model, in which the probability of a fish retaining an individual tag for at least as long as time t following release, $Q(t)$, was defined as

$$Q(t) = \alpha e^{-Lt},$$

where α is the estimated probability of immediate tag retention at release and L is the estimated instantaneous tag loss rate. The probability of a fish losing a tag by time t can then be obtained by computing $1 - Q(t)$. The Barrowman and Myers (1996) model is the most common model used to estimate tag loss in the fisheries literature (e.g., Hampton 1997; Adam and Kirkwood 2001; Vandergoot et al. 2012). We fit the model using the negative log-likelihood minimization technique described by Barrowman and Myers (1996; see McCormick and Meyer 2018 for additional details). We fit models using the "optim" function in program R (R Core Team 2021) and used nonparametric bootstrapping to estimate confidence intervals (CIs) for each parameter. Specifically, we conducted 10,000 bootstrap iterations and estimated 95% CIs using the 2.5% and 97.5% quantiles of the bootstrap distribution.

Statistically significant relationships between fish length and tag loss have been identified for other species (e.g., Nuhfer et al. 1996; Rude et al. 2011), so we sought to identify whether such a relationship was present in our data. First, we attempted to include steelhead FL as an additional covariate in the Barrowman and Myers (1996) model, but the model consistently failed to converge. Instead, we divided our data into two subsets consisting of small (<720-mm FL) and large (≥720-mm FL) steelhead and we fit separate Barrowman and Myers (1996) models to each data set. We selected the 720-mm breakpoint because this value (1) separated the mean adult body lengths of Snake River steelhead populations classified as "A-run" and "B-run" (two different life history strategies; Copeland et al. 2017; Figure 2); (2) separated two prominent modes in the length distribution of recaptured steelhead

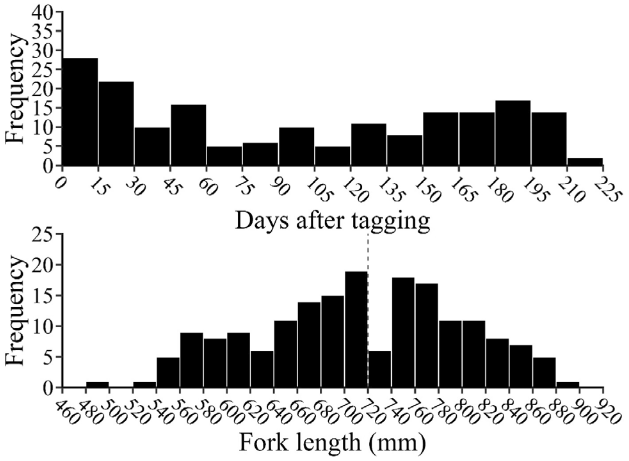

FIGURE 2 Number of days between tagging and recapture (days after tagging; top panel) and fork length at tagging (bottom panel) for the adult Snake River steelhead that were used to model T-bar anchor tag loss ($n = 182$ recaptured individuals). The gray dashed line marks the breakpoint used to separately model tag loss by small (<720-mm) and large (≥720-mm) steelhead.

TABLE 1 Parameter estimates and bootstrapped 95% confidence intervals (2.5% and 97.5%) for instantaneous T-bar anchor tag loss models fit to all available steelhead data (i.e., 500–900 mm fork length [FL]; $n=182$ fish) and to data subsets consisting of small steelhead (i.e., <720 mm FL; $n=89$ fish) and large steelhead (i.e., ≥720 mm FL; $n=93$ fish), where α denotes the probability of immediate tag retention at release and L denotes the instantaneous tag loss rate.

Data set	Parameter	Estimate	2.5%	97.5%
All fish	α	0.966	0.926	0.988
	L	3.58×10^{-4}	5.23×10^{-5}	5.14×10^{-4}
Small fish	α	0.975	0.913	0.996
	L	2.28×10^{-4}	-2.29×10^{-4}	5.98×10^{-4}
Large fish	α	0.960	0.898	0.995
	L	5.42×10^{-4}	-4.15×10^{-5}	1.14×10^{-3}

(Figure 2); and (3) created two subsets of roughly equal sample size (Table 1). We compared bootstrapped 95% CIs between models to infer whether α or L differed between small and large steelhead.

RESULTS

The 617 steelhead that we double-tagged and released averaged 717 mm FL but varied between 500 and 900 mm FL. Of these 617 fish, 182 individuals were encountered and reported by anglers 1–221 days after release (Figure 2). Of the 182 recaptured fish, 160 individuals retained both tags at the time of recapture and 22 retained only one tag. The instantaneous tag loss model estimated that the probability of tag loss was 0.034 (95% CI = 0.012–0.074) at release, whereas the probability of tag loss was 0.044 (95% CI = 0.011–0.088) at 1 month (i.e., 30 days) and 0.113 (95% CI = 0.00–0.18) at 8 months (i.e., 240 days, the approximate maximum duration of freshwater steelhead migrations [Busby et al. 1996] and 19 days longer than the duration of this study; Table 1; Figure 3).

The instantaneous tag loss models fit to the small (<720-mm FL; $n=89$) and large (≥720-mm FL; $n=93$) steelhead data sets both successfully converged. Estimates of α were 0.975 (95% CI = 0.913–0.996) for small steelhead and 0.960 (95% CI = 0.898–0.995) for large steelhead. Estimates of L were 2.28×10^{-4} (95% CI = -2.29×10^{-4} to 5.98×10^{-4}) for small steelhead and 5.42×10^{-4} (95% CI = -4.15×10^{-5} to 1.14×10^{-3}) for large steelhead (Table 1). Because the 95% CIs of α and L broadly overlapped between both models, we failed to identify a difference in α or L between small and large recaptured steelhead.

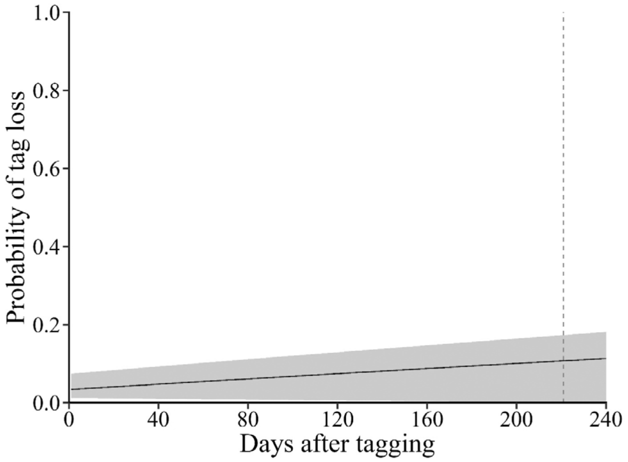

FIGURE 3 Probability of T-bar anchor tag loss over time for all recaptured adult steelhead, as estimated by the instantaneous tag loss model ($n=182$ recaptured individuals). Gray shading depicts bootstrapped 95% confidence intervals; the gray dashed line marks the maximum number of days between release and recapture observed in this study.

DISCUSSION

Retention of T-bar anchor tags by adult steelhead during their upstream migration was relatively high (e.g., 89% at 8 months after release), making them ideal tools for studying fishery exploitation during this short but critical life history stage. Our simple modifications to a low-cost tagging system developed for resident fishes improved the ease with which steelhead and other large salmonids can be properly tagged, and our instantaneous tag loss model will help to facilitate the future use of angler reporting to provide recapture data. These approaches may be particularly useful for studying anadromous salmonids during their upstream migration because angler encounter rates are typically high and fishery exploitation is rarely estimated directly (Lubenau et al. 2024 and references therein).

Previous investigations have noted an effect of habitat type on T-bar anchor tag loss (e.g., Ebener and Copes 1982; Nuhfer et al. 1996), which raises the question of whether our tag loss model is transferable to other systems. To our knowledge, in all instances in which habitat was shown to affect tag loss, the proposed mechanism was the snagging and accumulation of emergent vegetation and filamentous algae on tags in eutrophic lentic habitats (Carline and Brynildson 1972; Ebener and Copes 1982; Nuhfer et al. 1996). In contrast, the steelhead that we tagged subsequently migrated through a deep mesotrophic reservoir and oligotrophic river where emergent vegetation and filamentous algae were rare. As such, our results are likely transferable to other settings where the chance of tags snagging on vegetation or accumulating algae is low, as is the case with many salmonid migration corridors in the Pacific Northwest.

Our tag loss model is likely not transferable to steelhead or other anadromous salmonids that are actively spawning. Smith and McPherson (1981) provided the only available account of T-bar anchor tag loss by anadromous salmonids before and after spawning. In that investigation, estimated T-bar anchor tag loss by double-tagged adult Chinook Salmon *O. tshawytscha* that were recaptured over 150 km upstream of their tagging location in the Rogue River, Oregon, was 0%. One to 2 months later, 30% of tagged Chinook Salmon carcasses encountered during spawning ground surveys were missing one tag. Although some tags were certainly lost after spawning or death, the combined effect of snagging on woody debris and other complex structures in small streams, redd digging and egg burial by females, territorial biting and aggression by males, and rapid weight loss by both sexes likely elevates tag loss once spawning begins (Lister and Harvey 1969; Smith and McPherson 1981; Brewin et al. 1995).

Tag loss by some fish species is size dependent (e.g., Nuhfer et al. 1996; Rude et al. 2011). We investigated this possibility for adult steelhead and failed to identify a statistically significant difference in α or L between small and large individuals. Although our tests may have been conservative with respect to statistical power, we note that the 95% CIs for all models indicated that tag loss was generally low, particularly within the relatively short duration over which anadromous salmonids conduct their upstream migration (Busby et al. 1996; Copeland et al. 2017). As such, any undetected size bias in tag loss by 500–900-mm steelhead was likely minimal and does not preclude the use of T-bar anchor tags as a research tool.

Over the course of this study, we encountered a belief held by some fisheries professionals that T-bar anchor tags are not useful for studying anadromous salmonids because the fish are too large to effectively tag. Our results indicate that this concern may be unfounded. We hope that the novel tagging system and tag loss model presented here will help facilitate the future use of T-bar anchor tags to study anadromous salmonid populations, particularly during their upstream migration (e.g., Lubenau et al. 2024). Because angler reporting can be simultaneously used to provide recapture data and directly estimate exploitation, the T-bar anchor tag may become an increasingly useful tool for studying the popular anadromous salmonid fisheries in the Pacific Northwest and elsewhere.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest declared in this article.

DATA AVAILABILITY STATEMENT

Fish data are property of the Idaho Department of Fish and Game but can be made available upon reasonable request.

ETHICS STATEMENT

This work was conducted under protocol 2018-63 approved by the Institutional Animal Care and Use Committee at the University of Idaho.

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