MANAGEMENT BRIEF

Targeting Aggregations of Telemetered Lake Trout to Increase Gillnetting Suppression Efficacy

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Abstract

Conserving Yellowstone Cutthroat Trout *Oncorhynchus clarkii bouvieri* by suppressing invasive Lake Trout *Salvelinus namaycush* in Yellowstone Lake is a high priority for Yellowstone National Park resource managers. Here, we tested whether targeting telemetered Lake Trout could increase the efficacy of Lake Trout suppression by gill netting. Mobile acoustic tracking surveys were performed to identify aggregations of tagged Lake Trout in summer (June–August) 2017. Lake Trout aggregations were relayed daily to suppression crews by phone, radio, or text and a printed map. Suppression crews set 30 large-mesh gill nets targeting telemetered Lake Trout aggregations (target treatment) and 124 large-mesh gill nets not targeting telemetered aggregations (nontarget treatment). Mean $\log_e$(CPUE) was higher for the target treatment (0.37; 95% credible interval [CRI] = 0.08–0.65) than for the nontarget treatment (−0.37; 95% CRI = −0.51 to −0.21). Mean of the target treatment was higher than the mean of the nontarget treatment for over 99% of the 1,000 draws from the joint posterior distribution. Because of telemetry costs, mean CPUE per US$10,000 spent was similar between the target treatment (0.20; 95% CRI = 0.15–0.26) and the nontarget treatment (0.15; 95% CRI = 0.13–0.17). Telemetry is an effective strategy for improving Lake Trout CPUE, which corresponds to an increased efficiency in the Lake Trout suppression program.

The Lake Trout *Salvelinus namaycush* is an important commercial and recreational fish that has been widely introduced in North America (Crossman 1995). Through predation, competition, or both, invasive Lake Trout have caused the decline of salmonid populations throughout the intermountain western United States (Martinez et al. 2009; Guy et al. 2011; Syslo et al. 2013; Fredenberg et al. 2017). For example, the introduction of invasive Lake Trout into Lake Tahoe led to the extirpation of native Lahontan Cutthroat Trout *Oncorhynchus clarkii henshawi* (Crossman 1995). By the end of the 20th century, invasive Lake Trout had replaced Bull Trout *S. confluentus* as the most abundant salmonid in several lakes in Glacier National Park (Fredenberg 2002).

Suppression programs are often expensive and monetarily burdensome to natural resource agencies worldwide (Veitch and Clout 2002; Simberloff et al. 2005; Simberloff 2014), and many suppression programs fail to meet management objectives because of the long-term costs (Gozlan et al. 2010; Britton et al. 2011). Improving the efficacy and cost-effectiveness of suppression programs is a top priority for natural resource agencies (Buhle et al. 2005). When

suppression effort is limited, using the most efficient gear at the time when the target species is most vulnerable can increase suppression efficacy (Britton et al. 2011). In many cases, resource managers try novel and creative removal strategies to increase the efficacy of invasive species suppression (Loppnow et al. 2013; Bouska et al. 2017; Thomas et al. 2019).

Telemetry is a versatile tool and has proven to be beneficial in the suppression and control of invasive species (Lennox et al. 2016; Crossin et al. 2017). One creative use of telemetry is to locate and target aggregations of tagged individuals, often referred to as the "Judas technique." This removal strategy was developed for the eradication of invasive goats *Capra hircus* from small islands in the Pacific Ocean (Taylor and Katahira 1988; Campbell and Donlan 2005) and has been successfully applied to a variety of other terrestrial invasive species (McCann and Garcelon 2008; Cruz et al. 2009; Smith et al. 2016). For telemetry to be highly effective in suppression methods, the target species must form aggregations. Many fish species form aggregations at some point during their life history (Pitcher 1986); therefore, locating and targeting these aggregations may constitute an effective strategy for suppressing invasive fishes (Bajer et al. 2011). For example, Common Carp *Cyprinus carpio* form large shoals during the winter (Penne and Pierce 2008) and targeting aggregations was successful at suppressing the adult population in experimental lakes (Bajer et al. 2011).

Mature Lake Trout exhibit shoaling behavior during spawning and aggregate in specific habitats during the summer (Martin and Olver 1980; Binder et al. 2014; Williams 2019). Thus, targeting aggregations of telemetered Lake Trout should increase the efficacy of the Lake Trout suppression program in Yellowstone Lake and may be useful in the suppression of other aquatic invasive species. Our objective was to evaluate the efficacy and cost–benefit of targeting aggregations of telemetered Lake Trout by using gill nets during the summer, when catch rates of Lake Trout are lowest, in Yellowstone Lake.

METHODS

Study site.— Yellowstone Lake is located in Yellowstone National Park, Wyoming (Figure 1). Yellowstone Lake has a mean depth of 48 m, a maximum depth of 133 m, and a surface area of 34,020 ha (Kaplinski 1991). Yellowstone Cutthroat Trout *O. clarkii bouvieri* and Longnose Dace *Rhinichthys cataractae* are the only two native fish species in the lake. Four nonnative fish species are established there: the Lake Trout, Longnose Sucker *Catostomus catostomus*, Redside Shiner *Richardsonius balteatus*, and Lake Chub *Couesius plumbeus*.

Lake Trout were first discovered in Yellowstone Lake in 1994 and are believed to have been introduced in the mid-1980s (Kaeding et al. 1996; Munro et al. 2005). The introduction and establishment of invasive Lake Trout have resulted in the decline of native Yellowstone Cutthroat Trout abundance over the last three decades (Koel et al. 2019a). Yellowstone Cutthroat Trout are an important ecological resource within the Yellowstone Lake ecosystem due to their role as prey for terrestrial species, such as grizzly bears *Ursus arctos horribilis*, ospreys *Pandion haliaetus*, and others (Koel et al. 2005, 2019b).

The National Park Service implemented gill netting in 1995 to suppress Lake Trout abundance, with the intent of reducing the negative effects of Lake Trout on the Yellowstone Cutthroat Trout population (Koel et al. 2007; Syslo et al. 2011). About 3.2 million Lake Trout have been removed since suppression began, and population modeling indicates that the suppression effort is resulting in a decrease in Lake Trout abundance (Syslo 2015).

Sampling procedures.— Lake Trout used in this study were part of a concurrent study by Williams (2019). Mature Lake Trout ($N = 141$) were surgically implanted with CART series transmitters (Lotek Wireless, Newmarket, Ontario) and were tracked in 2017. For a detailed description of transmitter allocation, see Williams (2019). Lake Trout were located by using portable Lotek MAP 600 acoustic receivers equipped with two Lotek LHP_1 directional hydrophones. Yellowstone Lake was delineated into four tracking regions (Figure 1), and ArcMap version 10.3.1 (ESRI, Redlands, California) was used to construct standard tracking transects for each region. Each transect covered all depths <60 m and was surveyed twice per month in summer (June–August) 2017. Tracking surveys were conducted from 0600 through 1600 hours at a maximum speed of 9.7 km/h. Lotek MapHost software was used to determine Lake Trout locations. When a Lake Trout was detected, the boat was slowed to 4.8 km/h and was oriented in the direction of the target Lake Trout. The Universal Transverse Mercator position when the hydrophones passed over a target Lake Trout—indicated by a sudden change from high signal strength to low signal strength or no detection—was used as the estimated Lake Trout location.

Aggregations were defined as two or more tagged Lake Trout in close proximity (i.e., ≤500 m) of each other. Locations of Lake Trout aggregations were relayed to Hickey Brothers Research (HBR) contract gillnetting crews. The Universal Transverse Mercator locations and depths of aggregations were relayed in real time by radio, cell phone, or text message to HBR crews. After each tracking survey, a map of all Lake Trout locations and depths was provided to the HBR project leader to guide gill-net placement the following morning and the boat captain decided where to set nets at the identified locations.

Monofilament gill nets were 3-m high and 2,743–3,300-m long. Gill nets were constructed with a single mesh size
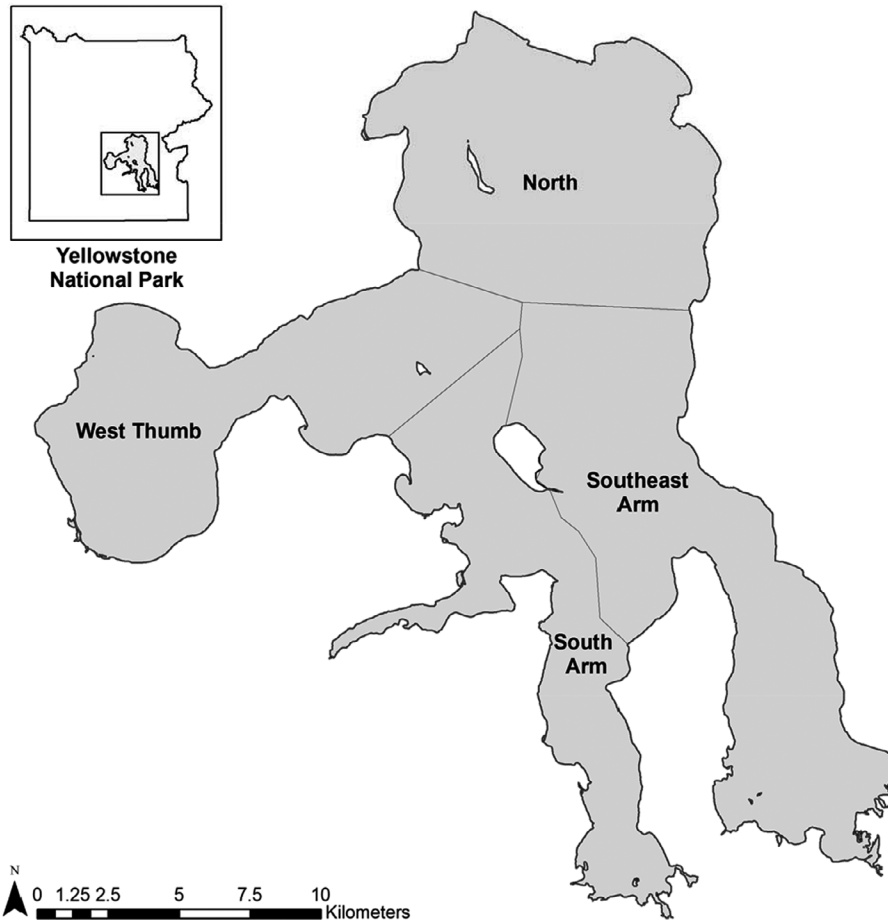
FIGURE 1. Map of the study site (Yellowstone Lake) in Yellowstone National Park, Wyoming. Gray lines delineate the four Lake Trout tracking regions within Yellowstone Lake (North, West Thumb, South Arm, and Southeast Arm).

(stretch) of 89, 102, 114, or 127 mm. Nets were set on the bottom, and soak time varied from one to four nights. The CPUE was calculated as the number of Lake Trout captured per 100 m of net per night. Nets set at Lake Trout aggregations were considered the target treatment ($N = 30$). All other HBR gill nets of the same mesh sizes that were set during the same time frame as the target treatment (June–August) were considered the nontarget treatment ($N = 124$). Nets were fished identically for both treatments.

Residuals of CPUE were analyzed by plotting the model and using the "compareqqnorm" function in the R package "blmeco" (Korner-Nievergelt et al. 2015). The analysis of the residuals and quantile–quantile plots indicated that the CPUE data were not normally distributed; thus, CPUE data were natural log transformed and the residual analysis was repeated. $\text{Log}_e(\text{CPUE})$ data were normally distributed, and Bayesian analysis was performed on $\text{log}_e(\text{CPUE})$ by using a linear model with a normal distribution. We used a Bayesian approach to evaluate the probability of the difference between

treatment means given the data and to avoid the pitfalls associated with P-values and significance testing (Amrhein et al. 2019). The Bayesian analysis followed methods outlined by Korner-Nievergelt et al. (2015). For the Bayesian analysis, we used the "sim" function with 1,000 independent simulation draws and uniform priors in the "arm" package (Gelman and Yu-Sung 2018). The means of the simulated values from the joint posterior distribution of model parameters were used to determine whether treatments differed, and the 2.5% and 97.5% quantiles were used for the lower and upper 95% credible intervals (CRI).

The CPUE for each US$10,000 spent was estimated for nontarget and target treatments to further evaluate the efficacy of using telemetry in suppression efforts (hereafter, all monetary values are reported in US$). Estimates of CPUE per $10,000 were derived from the 2017 total cost for suppression netting, total units of effort in 2017, and telemetry costs. The CPUE per $10,000 spent was calculated using the back-transformed mean CPUE from the Bayesian posterior distribution for nontarget and target treatments
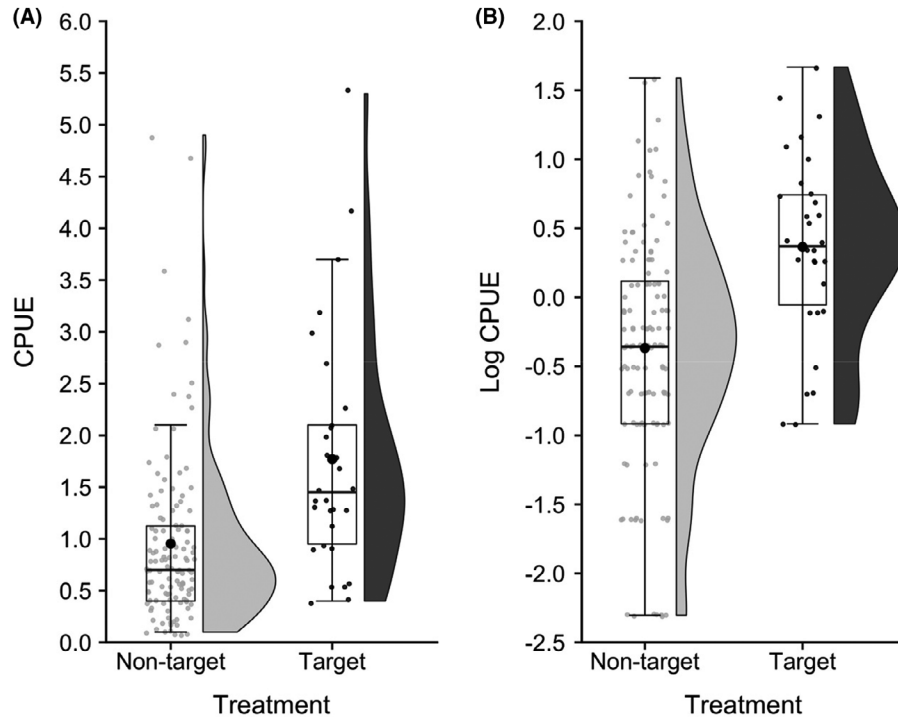
FIGURE 2. Lake Trout (**A**) CPUE (number of Lake Trout captured per 100 m of net per night) and (**B**) log$_e$(CPUE) from gillnetting efforts that were not informed by telemetry (nontarget treatment) and gillnetting efforts that were informed by telemetry (target treatment) in Yellowstone Lake, Yellowstone National Park. Box ends represent the 25th and 75th quartiles, horizontal lines are the median, large solid circles are the mean, whiskers represent 1.5 times the interquartile range, and small circles delineate raw data.

divided by the cost per unit effort standardized to 30 net-nights (i.e., the number of gill-net sets for the target treatment) multiplied by 10,000. The cost for the target treatment also included telemetry costs that were prorated for 3 years—the estimated life of the CART transmitters. Variation in CPUE per $10,000 spent was estimated using the back-transformed credible intervals for CPUE from the Bayesian posterior distributions (see above).

RESULTS

During summer 2017, suppression crews conducted 124 gill-net sets for a total of 13,575 net-nights that did not target telemetered Lake Trout aggregations (nontarget treatment). In addition, suppression crews deployed 30 gill-net sets targeting Lake Trout aggregations that were identified through telemetry (target treatment) for a total of 2,319 net-nights. Nontarget treatment nets captured 12,025 Lake Trout, and target treatment nets captured 3,033 Lake Trout. Untransformed mean CPUE varied from 0.95 for the nontarget treatment to 1.77 for the target treatment (Figure 2). The range in CPUE was similar between treatments: 4.8 for the nontarget treatment and 4.9 for the target treatment. Mean log$_e$(CPUE) varied from −0.37 (95% CRI = −0.51 to −0.21; $N = 124$) for the nontarget treatment to

0.37 (95% CRI = 0.08–0.65; $N = 30$) for the target treatment (Figure 2). The posterior distributions of the treatment means were well separated (Figure 3), and the mean difference between treatment means was −0.73 (95% CRI = −1.06 to −0.40). The mean of the target treatment was higher than the mean of the nontarget treatment for over 99% of the 1,000 draws from the joint posterior distribution. Thus, we are 99% certain that tracking Lake Trout and providing real-time information to the commercial netting operators increased the CPUE of Lake Trout in Yellowstone Lake.

The Lake Trout suppression contract was $1,660,000, and suppression crews performed 81,886 units of gill-net effort in 2017, which valued each unit of effort at $20.27. For 30 gill-net sets (2,319 net-nights), the cost was $47,006. The target treatment costs included the cost of 30 gill-net sets plus telemetry costs (personnel: $3,000; receiver and hydrophones: $3,213; CART transmitters: $21,150), totaling $74,369. The CPUE per $10,000 spent was 0.15 (95% CRI = 0.13–0.17) for the nontarget treatment and 0.20 (95% CRI = 0.15–0.26) for the target treatment.

DISCUSSION

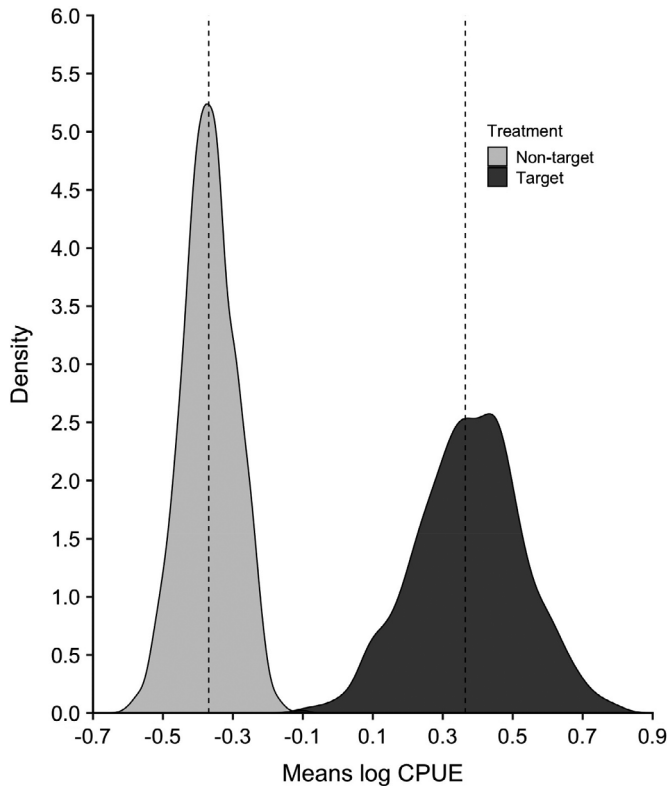Targeting the known locations of tagged Lake Trout during the summer increased the CPUE in large-mesh gill

FIGURE 3. Density distribution of simulated values from the joint posterior distributions of the treatment means ($\log_e$[CPUE] of Lake Trout). Vertical lines delineate the mean for each treatment (mean = −0.37 [nontarget] and 0.37 [target]).

nets compared to the standard gillnetting protocol in Yellowstone Lake. Despite the observed increase in CPUE for the target treatment, the added cost of telemetry methods caused the CPUE per $10,000 to be similar to that for the nontarget treatment. The additional telemetry costs could be decreased in the future by switching from a CART series transmitter ($450) to a standard acoustic transmitter (~$300) and by using the hydrophone and receiver for more than 3 years. Although targeting Lake Trout by use of telemetry did not provide much of a short-term cost savings, targeting Lake Trout did increase the CPUE by twofold during a period when the CPUE of Lake Trout in suppression efforts typically decreases. Increasing the CPUE will ultimately reduce the time required to meet the target objectives for Lake Trout abundance established by the National Park Service (NPS 2010), and the reduction in time will undoubtedly reduce the long-term monetary costs to the National Park Service.

We are aware of many anecdotal observations of using telemetry to increase CPUE in suppression programs. However, to our knowledge this study is the first that has experimentally tested the use of targeting telemetered invasive fish to increase suppression efficacy relative to nontargeted efforts. Targeting of telemetered Lake Trout was effective at increasing the CPUE, and the added telemetry costs did not outweigh the benefit of using telemetry to increase CPUE. Therefore, using telemetry and targeted netting will further increase the catch of adult Lake Trout and could decrease the time needed to meet management objectives (NPS 2010).

Telemetry is often used to target adult Lake Trout during the spawning season (e.g., Dux et al. 2011; Fredenberg et al. 2017; Williams 2019), with the goal of increasing the catch of adult Lake Trout to increase suppression efficacy. Although we did not evaluate targeting Lake Trout during the spawning season, we hypothesize that the results would be commensurate given a similar study design. Telemetry can be especially useful during the spawning season because Lake Trout are known to move among spawning locations in the presence of a disturbance, such as gill netting (C. Fredenberg, U.S. Fish and Wildlife Service, personal communication). Tracking of adult Lake Trout during the spawning season is also used to identify spawning locations (e.g., Dux et al. 2011; Fredenberg et al. 2017; Williams 2019), which is a prerequisite when considering novel suppression methods, such as embryo suffocation (Thomas et al. 2019). The premise for using multiple suppression methods (e.g., gill netting and embryo suffocation) to increase suppression efficacy is founded in the integrated pest management approach (Ehler 2006). Applying several suppression methods that target multiple life stages is more effective than the application of a single suppression method (Weber et al. 2011; Simberloff 2014; Lechelt and Bajer 2016).

The use of mobile telemetry to locate and target Lake Trout is labor intensive; therefore, investigation into less labor-intensive methods of tracking Lake Trout is warranted, such as autonomous watercraft (i.e., drones) that could continuously track fish and provide real-time locations to gillnetters. Recent technical advancements in autonomous surface vehicles (Liu et al. 2016) have expanded the potential for use of automated tracking in aquatic systems (Lennox et al. 2017). As adult Lake Trout densities decrease in Yellowstone Lake, which is predicted from statistical catch-at-age models (Koel et al. 2019a), continuing to track and target telemetered Lake Trout may help to maintain high catch rates and overall suppression efficacy.

nets in efforts to tag and target Lake Trout. The Montana Cooperative Fishery Research Unit is jointly sponsored by Montana State University; Montana Fish, Wildlife, and Parks; and the U.S. Geological Survey. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. This study was performed under the auspices of Protocol 2016-2 approved by the Institutional Animal Care and Use Committee at Montana State University. There is no conflict of interest declared in this article.

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