THESIS

EFFECTIVENESS OF LIGHT TRAPS FOR DETECTING RAZORBACK SUCKER LARVAE

Submitted by

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ABSTRACT

EFFECTIVENESS OF LIGHT TRAPS FOR DETECTING

RAZORBACK SUCKER LARVAE

Current management strategies for improving the status of wild and endangered Razorback Sucker *Xyrauchen texanus* rely on adequate larval sampling of wetland and riverine backwater habitats to evaluate post-reproductive survival, spatial and temporal patterns of distribution and abundance, and entrainment into wetlands. One strategy uses the detection of Razorback Sucker larvae to prompt flow releases to inundate Green River floodplain wetlands, habitat which may increase survival of those early life stages. Light traps, a passive sampling gear which exploits the innate attraction of fish early life stages to light, are thought an effective gear type for sampling, but little is known of their efficacy to capture or retain larvae. Therefore, we assessed usefulness of light traps for sampling or retaining Razorback Sucker larvae under a variety of environmental conditions using laboratory and field experiments.

In the laboratory, we investigated effects of light trap set time, release distance from trap, light presence, turbidity, light source, cover, and trap aperture on capture and retention probabilities of five early life stages of Razorback Sucker. Mean capture probability of protolarvae prior to the development of a swim bladder (7-9 mm total length [TL]) was 40% (28-55%) over the various treatments, but rose to 76% (73-80%) after protolarvae formed a swim bladder (9-10 mm TL). Mesolarvae (11-17 mm TL), the most commonly captured life stage in field sampling, had similar mean capture probabilities as later protolarvae at 86% (82-90%). Capture probability of metalarval (mean = 42%, range 21-63%; 15-24 mm TL) and juvenile

(mean = 24%, range 20-28%; 22-37 mm TL) life stages were lower. Retention probabilities of larvae placed in traps were generally >75% and increased to 97% for juveniles, but some fish nearly always escaped. The relationship between set time and release distances of 1, 3, and 5 m on capture indicated longer set times positively influenced capture probabilities while distance had little effect. Light presence in traps greatly increased capture and retention of larvae compared to unlit traps, and indicated traps lit with light-emitting diodes (LED) increased capture of Razorback Sucker larvae due to increased light intensity when compared to chemical-light-stick-lit traps. Light trap aperture widths of 4 or 6 mm did not influence capture or retention. Overall, laboratory experiments provided valuable information on how specific variables affect capture and retention of Razorback Sucker larvae in light traps and provide a framework for interpreting and designing field studies, which we were able to subsequently carry out.

Field experiments consisted of experimental releases of unmarked, single, and double-marked (immersion in oxytetracycline hydrochloride [OTC]) Razorback Sucker larvae over three nights in a managed wetland of the Green River, Utah at the Ouray National Wildlife Refuge. Batches of released larvae were paired with 1 of 12 light traps each night in various densities (10, 50, 250, 1,000 fish per trap), 3 and 10-m release distances from light traps, LED and chemical-light-stick light sources, and two release times to evaluate effects on larvae capture probabilities. In addition, batches of 25 single-marked larvae were placed in light traps and set on a fourth night in various environmental light conditions (night, sunrise, and sunlight) to evaluate effects on larvae retention. Light traps recaptured larvae each night, even with low density releases in the 53.5 ha wetland, and recapture probabilities ranged from 0 to 0.68. The LED trap capture probabilities were up to 2.5X greater than for chemical light stick traps, but capture probabilities

were not influenced by release distance or larvae density. Inexplicably, retention was very low, a result inconsistent with the previous laboratory tests.

Both laboratory and field experiments indicated light traps are a useful gear to monitor abundance of larvae, evaluate reproductive success of adults, and detect even low densities of larvae in large and open habitats. Additionally, light traps are suitable to detect presence of Razorback Sucker larvae in riverine backwaters each spring, the timing of which is used to begin high flow releases from Flaming Gorge Dam to inundate Green River, Utah, floodplain wetlands. Expanded ecological understanding of early life stages of Razorback Sucker will contribute to their conservation in the Colorado River basin.

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CHAPTER ONE:

LABORATORY EXPERIMENTS TO DETERMINE EFFECTIVENESS OF LIGHT TRAPS FOR CAPTURE AND RETENTION OF RAZORBACK SUCKER LARVAE

Captures of endangered Razorback Sucker *Xyrauchen texanus* larvae by light traps are used to monitor population recovery and prompt conservation activities including flow releases to inundate Green River floodplain wetlands, habitat which may increase survival of those early life stages. However, little is known about the efficacy of light traps to capture or retain larvae. In the laboratory, we investigated effects of light trap set time, release distance from trap, light presence, turbidity, light source, cover, and trap aperture on capture and retention probabilities of five early life stages of Razorback Sucker. Mean capture probabilities of protolarvae prior to the development of a swim bladder (7-9 mm total length [TL]) was 40% (28-55%) over the various treatments, but rose to 76% (73-80%) after protolarvae formed a swim bladder (9-10 mm TL). Mesolarvae (11-17 mm TL), the most commonly captured life stage in field sampling, had similar mean capture probabilities as later protolarvae at 86% (82-90%). Capture probabilities of metalarval (mean = 42%, range 21-63%; 15-24 mm TL) and juvenile (mean = 24%, range 20-28%; 22-37 mm TL) life stages were lower. Retention probabilities of larvae placed in traps were generally >75% and increased to 97% for juveniles. The relationship between set time and release distances of 1, 3, and 5 m on capture indicated longer set times positively influenced capture probabilities while distance had little effect. Light presence in traps greatly increased capture and retention of larvae compared to unlit traps, and indicated traps lit with light-emitting diodes (LED) may increase capture of Razorback Sucker larvae due to increased light intensity when compared to chemical-light-stick-lit traps. Light trap aperture widths of 4 or 6 mm did not

influence capture or retention. Light traps are a useful gear to monitor abundance of larvae and evaluate reproductive success of adults, as well as detect first presence of Razorback Sucker larvae in riverine backwaters each spring, timing of which is used to begin high flow releases from Flaming Gorge Dam to inundate Green River, Utah, floodplain wetlands. Expanded ecological understanding of early life stages of Razorback Sucker will contribute to their conservation in the Colorado River basin.

Introduction

The Razorback Sucker *Xyrauchen texanus* is a long-lived, large-bodied catostomid native to the arid Colorado River basin. Historically, Razorback Sucker was present from southwestern Wyoming downstream to the Gulf of California, occurring throughout the main stem river and larger tributaries including the Green, Colorado, San Juan, and Gila river basins (Bestgen 1990; Minckley et al. 1991; Platania et al. 1991; Marsh et al. 2015). Basin wide, Colorado River water development supports a rapidly expanding human population, now over 40 million people, in the southwestern US and Mexico. This has resulted in depleted or altered stream flow and sediment patterns, locally reduced water temperatures downstream from dams, blocked fish passage, and river channel narrowing from non-native vegetation establishment and diminution of peak flow magnitudes (Grams and Schmidt 2002; Udall and Overpeck 2017; Bestgen et al., in press). In addition to flow modification, introductions of more than 65 non-native species have also had negative impacts, as many prey upon and compete with native biota (Carlson and Muth 1989; Minckley et al. 1991; Bestgen et al. 2002; Olden et al. 2006; Bestgen et al., in press). These ecological modifications have resulted in widespread declines of native Colorado River basin fishes including Razorback Sucker, which was federally listed as endangered in 1991 (Minckley 1983; U.S. Fish and Wildlife Service 1991; Bestgen et al. 2002; Bestgen et al., in press; Figure

1.1). The once widespread and abundant wild populations of Razorback Sucker are believed extirpated (Marsh 1994; Bestgen et al. 2002; Bestgen et al., in press) but propagation and stocking of hatchery produced fish, which began in 1974, has reestablished many populations (Hamman 1985; Marsh et al. 2015; Bestgen et al., in press). Substantial stocking in the lower Colorado River basin, and the Green, Colorado, and San Juan Rivers has occurred since before the 1990s, and because of low or non-existent natural recruitment of young is considered the main mechanism by which these populations are maintained (Zelasko et al. 2010; Marsh et al. 2015; Bestgen et al., in press). Although stocked adult fish survive and reproduce, the few juvenile Razorback Suckers detected in widespread sampling indicates lack of survival of young fish to replace adult mortalities (Bestgen et al., in press).

The upper Colorado River basin, the area upstream of Lee's Ferry, AZ, has relatively natural flow regimes compared to the lower Colorado River basin and relatively fewer structures that are considered impassible to upstream fish movements (Bestgen et al. 2015; Bestgen et al., in press; Figure 1.1). Warmwater habitat of the Green River main stem upstream of the Colorado River is the longest unimpeded habitat remaining in the basin (588 km), and has high conservation value because it supports some of the largest populations of endangered and non-listed native fishes in the basin (Bestgen et al. 2015). There are two known spawning locations for Razorback Sucker in the middle Green River, including one located in the reach between the confluences of the Yampa and White rivers, where stocked hatchery fish return to and have been reproducing there since about 1999 (Muth et al. 2000; Bestgen et al. 2011; Zelasko et al. 2018). Razorback Sucker spawn on the ascending limb or peak of the hydrograph in the upper Green River, which when flows are of sufficient magnitude, transports larvae downstream and into floodplain wetlands in the reach (Tyus and Karp 1990; Wydoski and Wick 1998). Use of

floodplain wetlands by larval Razorback Sucker allows for rapid growth, a result of higher water temperatures than occur in the main-stem river and plentiful food, which increases potential for recruitment (Modde 1996; Modde et al. 2001; Bestgen 2008). Benefits of floodplain wetlands for recruitment of Razorback Sucker and other endangered fishes is witnessed in middle Green River managed floodplain wetlands such as Stewart Lake (e.g., Schelly et al. 2016; Bestgen et al. 2017). Larval Razorback Sucker entrainment into floodplain wetlands is maximized when peak snowmelt flows are concurrent with downstream dispersal of larvae from spawning areas.

Beginning in 2012, spring Green River flow releases from upstream Flaming Gorge Reservoir are triggered by first detection of larval Razorback Suckers, per the Larval Trigger Study Plan (LTSP) (Bestgen et al. 2012; LaGory et al. 2012). In contrast, releases prior to 2012 were typically earlier and timed to match the peak flow of the unregulated Yampa River. The LTSP was developed to test whether using first presence of larval Razorback Sucker as a flow trigger might maximize larvae entrainment in floodplain wetlands and increase recruitment (Brower et al. 2001; Hedrick et al. 2009; Bestgen et al. 2011; LaGory et al. 2012). Precise timing of detection of Razorback Sucker larvae and the ensuing flow release is essential to maximize entrainment and recruitment potential of larvae in floodplain wetlands (Bestgen et al. 2012; LaGory et al. 2012). Currently, detection of Razorback Sucker larvae as a trigger for spring flow releases is achieved using captures in light traps (Muth et al. 2000; Bestgen et al. 2011). Additionally, light traps are used for seasonal monitoring of Razorback Sucker larval abundance to understand how flows and water temperatures influence production (Bestgen et al. 2011). Thus, efficacy of light traps to capture larvae is an important part of recovery efforts for Razorback Sucker in the Colorado River basin.

Light traps are a passive gear type commonly used for sampling larval fish in low velocity habitats and are considered an effective way of sampling early life stages of Razorback Sucker (Secor et al. 1992; Hedrick et al. 2009; Bestgen et al. 2011; LaGory et al. 2012). Light traps attract fish because early life stages of many species, including Razorback Sucker, are positively phototactic (Floyd et al. 1984a; Mueller et al. 1993; Snyder and Meismer 1997; LaGory et al. 2012). However, knowledge of the effectiveness of light traps to sample fish larvae in a variety of field-relevant environmental conditions is sparse. Light trap light source, intensity, and color may influence capture, but their specific effects are not known (Kissack 1993; Mueller et al. 1993; Gehrke 1994; Marchetti et al. 2004). For example, the effects of turbidity on sampling efficiency by light traps are mixed (Snyder and Meismer 1997; Lindquist and Shaw 2005), and attraction distances, the maximum distance that a Razorback Sucker larva will detect and swim into a light trap, are unknown (Simpson 1999; Falke et al. 2010). Although larval Razorback Sucker sampling with light traps has been documented and is a widely used technique (Mueller et al. 1993; Muth and Haines 1994; Hedrick et al. 2009), effects of environmental variables on capture probability of Razorback Sucker are poorly understood (Bestgen et al. 2012). The goal of this study is to acquire a better understanding of factors that affect efficiency of light traps to detect Razorback Sucker larvae, and perhaps, estimate their abundance. This information is crucial to ensure sampling efforts are optimized to capture and retain larvae, determine the precise timing of peak flows needed to entrain early life stages of Razorback Sucker into floodplain wetlands, and provide an index to their abundance and reproduction throughout the season.

Methods

Fish handling and care

Razorback Sucker larvae were obtained from Ouray National Fish Hatchery, Grand Valley Unit, Grand Junction, Colorado on May 2, 2017 (8 days post hatch) and on April 23, 2018 (2 days post hatch) and transported to the Aquatic Research Laboratory at Colorado State University. Larvae in 2017 and 2018 had mean total length (TL) of 10.4 mm and 8.7 mm, respectively. Capture and retention probabilities for mesolarvae from 2017 and 2018 in the same experimental conditions indicated batch differences, though significant, were minimal and not considered biologically meaningful (capture probabilities of 0.85 and 0.74 respectively, P=0.02, retention probabilities of 0.86 and 0.94 respectively, P=0.05). Thus, we assumed no difference in fish between years for comparing our light trap test results. Fish were held in two separate flow-through troughs in well water saturated with oxygen (6-10 mg/L). Fish were fed a mixture of newly hatched brine shrimp *Artemia sp.* and commercial flake food 3-times daily throughout the duration of the study. Larvae received preventative pathogen (fungus, bacterial infections) treatments every other week using a 167 mg/L formalin mixture in a 1 h static bath each day for three consecutive days; no infestations were noted during our studies. Anaesthetized larvae were preserved in 5% formalin at regular intervals to track growth and development (Figure 1.2). Fathead Minnow *Pimephales promelas* (obtained from Aquatic Biosystems in Fort Collins, CO) protolarvae (<5 mm TL), mesolarvae (7-9 mm TL), metalarvae (12-15 mm), and juvenile (18-21 mm TL) were tested in some experiments, to increase understanding of light trap capture and retention probabilities with another fish species.

Experimental materials

Light trap capture and retention efficiency trials were conducted in 6 steel troughs, each 4.9 m long, and 0.45 m wide, that were painted black and filled with well water to a depth of 0.29 m. Trough water volume was approximately 640 L. After filling, water remained static and was left in the troughs for the duration of trials for a life stage. Trough water temperature ranged from 16.9-17.4°C, similar to riverine wetlands and backwaters in the Green River system in spring (Bestgen 2008), and surface diffusion maintained dissolved oxygen levels at 6-8 mg/L.

The light traps used were a design modified from Killgore (1994), and had four, 4-mm-wide vertical apertures, which allowed fish to enter the trap (Figure 1.3). A 5-cm-thick foam ring fastened to the top of the trap suspended it in the water column. A metal capture basin was attached to the trap with spring clamps and had two mesh-covered holes (500-µm mesh Nitex screen) that allowed most water to drain after an experiment, but retained fish and a slight amount of water to facilitate handling (Figure 1.3. Green Duralume 24 h chemical light sticks (15-cm long) were used as the baseline light source, the same illumination source used in field light trap sampling, and in a color known to attract fish larvae (Marchetti et al. 2004; M. T. Jones, U.S. Fish and Wildlife Service, personal communication). To limit waste, we reused light sticks in shorter-term trials for a combined time up to 8 h. Before each new trial, each light stick was removed from the trap and shaken vigorously for at least 10 seconds, remixing the chemicals to restore light intensity.

General experimental design

Prior to beginning each trial, we randomly selected 25 fish, unless otherwise stated, using nets and scoops made from 500-µm mesh Nitex and placed them into clear plastic cups. For tests

to assess capture probabilities, fish were released into the trough at the desired location by slowly pouring larvae from the cup into the trough. Acclimation was not deemed necessary because the water in the troughs was from the same source as that in holding tanks and was a similar temperature. After fish release, a light impermeable black plastic tent was placed over the trough to simulate dark, new moon night light conditions in the field. After each trial, each light trap was removed from the trough and captured fish were enumerated and preserved in 5% formalin. Fish not captured in traps were removed from the troughs by sweeping a custom-fit fine mesh net the length of the trough at least 4 times. Preliminary tests showed this level of effort was successful to remove all fish not captured by light traps. Fish removed from the troughs were euthanized.

Even though light trap aperture widths are narrow to deter escape, retention of larvae in light traps was measured to assess the probability that larvae remained in a light trap after capture. In each retention trial 25 larvae were placed directly into the light trap catch basin, which had water to the level of the drain screens. The catch basin was then attached to the light trap, placed in the center of the trough, and troughs were covered as previously described. Unless otherwise stated, retention trials lasted 1.5 h after which traps were removed, and the fish in traps and troughs were processed similarly to capture probability experiments. In general, five experimental replicates for each treatment combination were conducted, unless otherwise noted. Specific experimental conditions for capture and retention experiments are described below.

Life stage

Because life stage may be an important factor affecting capture and retention success with light traps, we tested five fish stages: pre-swim bladder development protolarvae (early protolarvae; 8-10 mm TL), post-swim bladder development protolarvae (late protolarvae; 10-11

mm TL), mesolarvae (11-17 mm TL), metalarvae (18-26 mm TL), and juveniles (27-50 mm TL; Snyder 1981; Snyder and Muth 1998; Table 1.1). These life history stages have progressively developed features which affect swimming ability and perhaps phototactic response. For example, early protolarvae may retain some yolk, have no fin rays, and other less developed anatomical features, while mesolarvae possess at least one ray in a median fin and increased swimming ability. Juveniles, the oldest life stage, possess the same number of fin rays as adults and are the most developed life stage tested.

Set time

Understanding effects of time on capture probability may allow increased flexibility in field applications because reduced set times could permit sampling of additional sites. Set time of light traps in the field is generally 8 h (overnight), but can range up to 24 h due to logistical constraints. To identify optimum set times for our trials we first ran trials at 2-,4-, and 8-h intervals where larvae were all released at the same 3-m distance from the light trap. Set time with the highest capture rate was determined the most appropriate for conducting subsequent light trap experiments. Analysis of initial set time tests indicated capture rates were greatest in 2 h sets (11.2 fish/h) as opposed to those at 4 h (5.7 fish/h) and 8 h (2.6 fish/h). However, total captures of fish were similar across the three set times. Thus, all capture probability experiments, not directly testing effects of set time on capture probabilities, were conducted with 2 h set times.

Distance

Release distance of larvae from light traps may affect capture probabilities, particularly when set times are short, because larvae are relatively weak swimmers. Thus, understanding distance, set time, and their interaction effects on capture probabilities may aid in understanding

the behavior and phototaxis of early life stages of Razorback Sucker, and provide information regarding attraction distances of light traps in the field. Therefore, we tested effects of short (1 m), medium (3 m), and long (4.9 m, herein rounded to 5 m for simplicity) distances on capture probabilities using 0.5-, 1-, 2-, and 4-h set times (Table 1.2).

Turbidity

Turbidity is a naturally fluctuating environmental feature of most large western North American rivers that may affect light perception or activity levels of larval fish (Boehlert and Morgan 1985; Unte-Palm 2004). To test turbidity effects on capture probability, a bentonite clay slurry was mixed in troughs to achieve light penetration levels of about 75 NTU. This turbidity measurement represented about a 9-10 cm Secchi depth (visibility of a white object), which is common in Green River sampling areas at the time Razorback Sucker larvae hatching begins. Prior to each trial, trough water was mixed to re-suspend any particles that had settled. Turbidity was measured prior to and at the conclusion of each trial to assess any changes in turbidity due to settling. The effects of turbidity on capture probabilities were tested at short and long distances to assess turbidity and distance interactions (Table 1.2). Turbidity effects on retention probabilities were also tested in similar conditions to that previously described (Table 1.3).

Light source presence

Light presence is generally recognized as the main mechanism that attracts fish larvae into a light trap (Floyd et al. 1984b; Zigler and Dewey 1995; Snyder and Meismer 1997; Vilizzi et al. 2008; Massure et al. 2015). Importance of light presence on trap capture probabilities was tested using short distance release trials compared to traps that lacked a light source (Table 1.2). Additionally, the effect of light source presence on retention probabilities was tested by placing

fish in traps which lacked a light source in conditions otherwise similar to that described for other retention tests (Table 1.3). Results of capture and retention experiments were subsequently compared with results from lit traps, where all other conditions were similar.

Larvae density

Determining larval density effects on capture probabilities may aid understanding if light trap catches can be used as an index of abundance in field light trap sampling locations. Thus, we tested effects of low (0.04 larvae*L^{-1}, i.e. 25 larvae per/trough) and high density releases (0.08 larvae*L^{-1}, i.e. 50 larvae per/trough) on capture probabilities at both short and long distances, to assess their effects and their interaction on capture probabilities (Table 1.2).

Cover presence and location

Cover, in the form of vegetation or rocks, may influence capture of larval fishes by light traps because light may be partially obstructed and impede fish captures (Gregory and Powles 1985; Dewey and Jennings 1992; Gorski et al. 2011; Wu et al. 2013). Vegetation or rock is often present in floodplain wetlands and occasionally, in channel margin backwaters of the Green River. To assess vegetation or rock cover effects, we placed plastic vegetation stems or cement cinderblocks into troughs both in front of and behind the light traps and released fish at a single, medium distance.

Environmental light condition

Environmental light condition, including new moon night or sunrise light levels, may affect probability of retaining larvae in light traps because the light stick intensity relative to the surrounding area is reduced. To test this, we determined retention probabilities of Razorback Sucker in light traps under simulated new moon natural light conditions and under simulated

sunrise conditions. Night conditions were simulated by excluding light from the troughs for the duration of the set. Sunrise light conditions were simulated by excluding light from troughs for the initial 0.5 h, and then exposing the trap to laboratory light levels for an additional 1 h (Table 1.3).

Trap aperture

Width of light trap apertures may affect the probability of capturing and retaining different sizes of early life stages of fish, which we tested using light traps with aperture widths of 4 and 6 mm and mesolarval and metalarval life stages released at a single medium distance (Table 1.2). Conservative numbers of larvae (10 larvae per/trough) were released for metalarval trials to reduce fish use. Tests investigating effects of trap aperture width on probability of retention were conducted for mesolarval and juvenile life stages in simulated new moon night light conditions (Table 1.3). Because environmental light condition and the presence of light in a light trap may also influence probabilities of retention, juvenile Razorback Sucker retention probabilities were further tested in traps with 6 mm aperture widths in simulated sunrise conditions, and in simulated new moon night light conditions with no light source present in the trap. With the exception of the aforementioned tests, all other experiments used light traps with 4 mm aperture widths.

Light source

To test how light source and intensity in traps affects capture probability of Razorback Sucker, trials were run with recently activated chemical light sticks, light sticks activated 16 h previously (old chemical light sticks), and LED (light-emitting diode) light sources with medium distance releases of mesolarvae. Old chemical light sticks simulate field sampling conditions

where light sticks are activated and traps set in the morning, which eliminates the need for workers to return to the site later that day to set the trap for night sampling (Gehrke 1994). The LED-lit traps were designed to be similar to the chemical light sticks in that light was dissipated along a 15-cm long etched acrylic rod suspended in the center of the light trap and emitted green light (Figure 1.4). Effects of light source on the probability of retention of Razorback Sucker larvae were additionally investigated with chemical light sticks and LED light sources in new moon natural light simulations. Effect of light source on capture and retention probabilities of Razorback Sucker larvae was only tested with the mesolarval life stage, as it is the most commonly sampled life stage in the Green River (K. Bestgen, Larval Fish Laboratory, Colorado State University, personal communication; Table 1.2; Table 1.3).

To directly test preference of Razorback Sucker larvae for LED or chemical-light-stick-lit traps, one light trap with each light source was placed at opposite ends of a trough. Placement location (end of the trough) of each trap light type was randomized using a coin flip. Razorback Sucker larvae were then released equidistant between the two traps.

Environmental light condition: ambient sunrise

Ambient sunrise (~1,000 lx) light is substantially more intense than light in the laboratory (~80 lx) which may affect the probability of retention of Razorback Sucker larvae in light traps. Thus, we used outdoor light conditions and 50 L buckets to test retention probabilities in ambient sunrise light conditions. To isolate the environmental light effect from the container effect, retention trials in the buckets were also conducted in new moon night light conditions and simulated sunrise conditions in the laboratory. Simulated ambient outdoor sunrise conditions were conducted by excluding light from the light traps for the initial 0.5 h of the set, and then exposing the traps to shaded outdoor light for the remaining 1 h of the set. Effects of

environmental light conditions conducted in buckets were only tested with mesolarval Razorback Sucker (Table 1.4). We also tested the same environmental light condition effects on retention probabilities of various life stages of Fathead Minnow.

Container

Perception of increased area surrounding the light trap may affect the probability of retaining larval fish in light traps. To test this, retention probabilities were compared among the troughs, 50 L round buckets, and 2000 L stock tanks. Probabilities of retention were compared under new moon night light simulations between the troughs and 50 L buckets. Retention tests in the tanks were carried out overnight at the Foothills Fisheries Laboratory at Colorado State University's foothills campus and compared to retention probabilities of overnight trials conducted in troughs under simulated new moon night light conditions. Effects of surrounding area on retention probabilities in light traps was tested only with the mesolarval Razorback Sucker life stage.

Rapid growth and development during the protolarval life stages resulted in limited time to conduct experiments, particularly late protolarvae. Thus, not all experimental combinations were conducted for these life stages (Table 1.2; Table 1.3). Some mesolarval tests and all metalarval and juvenile tests were conducted in 2017. All protolarval tests and some additional mesolarval tests were conducted in 2018. Additional mesolarval tests in 2018 were used to compare the 2017 and 2018 batches, which was determined to be an unimportant effect (see results).

Data Analysis

To understand effects of treatments on capture and retention probabilities of early life stages of Razorback Suckers in light traps, we treated each trial as an experimental unit where number of fish captured or retained was treated as a binomial proportion. Thus, one experimental unit was each instance a batch of fish was released in a trough, with the response consisting of the proportion of larvae captured or retained in light traps. In analyses conducted in Program R (R Core Team 2017), this was number of fish captured divided by the number of fish retrieved from the trough plus the number of fish captured (successes/total number of fish released). The proportion data were then analyzed using logistic regression (logit link), which ensured our predictions and confidence intervals were constrained to a range between 0 and 1. Logistic regression analysis was conducted with the glm function in Program R, where variables were further examined for significant effects on the probability of capture or retention using likelihood ratio tests (Type III) with the "Anova" function in package car (Fox and Weisberg 2011; R Core Team 2017). If necessary, additional pairwise comparisons of odds and odds ratios were determined via the emmeans function in the emmeans package (Lenth 2018). Paired tests were analyzed using conditional logistic regression with the glmer function in program lme4 (Bates et al. 2015) and Type III Wald chi-square tests. Rather than report a large number of multiple-comparison tests among treatment combinations to judge differences among experimental effects, overlap (or not) of 95% confidence intervals was used as a *de facto* significance test for experimental comparisons (Shenker and Gentleman 2001).

Results

Distance, set time, and life stage

The ANOVA revealed distance, set time, life stage, and their interactions all importantly affected probability of capture of early life stage Razorback Sucker (Table 1.5). Overall, capture probabilities were relatively high, especially for late protolarvae, mesolarvae, and metalarvae with longer set times (4 h), with lower capture probabilities evident for early protolarvae and juveniles and for shorter test times (0.5-2 h, Figure 1.5). For example, capture probabilities for the three intermediate life stages during a 4 h set time, over all distances, were usually 0.80-0.90. In contrast, capture probabilities for early protolarvae and juveniles in those same conditions was about 0.60 and 0.50, respectively (Table A.1). Additionally, as Razorback Sucker grew into the next developmental state, about twice the sampling time was needed to achieve the same capture probabilities (Figure 1.6). For example, probabilities of capture among 3-m release distance tests were similar for late protolarvae in a 0.5-h set, mesolarvae in a 1-h set, metalarvae in a 2-h set, and juveniles in a 4-h set.

The effect of distance, when examined by life stage and set time, was less evident, a surprising result given the small size of larvae and their relatively weak swimming ability. For example, capture probabilities across 1-, 3-, and 5-m distances in 4-h tests usually varied by only about 0.04-0.15 for all life stages. Variation in capture probabilities over different release distances increased in experiments with shorter set times. This was especially true for early protolarvae, metalarvae, and juveniles in 0.5-h set times, where capture probabilities declined with increasing distance (Figure 1.5; Table A.1).

Capture probabilities of Razorback Sucker increased with longer set times for all life stages. For example, capture probabilities increased at least 60% as set time increased from 0.5- to 4-h over all distances and life stages (Figure 1.5; Table A.1). However, capture probability differences were negligible between 4- and 8-h experiments for all life stages, except for juveniles. Differences in capture probabilities were significant among treatment types with 3-m distances across all life stages and 0.5- to 8-h set times, and their interactions (Table 1.6).

Turbidity, distance, and life stage

Turbidity, distance, life stage, and their interactions all significantly affected the probability of capture of Razorback Suckers, with life stage having the greatest overall effect based on the magnitude of the X^2 value; life stage trends were similar to those already reported (Figure 1.7; Table 1.7; Table A.3). Additionally, capture probabilities of each life stage were affected differently by turbidity, distance, and their interaction (Figure 1.7; Table B.1). Early protolarvae were the only life stage where distance, turbidity, and their interaction all had significant effects on capture probabilities, but the direction of trends were not consistent. For example, in 1-m distance experiments, turbid conditions yielded greater capture probabilities, but at a 5-m distance, the opposite was true. Mesolarvae had minimal differences in capture probabilities in turbid conditions compared to clear water, but metalarvae and juveniles capture probabilities increased in turbid conditions. Distance influenced capture probabilities most in early protolarval and metalarval life stages.

Life stage and light source presence

Presence of light in traps was the largest experimental effect we noted on Razorback Sucker larvae probability of capture (Table 1.8; Figure 1.8). In the absence of light, few larvae of

any life stage were captured (capture probabilities of 10% or less), except for juveniles, where capture probabilities were similar when light was present (Table A.4). Differences between juvenile life stage capture probabilities compared to the others was likely the reason for the large interaction effect. Differences between capture probabilities when light was present or absent was greatest for mesolarvae (0.86 and 0.01, respectively).

Light source presence and turbidity

Probability of retention of Razorback Sucker was high (>0.77) across all life stages when light was present (Figure 1.9; Table 1.9). However, retention probabilities of various life stages of larvae declined by approximately 45-85% when light was absent (Table A.5). Differences in retention probabilities due to turbidity was minimal for all life stages under the same light conditions, but for early protolarvae when light was absent, retention probability declined from 0.39 to 0.05.

Larval density, life stage, and distance

The ANOVA revealed life stage, distance, and their interactions all influenced capture probabilities, but density did not (Table 1.10). Capture probabilities generally declined as fish developed to succeeding life stages, per previous trends (Table A.6; Figure 1.9). Within-life-stage ANOVA showed capture probabilities for mesolarvae at high and low densities were similar at 1- and 5-m distances (Table B.2; Figure 1.10). Metalarval Razorback Sucker capture probabilities were influenced by both distance and density, although the direction of this relationship was not clear. For example, capture probabilities at 1-m distances were greater with low density releases, but the opposite was true at 5-m release distances. For juveniles, more fish were captured at 1-m than 5-m distances, though differences were minimal. For example, the

probability of capture declined for juveniles by 0.05 and 0.19 as distance increased for both low and high-density releases, respectively.

Cover presence, cover location, and life stage

Effects of vegetation and rock on capture probabilities varied substantially with life stage, similar to most other experiments (Table 1.11). For mesolarvae and metalarvae, capture probabilities declined when vegetation or rock cover was in front of the light trap (Table A.7; Figure 1.11). Capture probabilities for mesolarvae and metalarvae (not juveniles) were also reduced when vegetation was placed behind the trap, although differences were slight (9-12%), and this result was not observed when rock was behind the trap. In contrast to other life stages, capture probabilities of juveniles in both vegetation and rock cover trials was consistently lowest in the absence of cover, highest when cover was behind the trap, and intermediate when cover was in front of the trap.

Environmental light condition and turbidity

Although retention probabilities were high (>0.70) across all environmental light conditions and life stages (Figure 1.12), there were life-stage-specific effects of turbidity, environmental light condition, and their interaction (Table 1.12). Effects of turbidity were especially noteworthy for early protolarvae, where retention probabilities increased 0.12 in turbid conditions in both night and sunrise simulated conditions compared to clear water (Table A.8). Notably, reduced retention probabilities were evident for the four youngest and smallest life stages in sunrise simulations compared to night light simulations regardless of turbidity, although effects were statistically significant only for early protolarvae and mesolarvae; juvenile retention probabilities were high and similar across all conditions.

Trap aperture

Capture and retention probabilities were similar for light traps with 4 and 6 mm trap apertures for all life stages tested (Table 1.13; Figure 1.13). For juvenile Razorback Sucker, retention probabilities were similar among environmental light conditions and trap aperture (Table A.9). However, light source presence, trap aperture, and their interaction importantly influenced retention probability of juveniles in light traps. For example, similar to previous results when light was absent, the probability of retention declined by 0.49-0.69, but additionally, retention probability was lower in traps with no light source and in traps with the larger, 6 mm apertures (Table A.10).

Light source

Razorback Sucker.—Light source (chemical light stick, LED, and old chemical light stick) significantly influenced the capture probability of mesolarval Razorback Sucker (Table 1.14). While capture probabilities between LED and chemical light sticks were similar (about 0.80), each was notably higher than capture probabilities using old chemical light sticks (0.54, Figure 1.14a; Table A.11). Light source (LED and chemical light stick) did not influence mesolarval Razorback Sucker retention probabilities (Figure 1.14b; Table A.12). In preference tests, substantially more (6X) mesolarval Razorback Sucker were captured in LED-lit traps compared to those with a chemical light stick (Table 1.15; Figure 1.15). The remaining 23% of larvae were not captured by either light trap.

Fathead Minnow.—Similar to Razorback Sucker, capture probabilities of Fathead Minnow were influenced by life stage, light source, and their interaction (Table 1.16). Capture probabilities increased consistently as fish age and size increased (Figure 1.16a; Table A.11).

Traps which had an LED light source had notably higher capture probabilities for protolarval and juvenile Fathead Minnow but were similar among mesolarvae and metalarvae. Life stage influenced probability of retention of Fathead Minnows, although light source and their interaction did not (Figure 1.16b). For example, mesolarvae retention probability when traps had chemical light sticks was greater than metalarval and juvenile retention probabilities in otherwise similar conditions. Retention probabilities were similar between traps with LED and chemical light sources for all life stages (Table A.12).

Environmental light condition: ambient sunrise

Razorback Sucker.—Of treatments conducted in 50 L buckets, environmental light condition affected retention probability of mesolarval Razorback Sucker (Table 1.17). Probability of retention was high in all treatments, but greatest in the sunrise simulation conducted in the laboratory, followed by night simulation, and then ambient sunrise simulation conducted outside the laboratory (Figure 1.17a; Table A.13).

Fathead Minnows.—Overall probability of retention for Fathead Minnow was high and similar among all life stages (between 0.75-0.99; Figure 1.17b). The interaction of environmental light condition and life stage importantly affected retention probabilities (Table 1.18). Generally, retention probabilities increased with life stage although differences were minimal (0-25%; Table A.13). Environmental light condition had the greatest influence on protolarvae retention probabilities, which declined in ambient sunrise simulation treatments conducted outside of the laboratory (Table B.3).

Container

Razorback Sucker.—Retention probabilities between treatments conducted in 50 L buckets and the troughs were similar (Table 1.18; Figure 1.18a). However, retention probabilities did differ between overnight treatments conducted in the troughs and tanks; retention was lower in the tanks, although the difference was minimal (7%; Figure 1.18b; Table A.15).

Fathead Minnow.—Container type influenced retention probability of Fathead Minnow, but life stage and their interaction did not (Table 1.18). Retention probabilities were relatively high in all treatments and differences were noted only for juveniles, which showed increased retention probabilities in treatments conducted in the 50 L buckets (Figure 1.18c, Table B.4).

Discussion

Capture and retention of Razorback Sucker in light traps was high overall across a variety of conditions tested, although was influenced by life stage. Additionally, presence of light in the trap and the intensity of light greatly affected capture and retention probabilities; when light was absent captures were almost non-existent and retention declined 50-75%. Increasing set time consistently increased capture probabilities, although there was little evidence that capture probability was affected by release distances up to 5 m from the trap. This was surprising given the relatively low swimming speed and small size of the youngest larvae, as trough length was 400-500 times fish body length. Turbid conditions, while not affecting retention, reduced capture of earliest life stage Razorback Sucker, but increased capture of more developed life stages. Light trap apertures of 4 and 6 mm did not substantially influence either Razorback Sucker capture or retention, but capture data indicated higher light intensities, provided by LED, may increase capture. High capture and retention probabilities of Razorback Sucker larvae under a

variety of environmental conditions indicated light traps may be a useful tool to monitor their presence and abundance.

Life stage

One of the strongest influences on capture probabilities of Razorback Sucker larvae was life stage, which is generally a proxy for age at size. Capture probabilities across life stages were dome-shaped, and peaked among late protolarvae and mesolarvae, but were lowest for early protolarvae and juveniles. Metalarvae capture probability was intermediate between mesolarvae and juveniles. Despite slower swimming speeds and not having fully developed fins, over 50% of late protolarvae and mesolarvae swam 5 m, entered a trap, and remained over a set time of 0.5 h. Early protolarvae had lowest capture probabilities, likely because of reduced swimming ability and lack of an inflated swim bladder, which may reduce their mobility. Additionally, juveniles were less likely to be captured by light traps, but swimming ability was clearly not a constraint for that more advanced life stage. Thus, we hypothesize that the juvenile phototactic response may diminish with increasing age. Higher capture probabilities may also be affected by buoyancy control, as the highest capture probabilities did not occur until after protolarvae had developed a swim bladder. The relationship between development and phototactic response resulted in a right-skewed quadratic relationship between capture probability and size and age, a relationship seen in other light trap studies with young Northern Pike *Esox lucius* (Pierce et al. 2006). Our capture probabilities of Razorback Sucker larvae and juveniles exceeded those in previous studies (Snyder and Meismer 1997).

Light source presence

Presence of a light source is the main mechanism of capture in light traps, which capitalizes on the positively phototactic nature of most fish larvae (Floyd et al. 1984b; Zigler and Dewey 1995; Snyder and Meismer 1997; Vilizzi et al. 2008; Massure et al. 2015). Snyder and Meismer (1997) and our results provide additional evidence of this, particularly for Razorback Sucker, with the exception of juveniles. Capture of juveniles by light traps may instead be due to other factors, like attraction to cover. Retention of larvae in the trap is greatly influenced by light source presence, a conclusion reached by Snyder and Meismer (1997). In fact, our data indicated if a light source failed, between 50-75% of larvae in traps would escape, and reduce capture probabilities in field monitoring. Interestingly, although it did not affect capture of juveniles, light greatly influenced retention, because we observed a significant decline when the light source was absent. This may be related to the inverse square relationship of light intensity and distance, where intensity diminishes with distance (Voudoukis and Oikonomidis 2017). If the light source is intense enough, i.e. close enough to the larvae, it may be sufficient to attract and retain even the less phototactic life stages. If this is the case, it indicates that use of brighter light sources may be more effective at attracting older and larger life stages of fish.

Current understanding of the influence of light intensity on capture of larval fish by light traps is confounded with light color (Gehrke 1994; Marchetti et al. 2004), because certain light colors that captured relatively high numbers of fish also had the highest light intensity. However, data gathered from our LED light trap tests support the hypothesis that increased light intensity increased capture probabilities of Razorback Sucker because capture probabilities with LED traps and brighter, recently activated chemical light sticks were higher than capture probabilities with traps using old chemical light sticks which were activated 16 h earlier. This is in opposition

to Snyder and Meismer (1997), who found no effect of light intensity on the capture of Razorback Sucker by light traps, except for juveniles, where negative effect on capture was observed; it is possible their findings were confounded by use of differing light trap designs.

Set time

Capture of all Razorback Sucker life stages consistently increased with set time, implying greater set times maximizes the probability larvae will be sampled by light traps, similar to Snyder and Meismer (1997). Given that some Razorback Sucker management strategies rely on initial detection of larvae to begin an action, we recommend continued use of overnight light trap sets in field settings. Additionally, considering substantial effects of sampling time on capture, maintaining similar sampling duration among nights and years will ensure consistent comparisons of larval abundances for long-term monitoring. Maintaining overnight sets may also ensure that various life stages are captured at maximal probabilities, given that longer set times were needed to capture progressively older life stages of larvae (Figure 1.5). The mesolarval life stage is the most commonly sampled life stage in field light trap sampling, while metalarvae and especially juvenile Razorback Suckers are less common (Bestgen et al. 2011). While it has been hypothesized that these life stages were less common in field samples due to low survival and subsequent low abundance in the wild, our experiments showed light traps were less effective at sampling these later life stages and that field sampling may underestimate their presence and abundance.

Distance

We found no substantial differences among capture probabilities of Razorback Sucker larvae released 1, 3, and 5 m from the light trap, and thus we were not able to determine an upper

limit to attraction distances. Even capture probabilities of most life stages using short set times (0.5 h) were little influenced by distance. This was demonstrated by an opportunistic test, where we captured larvae in light traps released 3 m distant from traps after only 5 min. Thus, our experiments indicated release distances up to 5 m are not an obstacle for even very young and relatively slow-swimming Razorback Sucker. Observations indicated these few-day-old larvae were active and vigorous, if not relatively slow, swimmers. Given ample time, Razorback Sucker larvae may be able to swim relatively long distances in static backwaters, along river margins, and in floodplains; laboratory tests of swimming performance would be useful to determine their swimming ability. Reduced capture probabilities of older and larger Razorback Suckers were likely due to factors other than reduced swimming speed.

A logical question to ask regarding attraction distances of a larva to a trap, is how far away young fish can detect light, and whether other mechanisms such as fish swimming affect effective distances for light trap capture. Observations of larvae swimming behavior after release in troughs indicated active swimming and dispersal throughout troughs. Thus, active swimming of larvae in troughs and natural waters may play a role in fish encountering light traps, which will affect subsequent capture probabilities and inferences about attraction distances of larvae to traps. For example, in a field experiment we were able to detect larvae in light traps that were released in a large turbid wetland (10-1,000 fish batches) up to 10 m from the light trap, a distance 800-1,000 X their body length (Chapter 2). Preliminary light measurements taken in the laboratory determined that in 75 NTU water, light from a recently activated chemical light stick did not travel greater than 3 m. Although the wetland turbidity was around 30 NTU, it is unlikely that the light traveled 10 m. Thus, if fish cannot detect light 10 m away, but we capture larvae and sometimes in large numbers, fish behavior likely enhanced capture probabilities.

For a fish larva to be captured in a light trap, several key things have to occur. First, the larva had to swim in the direction of the light trap rather than away, a small likelihood given fish can swim any direction in the 360° radius. Larvae then have to navigate the release distance, and in field conditions, in sometimes windy, turbid, and predator-filled environments. Finally, the larva had to come close enough to the trap to be attracted to the light, choose to enter it, and then stay inside until the trap was pulled, an endpoint involving many probabilities. We now know more about the factors that affect capture probabilities of larvae once they are in the cone of influence of light in the trap. However, a better understanding of other factors such as fish physiology and swimming behavior will enhance efficient use of light traps to sample fish, especially in large open habitats.

Turbidity

Although we hypothesized turbidity would decrease capture probabilities because reduced light intensity would be less attractive to larvae, capture data indicated turbidity effects acted only on earlier developmental life stages (Figure 1.6). Although results of protolarvae turbidity treatments seem inconsistent, overall data show turbid conditions were associated with notable declines in capture probabilities. Despite late protolarvae not being tested in turbid conditions, their clear water tests were run shortly after (<24 h) early protolarval turbidity trials, which may provide better comparisons to the early protolarval turbidity treatments. This is further evidenced by inconsistencies in early protolarval set time treatments and similarities of capture probabilities between the two life stages which were conducted at similar times (<24 h apart; Figure 1.4; Figure 1.6). The substantially lower capture at of early protolarvae turbidity tests at 5 m compared to both protolarval clear water equivalents indicated turbidity hindered capture probabilities. This is important to consider while sampling for first detection and

monitoring of larval Razorback Sucker, because higher turbidity during snowmelt runoff conditions may hinder capture probability of those earliest life stages, which are the first ones present in spring.

Despite the potential negative effect of turbidity on earlier life stages, data suggest the opposite effect for later stages, with increased capture probabilities of metalarval and juvenile Razorback Sucker in turbid conditions. Those life stages are faster swimming and thus may encounter traps more frequently. The perceived cover provided by turbid conditions may cause larval activity to increase as the risk for increased feeding activity declines (Boehlert and Morgan 1985; Unte-Palm 2004), as found by Snyder and Meismer (1997). Despite seeing variable effects of turbidity on capture probabilities of Razorback Sucker, there appeared to be no effect on light trap retention probabilities.

Cover

We investigated effects of cover on capture probabilities of Razorback Sucker larvae in light traps because backwaters, floodplain wetlands, and other low velocity near-shore habitat often feature rocks or dense vegetation, which may obstruct light travel and reduce capture probabilities (Snyder and Meismer 1997). When we placed cover behind the trap, capture probabilities were little affected. In contrast, if cover was between the trap and larvae, capture of Razorback Suckers was reduced. Cover effects were different for juvenile Razorback Sucker, where capture was higher when cover was both in front of and behind the trap when compared to no cover experiments. Though the data suggest that juveniles have a reduced phototactic response, the results of the cover treatments suggest they may have an increased ability over earlier life stages to perceive and actively seek out cover. This increased capture may be due to juveniles actively seeking the cover before swimming close enough to the trap that the emitted

light is intense enough to activate a phototactic response before capture. Thus, placing traps near vegetation or rocks may increase ability to target this later life stage.

Environmental light condition

Once larvae enter a trap, most are thought to be retained until sampling is completed. However, traps are sometimes not pulled until after sunrise, which is hypothesized to result in lower retention probabilities as larvae escape with the decrease in the relative light trap light intensity compared to the surrounding area. We found when a light source was present, retention of larvae in light traps was high and ranged from approximately 75-99%. The probability of retention was lower in sunrise simulations than in night simulations for all life stages except juveniles. While this difference was marginal (between 3-25%), it was large enough to be of concern particularly for the earliest life stages of Razorback Sucker, as was found by Snyder and Meismer (1997). Additional environmental light condition experiments conducted to assess outdoor and brighter ambient sunrise conditions also showed lower retention probabilities for both Razorback Sucker and Fathead Minnow. Thus, to maximize captures of larvae, sampling should conclude before traps are exposed to sunlight.

Of note is that the escape of larvae from traps always occurred, because retention probabilities were never 100%. We have evidence that retention probabilities may be somewhat dependent on random movement of larvae, with fish moving into and out of the trap, but apparently preferring to be near light in the trap. Video recordings with a GoPro camera placed inside of the catch basin of a light trap indicated that even with a light source present, larvae moved easily out of and then back through the trap aperture. Thus, it is possible that larvae are escaping and re-entering the trap throughout the sampling period, where the resulting sample does not necessarily represent the maximum number of larvae that had entered the trap.

Maximizing retention of larvae after they first entered the trap is important to consider when using light traps as a sampling gear. Movement of larvae into and out of traps was based on just a few observations and was sufficient only to suggest that further investigation was warranted, a conclusion confirmed by field retention trials (Chapter 2).

Trap aperture

Aperture width of the light trap may exclude certain sizes of fish from entering, including non-target life stages, and may also regulate whether larvae can escape. The commonly used light trap in the upper Colorado River basin has 4 mm apertures. Traps with 6 mm aperture widths have been deployed, but because few studies existed, we examined effects of aperture width on capture and retention of larvae. Because 4 and 6 mm aperture traps functioned similarly in our experiments, and because the smaller aperture may exclude larger nonnative fishes that are potential predators on captured fish larvae, we recommend continued use of traps with the 4 mm (Vilizzi et al. 2008, M. T. Jones, U. S. Fish and Wildlife Service, personal communication). However, it is important to know maximum widths of the target species and life stage to ensure that they are not excluded by the smaller apertures.

Larvae density

Differences in capture probabilities in the presence of different densities of larvae in backwaters and floodplains may affect ability to estimate their relative abundance. Our tests with 25 and 50 larvae released indicated capture proportions were equivalent in tests using two release distances and three life stages. Thus, absence of density-dependent effects on capture probabilities in our experimental conditions indicated light trap captures may be a reasonable

index to assess abundance of larvae in the wild. Chapter 2 of this thesis reports on additional experiments to test the role of larvae density on capture probability.

Light source

A desire for a more sustainable light source for light traps prompted us to design a new waterproof LED light source specifically for quatrefoil style traps. Currently, chemical light sticks are commonly used as a light source in light traps due to convenience and low cost (Kissack 1993; Killgore 1994; Marchetti et al. 2004; Vilizzi et al. 2008). However, chemical light sticks lose intensity over the duration of a light trap set, are generally not as bright as electrical light sources (Kissack 1993; Mueller et al. 1993; Cranor 2000), and old chemical light sticks had substantially lower capture probabilities than other sources. LEDs are an inexpensive, higher intensity alternative to both incandescent and chemical light source options. We designed an LED light source specifically for use with modified quatrefoil light traps currently used in larval Razorback Sucker sampling. Traps were designed to dissipate LED bulb light along the length of the trap, similar to Floyd et al. (1984a), by placing the LED in a threaded acrylic rod, which resembles the plastic housing of a chemical light stick. Traps also used green-colored LEDs, a color attractive to fish (Kurien et al. 1952; Marchetti et al. 2004). Finally, for sustainable and consistently high light intensity over time, a rechargeable lithium ion battery was used as the power source. Preliminary tests showed that our LED design had greater light intensity than the chemical light sticks and that the batteries provided consistent intensity for 120 h on one charge.

For Razorback Sucker light trap experiments, LED-lit traps had greater capture probabilities than traps using chemical light sticks which had been activated greater than 16 h prior to starting the trial. This situation is common in field settings where traps are set in the

morning with an activated light stick and pulled 24 h later. However, traps lit with chemical light sticks activated less than 8 h prior to starting the trial had similar results as the LED-lit traps. This indicated the difference in light intensity between the two chemical light sticks is the reason for the decline in capture probabilities, and not the light source specifically. Preference tests also showed that Razorback Sucker larvae preferred LED-lit traps over those with recently activated chemical light sticks. The LED traps we fabricated were used in annual Green River larval Razorback Sucker monitoring in spring 2018 and captured an array of species including Razorback Sucker, Fathead Minnow, Red Shiner *Cyprinella lutrensis*, Sand Shiner *Notropis stramineus*, Bluehead Sucker *Catostomus discobolus*, Flannelmouth Sucker *Castostomus latipinnis*, White Sucker *Catostomus commersonii*, Iowa Darter *Etheostoma exile*, Brook Stickleback *Culaea inconstans*, and Colorado Pikeminnow *Ptychocheilus lucius* (M. T. Jones, U.S. Fish and Wildlife Service, personal communication, K. R. B., unpublished data). Preliminary comparisons of field samples from traps with the two light sources indicated similar capture probabilities (Chapter 2).

Fathead Minnows

To increase knowledge of effectiveness of light traps for sampling larval fish, additional experiments were conducted with various life stages of Fathead Minnow, an introduced cyprinid common in Green River backwater and wetland habitat (Bestgen et al. 2017). Capture probabilities indicated a strong life stage effect, but one that was slightly different than for Razorback Sucker, because capture probabilities continued to increase with life stage and did not show the dome-shaped relationship evident for suckers. Fathead Minnows were incubated and reared in 25°C water, an optimal temperature for their growth and development. Laboratory well water temperatures were approximately 17°C, closer to actual Green River water temperatures.

Although the Fathead Minnows had >24 h to acclimate to the new conditions prior to conducting treatments, we hypothesize temperature differences may explain different capture patterns of various life stages. Smaller and less developed fish likely had reduced activity levels in the colder water conditions, which were apparently less problematic for older and larger juvenile Fathead Minnows. The potential influences of temperature on capture probabilities may hinder any comparisons of captures between life stages of Fathead Minnow. However, we believe comparisons of treatments conducted within each life stage (e.g. LED vs chemical light stick) are valid because difference would be due only to the experimental condition.

Management Implications

Light traps are an effective method of detecting and sampling early life stages of Razorback Sucker, supporting the earlier findings of Snyder and Mesimer (1997), and can be used with confidence under a variety of environmental conditions to capture and retain Razorback Sucker larvae. Chapter 2 provides supporting evidence from field tests conducted in a large floodplain wetland, where light traps were used to detect Razorback Sucker in low and high-density experiments, including tests in which fish were released as far as 10 m from light traps, a distance 800-1,000 X the body length of larvae.

To maximize capture of Razorback Sucker larvae, traps should maximize sampling time and have a consistently bright light source, similar to a LED-lit trap. Chemical light sticks are a suitable light source if used for shorter sampling durations (<8 h). Sampling should be terminated either prior to sunrise or shortly thereafter to ensure maximum Razorback Sucker retention. Initial detection of larvae in the Green River following the onset of larval drift, and general sampling for monitoring abundance in riverine backwaters, may be hindered by increased turbidity. Biologists may need to increase trap density, sampling frequency, or both in

these cases to ensure earliest detection. It is worth noting, however, that the earliest life stages, protolarvae, are relatively rare in field samples and may be present mainly near spawning sites. Traps should be placed in an open area where light obstruction by vegetation or rocks is minimized, to ensure efficient sampling in backwaters and side channels; more traps may be needed in areas with heavy cover to achieve the same results. Light traps with 4 mm apertures had similar capture and retention probabilities as those with 6 mm apertures and the smaller aperture size may limit capture of larger non-target organisms. Finally, Razorback Sucker larvae light trap sampling is most efficient for late protolarvae and mesolarvae, so if older life stages are desired (e.g., juveniles), effort should be increased by either increasing sampling duration, trap density, or both, or using other gears to better determine backwater presence and relative abundances. Light trap experiments expanded the ecological understanding of early life stages of Razorback Sucker and may contribute to conservation of the species in the Colorado River basin.

TABLE 1.1. Description of early life stages of fishes which as characterized by Snyder (1981) and Snyder and Muth (1988).

Variable	Description
Protolarvae	Protolarval life stage is characterized by the absence of dorsal-, anal-, and caudal-fin spines and rays.
Early Protolarvae	Protolarval life stage prior to swim bladder development.
Late Protolarvae	Protolarval life stage post swim bladder development.
Mesolarvae	Mesolarval life stage is characterized by the presence of at least one dorsal-, anal-, or caudal fin spine or ray, but either lacking the full complement of principle soft rays in at least one median fin or lacking pelvic-fin buds or pelvic fins (if present in adult).
Metalarvae	Metalarval life stage is characterized by the presence of a full complement of fin rays and pelvic fin buds or pelvic fins (if present in adult).
Juvenile	Juvenile life stage is characterized by loss of larval characteristics including fin-fold, but prior to full adult development.

TABLE 1.2. Release distances (m) of early life stages of Razorback Sucker among various treatment types. The "—" symbol indicates no trials were conducted for that life stage and treatment type. Unless otherwise stated, trials were conducted with releases of 25 fish (low-density treatment) for a 2 h set time in clear, structure-free water with light traps (4-mm aperture width) illuminated by a chemical light stick. Cover included both vegetation and rock. Each treatment type was compared with its logical counterpart to examine effects of each variable. For example, turbid water experiments with 1-m release distances and a 2 h set time, were compared to the clear water trials with otherwise similar conditions. E and L Protolarvae refer to the early and late protolarval life stages. LED refers to Light Emitting Diode. Front refers to the cover being placed in front of the trap. Behind refers to cover being placed behind the trap. Generally, five replications of each treatment were used*.

	Set Time (h)				Light Source		Turbidity		Density		Cover		Aperture
Life Stage	0.5, 1, 2, & 4			8	Absent	LED	Turbid		High		Front	Behind	6 mm
E Protolarvae	1	3	5	3	1	—	1	5	—	—	—	—	—
L Protolarvae	1	3	5	3	1	—	—	—	—	—	—	—	—
Mesolarvae	1	3	5	3	1	3	1	5	1	5	3	3	3
Metalarvae	1	3	5	3	1	—	1	5	1	5	3	3	3
Juvenile	1	3	5	3	1	—	1	5	1	5	3	3	—

*Mesolarval treatments run in clear, structure free water in 2 h sets and 3 m low density releases with 4 mm aperture width chemical-light-stick-lit trap had 13 replications. Treatments where cover were in front of the light trap, for mesolarvae in aforementioned conditions, had 6 replications. Treatments where vegetation was behind the light trap for mesolarvae in aforementioned conditions also had 6 replications.

TABLE 1.3. Number of replications for each Razorback Sucker light trap retention treatment combinations. A "— " symbol indicates the treatment combination was not tested. Unless otherwise stated, trials were conducted with chemical light sticks in new moon night conditions for a 1.5 h set time. Each treatment combination was compared with its logical counterpart for analysis. For example, mesolarval clear water night simulation tests were compared to mesolarval clear water tests where the light source was absent to determine the effect of light source on the retention of mesolarval Razorback Sucker. LED refers to Light Emitting Diode.

	Simulation				Light Source			Aperture Width
	Night		Sunrise		Absent		LED	6 mm
Life Stage	Turbid	Clear	Turbid	Clear	Turbid	Clear	Clear	Clear
Early Protolarvae	5	5	5	5	5	5	—	—
Late Protolarvae	—	5	—	5	—	5	—	—
Mesolarvae	5	10	8	8	5	10	5	6
Metalarvae	5	5	5	5	5	5	—	—
Juvenile	5	5	5	5	5	5	—	5

TABLE 1.4. Light trap retention treatment combinations examining various environmental light simulations. The "X" represents treatment combinations conducted with 5 replications. No sunlight trials were conducted in troughs.

		Simulation				
		50 L Buckets			Troughs	
Species	Life stage	Night	Sunrise	Sunlight	Night	Sunrise
Razorback Sucker	Mesolarvae	X	X	X	X	X
Fathead Minnow	Protolarvae	X	X	X	X	X
	Mesolarvae	X	X	X	X	X
	Metalarvae	X	X	X	X	X
	Juvenile	X	X	X	X	X

TABLE 1.5. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of effects of life stage, distance, set time, and interactions on capture probability of early life stage Razorback Sucker in light traps. The "X" indicates an interaction between variables. X^2 is the likelihood chi-square statistic.

Variable	X^2	*df*	*P*
Life Stage	47.44	4	<0.01
Distance	11.06	2	<0.01
Set Time	77.97	3	<0.01
Life Stage X Distance	57.16	8	<0.01
Life Stage X Set Time	65.28	12	<0.01
Distance X Set Time	37.30	6	<0.01
Life Stage X Distance X Set Time	91.31	24	<0.01

TABLE 1.6. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, set time, and their interactions on capture probabilities of Razorback Sucker with light traps. All treatment combinations included 3-m release distances and set times of 0.5 to 8 h.

Variable	X^2	*df*	*P*
Life Stage	80.22	4	<0.01
Set Time	190.60	4	<0.01
Life Stage X Set Time	148.39	16	<0.01

TABLE 1.7. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, distance, turbidity, and their interactions on capture probabilities of Razorback Sucker with light traps.

Variable	X^2	*df*	*P*
Life Stage	307.92	4	<0.01
Distance	24.97	1	<0.01
Turbidity	13.65	1	<0.01
Life Stage X Distance	16.94	4	<0.01
Life Stage X Turbidity	21.32	3	<0.01
Distance X Turbidity	7.82	1	<0.01
Life Stage X Distance X Turbidity	94.00	3	<0.01

TABLE 1.8. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, light source presence, and their interaction on capture probabilities of Razorback Sucker with light traps.

Variable	X^2	*df*	*P*
Light Source Presence	29.48	1	<0.01
Life Stage	43.56	4	<0.01
Light Source Presence X Life Stage	115.29	4	<0.01

TABLE 1.9. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of turbidity, light source presence, and their interaction on the retention probabilities of each life stage of Razorback Sucker in light traps. Turbidity treatments were not conducted with the late protolarval life stage due to rapid development and inadequate time to conduct experiments.

Life Stage	Variable	X^2	*df*	*P*
Early Protolarvae	Turbidity	46.51	1	<0.01
	Light Source Presence	73.06	1	<0.01
	Turbidity X Light Source Presence	58.57	1	<0.01
Late Protolarvae	Light Source Presence	181.39	1	<0.01
Mesolarvae	Turbidity	0.80	1	0.37
	Light Source Presence	240.37	1	<0.01
	Turbidity X Light Source Presence	0.004	1	0.95
Metalarvae	Turbidity	1.44	1	0.23
	Light Source Presence	110.69	1	<0.01
	Turbidity X Light Source Presence	3.28	1	0.07
Juvenile	Turbidity	0.0002	1	0.99
	Light Source Presence	117.23	1	<0.01
	Turbidity X Light Source Presence	3.11	1	0.08

TABLE 1.10. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, density, distance, and their interactions on capture probabilities of Razorback Sucker with light traps.

Variable	X^2	*df*	*P*
Life Stage	226.20	2	<0.01
Density	0.50	1	0.42
Distance	27.26	1	<0.01
Life Stage X Density	16.53	2	<0.01
Life Stage X Distance	13.11	2	<0.01
Density X Distance	6.26	1	0.01
Life Stage X Density X Distance	22.66	2	<0.01

TABLE 1.11. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, cover type and location, and their interaction on capture probabilities of Razorback Sucker with light traps. Cover type and location analyses were run separately for vegetation and simulated rock.

Cover Type	Variable	X^2	*df*	*P*
Vegetation	Vegetation	2.38	2	0.30
	Life Stage	159.00	2	<0.01
	Vegetation X Life Stage	25.40	4	<0.01
Rock	Rock	10.39	2	<0.01
	Life Stage	75.20	2	<0.01
	Rock X Life Stage	24.91	4	<0.01

TABLE 1.12. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of turbidity, environmental light condition, and their interaction on retention probabilities of each life stage of Razorback Sucker in light traps. Turbidity treatments were not conducted with the late protolarval life stage due to rapid development and inadequate time to conduct experiments.

Life Stage	Variable	X^2	*df*	*P*
Early Protolarvae	Turbidity	13.40	1	<0.01
	Environmental Light Condition	6.27	1	0.01
	Turbidity X Environmental Light Condition	4.08	1	0.04
Mesolarvae	Environmental Light Condition	0.89	1	0.34
Metalarvae	Turbidity	0.69	1	0.41
	Environmental Light Condition	1.87	1	0.17
	Turbidity X Environmental Light Condition	0.0001	1	0.99
Juvenile	Turbidity	2.12	1	0.15
	Environmental Light Condition	0.69	1	0.40
	Turbidity X Environmental Light Condition	0.06	1	0.80

TABLE 1.13. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of life stage, light trap aperture width, and their interaction on the capture and retention probabilities of Razorback Sucker. Additional logistic regression analysis estimating effects of environmental light condition, light trap aperture width, and their interaction, along with light source presence, light trap aperture width, and their interaction on retention probabilities in light traps with juveniles was conducted.

Trial Type	Variable	X^2	*df*	*P*
Capture	Trap Aperture	0.98	1	0.32
	Life Stage	56.07	1	<0.01
	Trap Aperture X Life Stage	1.21	1	0.27
Retention	Life Stage	0.82	1	0.36
	Trap Aperture	1.29	1	0.26
	Life Stage X Trap Aperture	0.005	1	0.94
Retention: Juvenile Environmental Light Condition	Environmental Light Condition	0.69	1	0.40
	Trap Aperture	1.29	1	0.26
	Environmental Light Condition X Trap Aperture	0.01	1	0.92
Retention: Juvenile Light Presence	Light Source Presence	75.73	1	<0.01
	Trap Aperture	8.30	1	<0.01
	Light Source Presence X Trap Aperture	5.19	1	0.02

TABLE 1.14. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of light source on the capture and retention probabilities of Razorback Sucker with light traps. Light source in capture trials included chemical light stick, LED, and old chemical light stick light trap light sources, while light source for retention trials included only chemical light stick and LED light sources.

Trial Type	Variable	X^2	*df*	*P*
Capture	Light source	35.45	2	<0.01
Retention	Light source	3.77	1	0.05

TABLE 1.15. Results from a Type III Wald X^2 test analyzing the results of paired LED-lit versus chemical-light-stick-lit-lit light trap preference tests with mesolarval Razorback Sucker. The X2 values indicate that the light source, LED or chemical light stick, had a statistically significant effect on capture of Razorback Sucker larvae.

	X^2	*df*	*P*
Intercept	52.94	1	<0.01
Light source	63.71	1	<0.01

TABLE 1.16. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of light source, life stage, and their interaction on the capture and retention probabilities of Fathead Minnow with light traps. Types of light source in these analyses include LED and chemical light stick light sources.

Trial Type	Variable	X^2	*df*	*P*
Capture	Light source	12.66	1	<0.01
	Life Stage	58.71	3	<0.01
	Light source X Life Stage	20.84	3	<0.01
Retention	Light source	3.34	1	0.07
	Life Stage	13.19	3	<0.01
	Light source X Life Stage	4.24	3	0.24

TABLE 1.17. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of environmental light condition on retention probabilities of mesolarval Razorback Sucker for treatments conducted in 50 L buckets. Additionally, environmental light condition, life stage, and their interaction on retention probabilities of Fathead Minnow for treatments conducted in 50 L buckets.

Species	Variable	X^2	*df*	*P*
Razorback Sucker	Environmental Light Condition	19.62	2	<0.01
Fathead Minnow	Environmental Light Condition	5.94	2	0.05
	Life Stage	5.57	3	0.13
	Environmental Light Condition X Life Stage	39.51	6	<0.01

TABLE 1.18. Two separate logistic regression analyses (Type-III likelihood ratio tests), with the first presenting the effect of the container type on retention probabilities of mesolarval Razorback Sucker. The second presents effects of container type, life stage, and their interaction on retention probabilities of Fathead Minnow.

Species	Variable	X^2	*df*	*P*
Razorback Sucker	Container- Bucket vs Trough	0.13	1	0.72
	Container- Trough vs Tank	7.21	1	<0.01
Fathead Minnow	Container- Bucket vs Trough	7.74	1	<0.01
	Life Stage	5.57	3	0.13
	Container X Life Stage	7.49	3	0.06

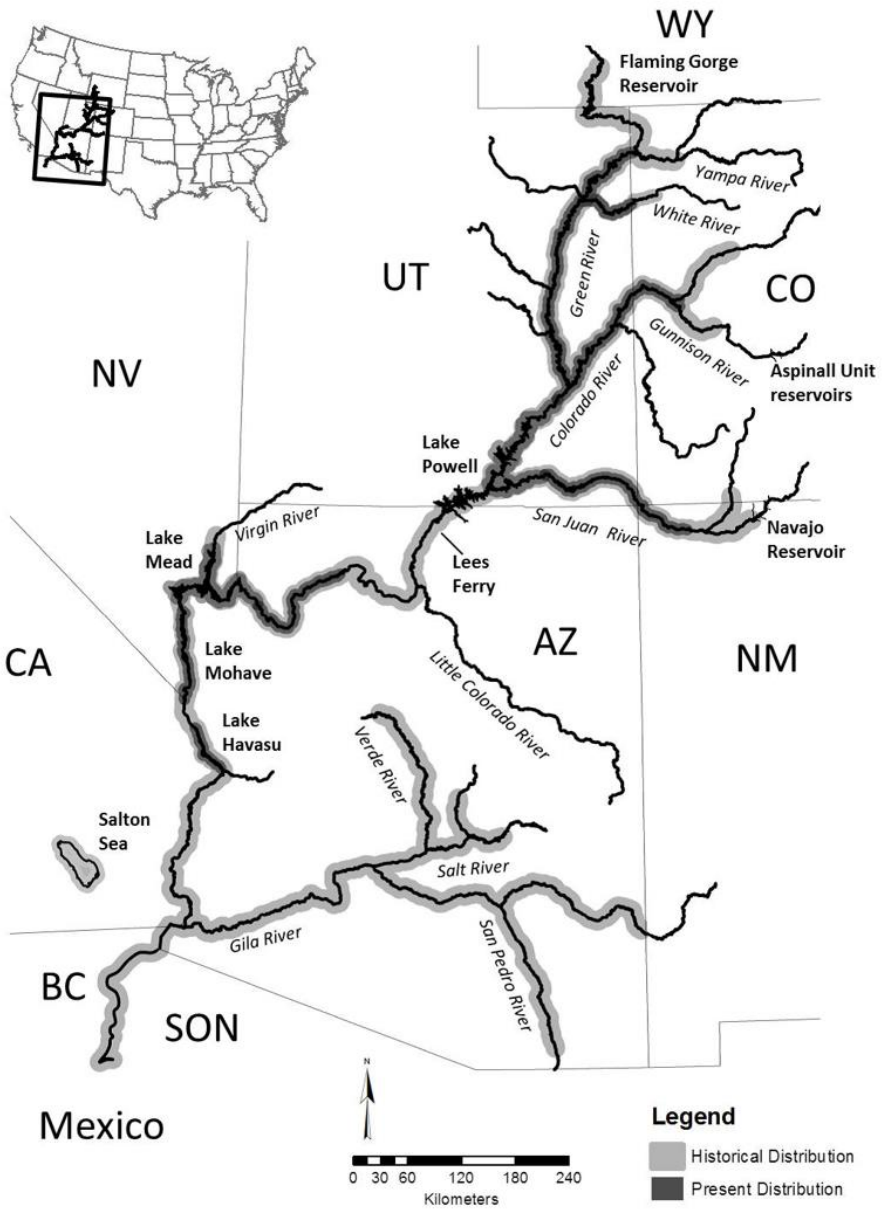

FIGURE 1.1. Historical (light grey shading) and present (dark grey shading) distribution of Razorback Sucker in the Colorado River Basin. Reservoirs appear as solid black. Waters upstream of Lees Ferry, AZ are designated as the upper Colorado River Basin for water management purposes (adapted from Bestgen et al., in press)

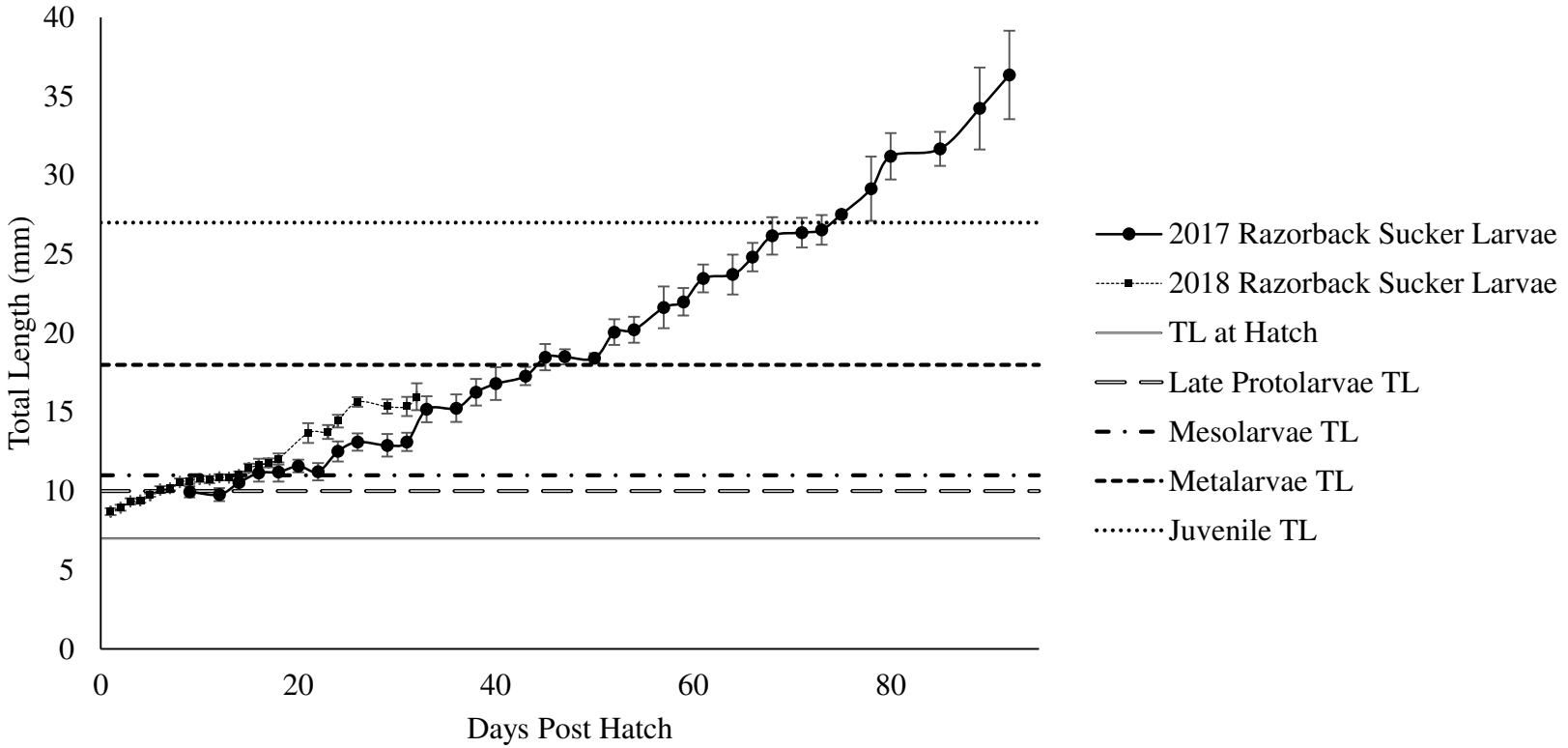

FIGURE 1.2. Total length (TL) of Razorback Sucker larvae used in 2017 and 2018. Lengths were measured on a subset of larvae preserved from our holding tanks every 1-5 days. Average TL at life stage transitions are represented by horizontal lines.

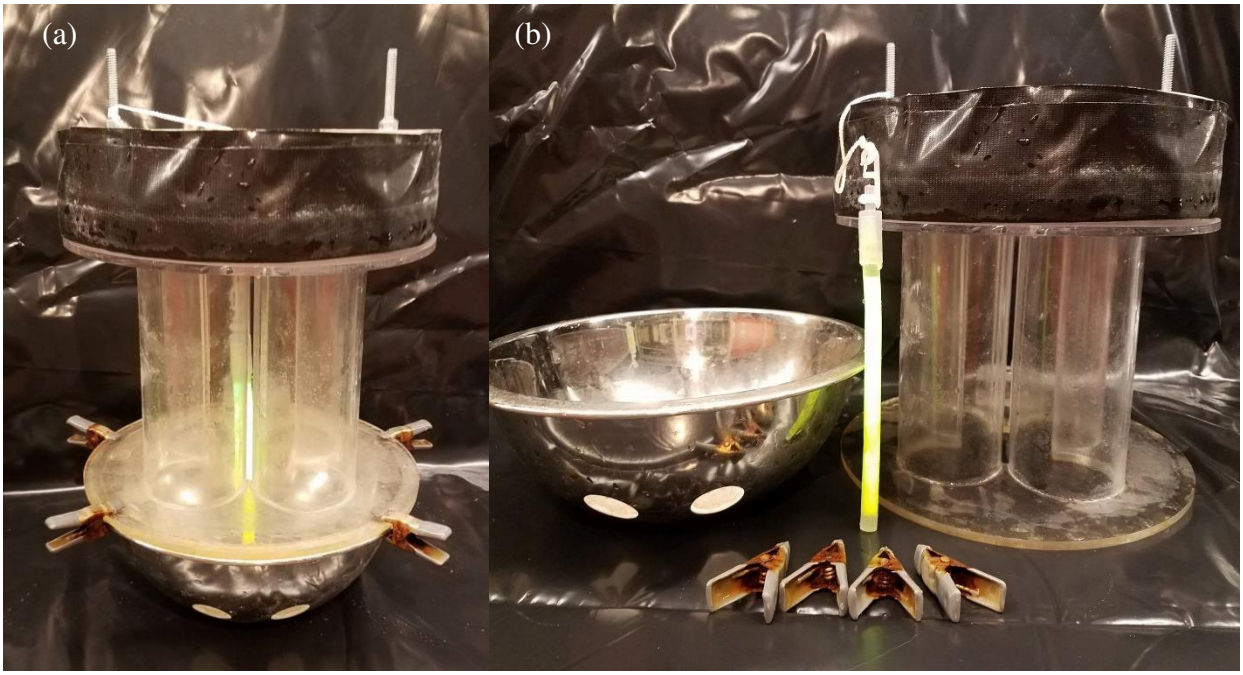

FIGURE 1.3. An assembled (a) and disassembled (b) quatrefoil light trap, adapted from Killgore (1994). The 5 cm-thick foam, covered with black tape for protection, allowed the light trap to be suspended from the water surface. The catch basin is attached using the 4 mini spring clamps. The 24-h Duralume chemical light stick is placed through a hole in the top and suspended in the center of the trap.

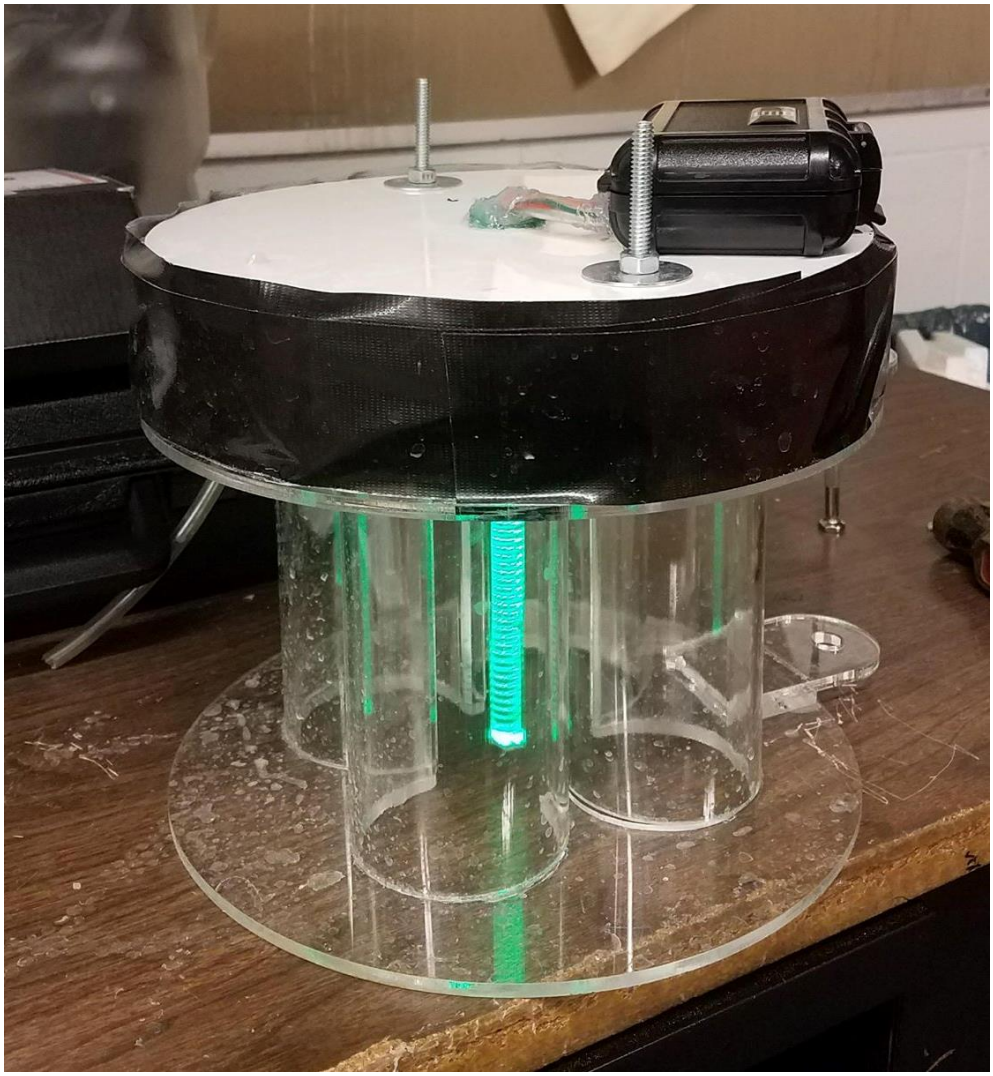

FIGURE 1.4. A new Light Emitting Diode (LED) light source for a quatrefoil light trap without the catch basin attached. Green light from a single LED is dispersed the length of trap using a threaded 15.2 cm acrylic rod and is powered with a rechargeable lithium ion battery housed in a waterproof box fixed to the top of the trap. The LED power source and mechanism were waterproofed with the addition of watertight rubber stoppers, silicon, and PVC tubing.

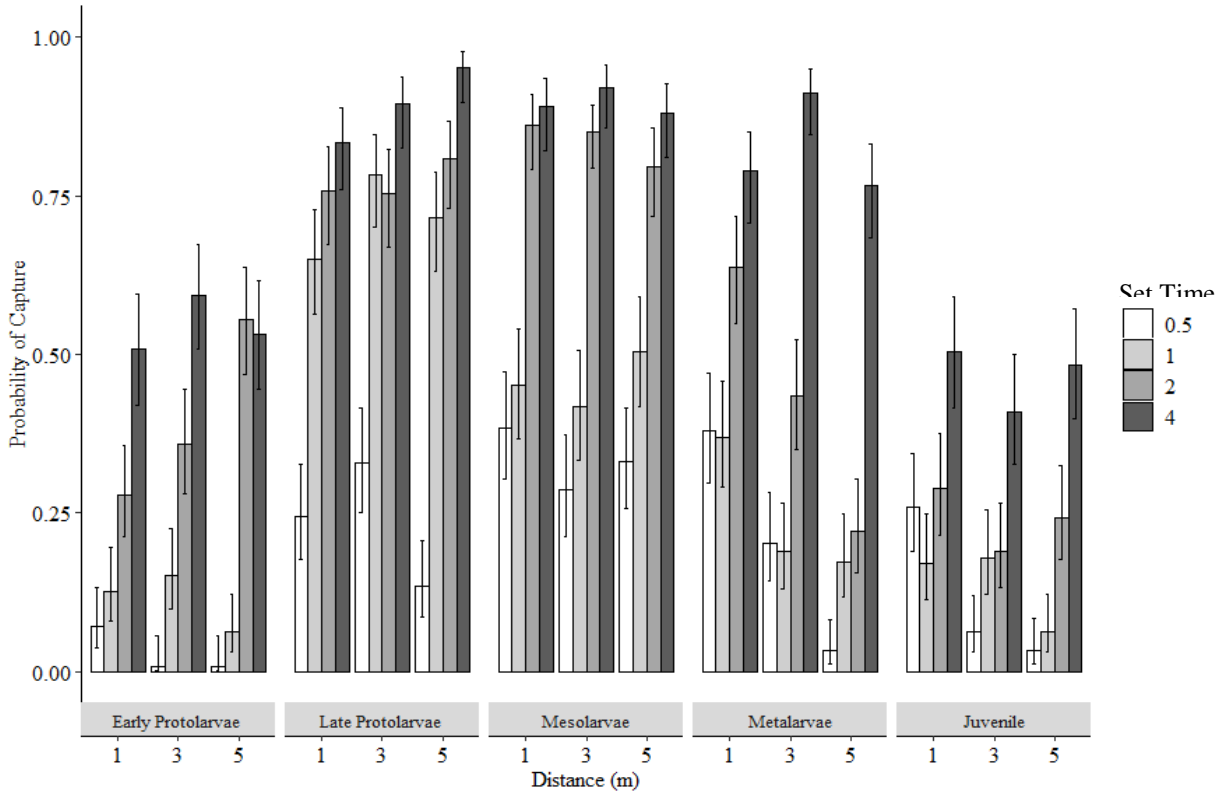

FIGURE 1.5. Probability of Razorback Sucker capture compared among life stage, distance, and set time. Life stages, from left to right, are in order of increasing age and size. Error bars represent 95% confidence intervals.

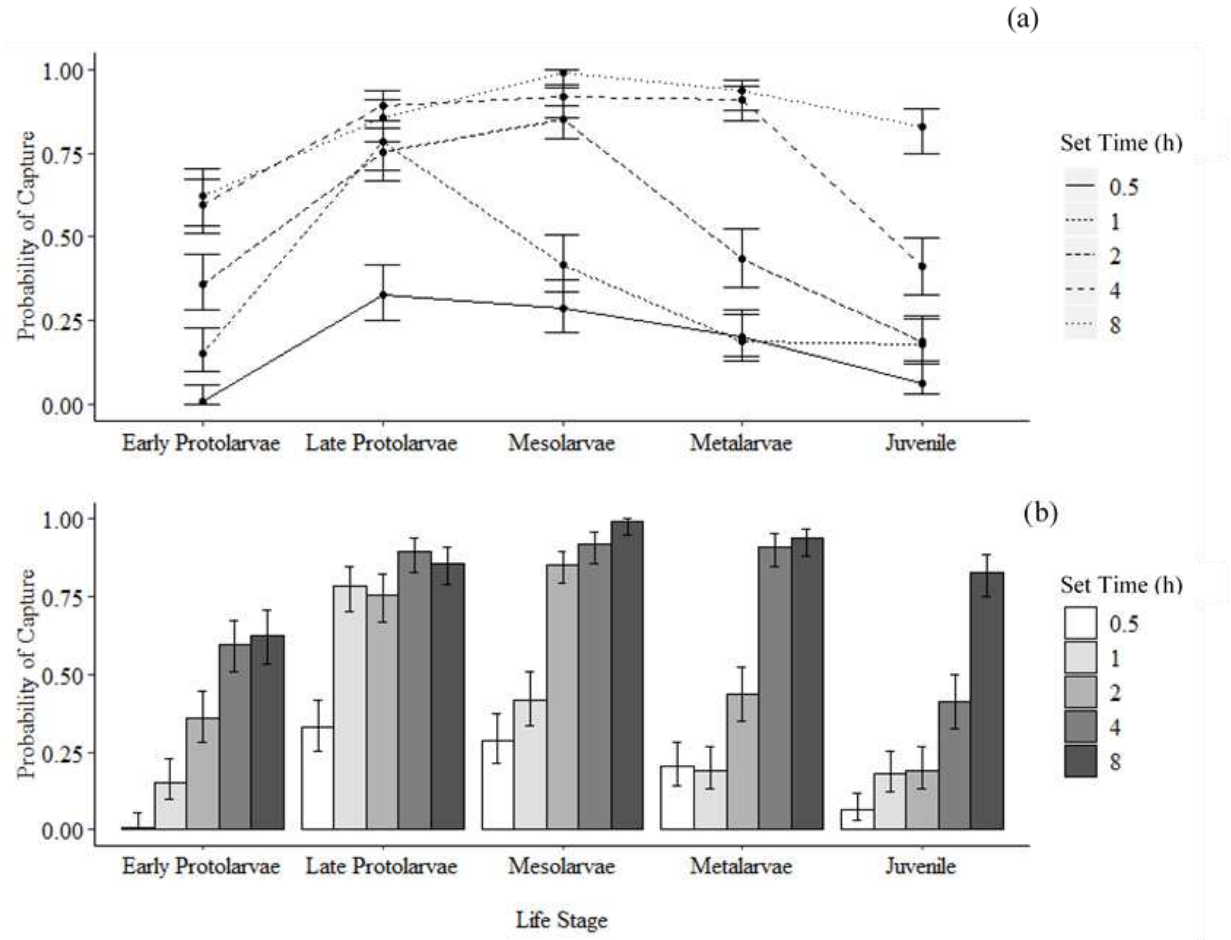

FIGURE 1.6. Probability of capture among various life stages of Razorback Sucker, in order of increasing age and size, at various set times at a 3-m distance. Set times are connected by lines (a) to further exemplify capture probabilities trends which vary by life stage. The same data are shown below (b) to indicate time needed to result in similar capture probabilities between life stages. For example, capture probabilities are similar for early protolarvae at 0.5 h, mesolarvae at 1 h, metalarvae at 2 h, and juvenile at 4 h. Error bars represent 95% confidence intervals.

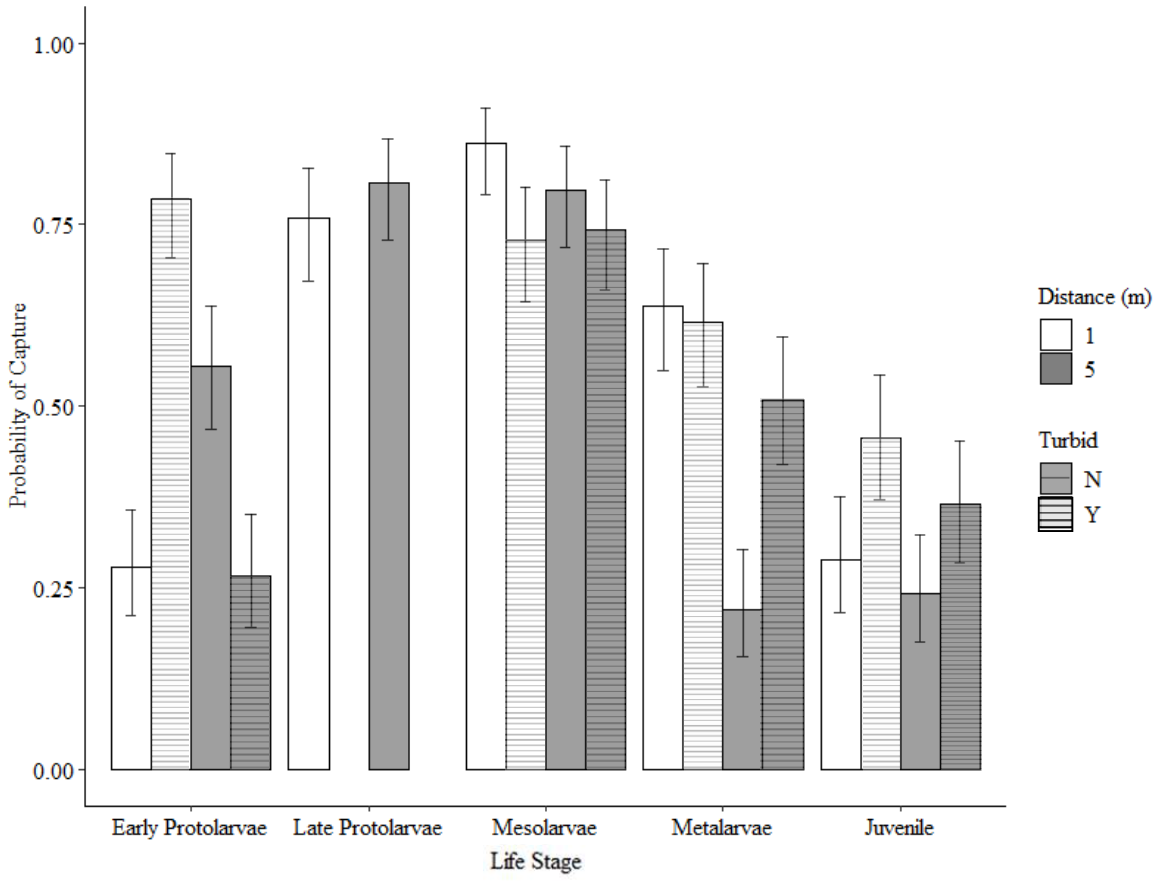

FIGURE 1.7. Probability of capture among various life stages of Razorback Sucker and release distances in turbid and clear conditions. Empty bars represent clear water conditions; bars with horizontal lines represent turbid water conditions. White represents a 1-m distance; grey represents a 5-m distance. Turbidity treatments were not conducted with the late protolarval life stage due to rapid development and inadequate time to complete experiments. Error bars represent 95% confidence intervals.

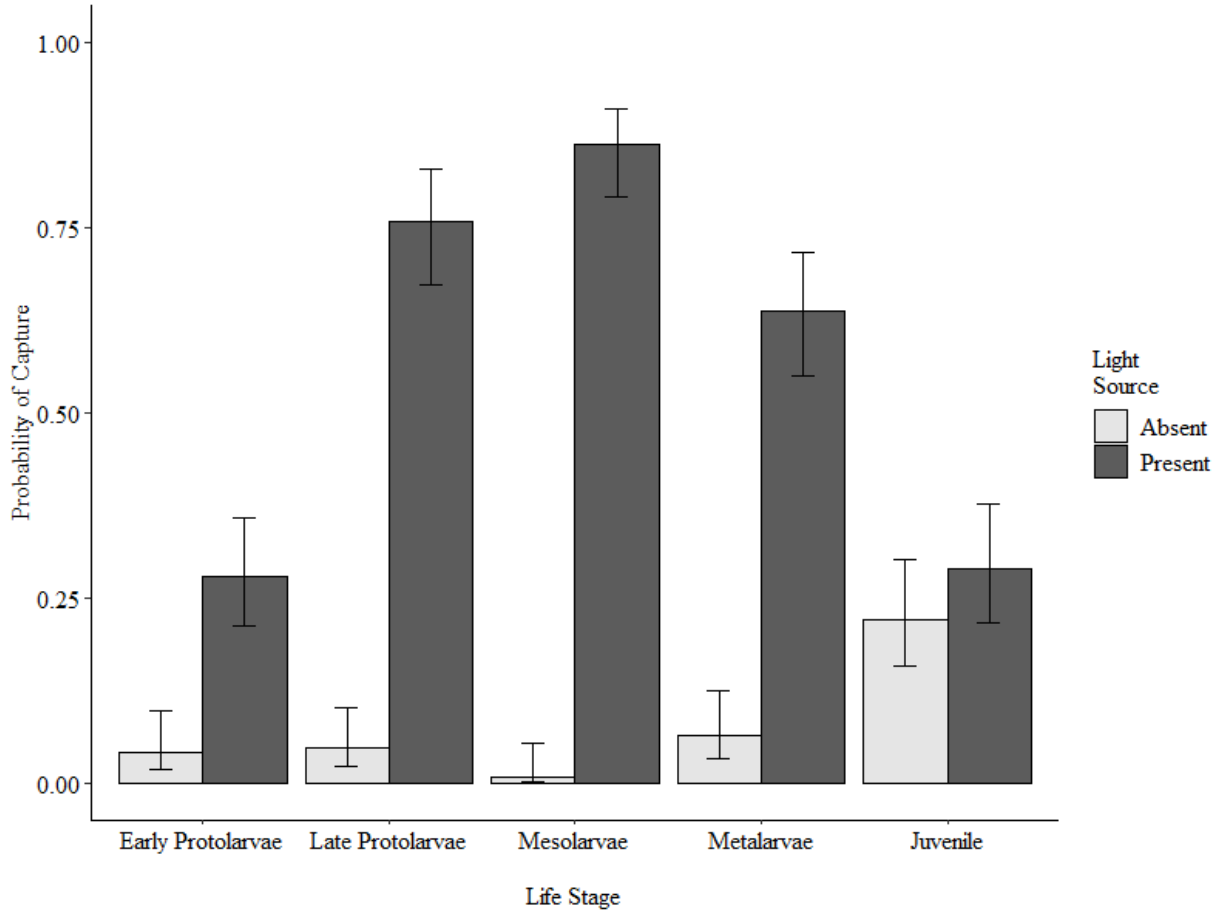

FIGURE 1.8. Probability of capture among various Razorback Sucker life stages with and without a light source present at a 1-m release distance. Error bars represent 95% confidence intervals.

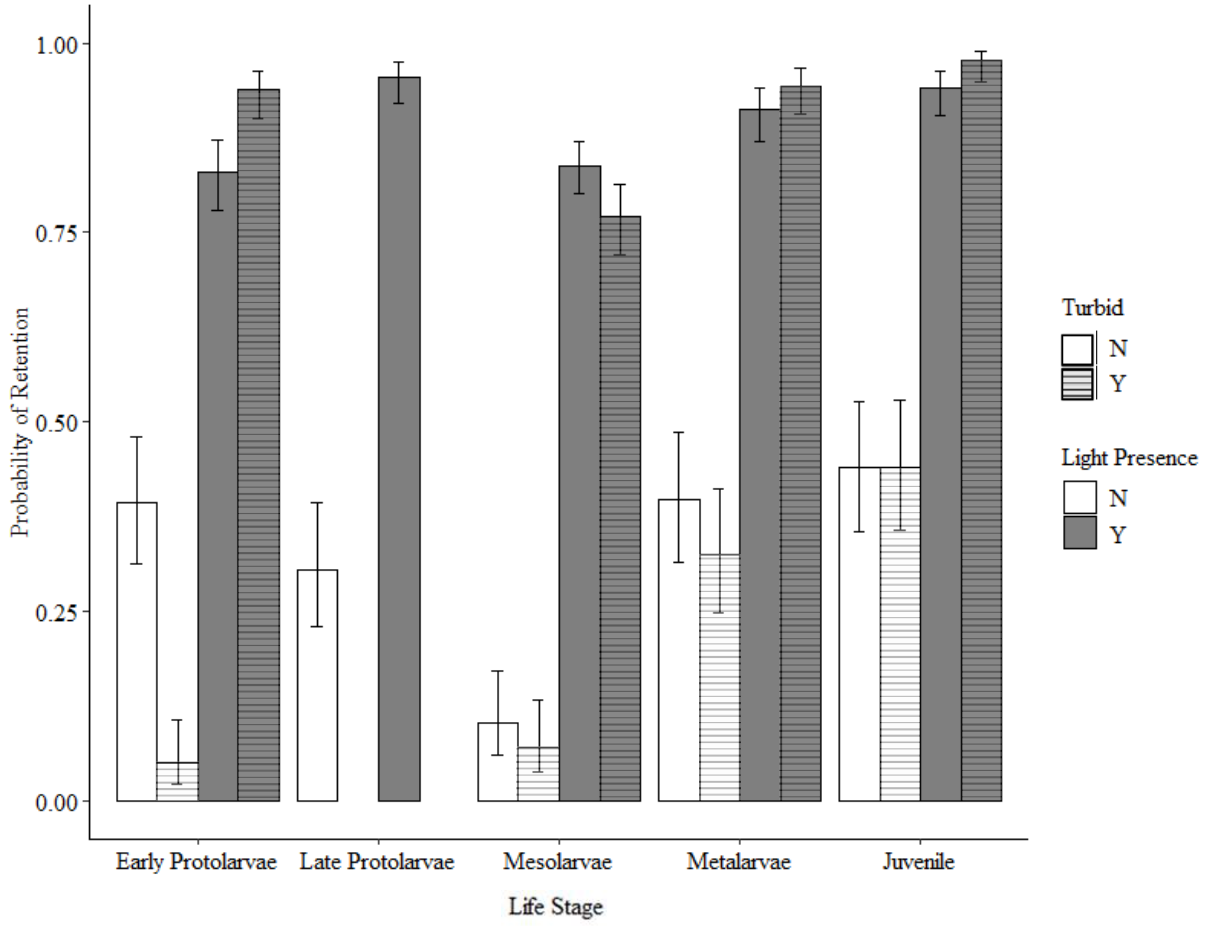

FIGURE 1.9. Probability of retention among various Razorback Sucker life stages, light source presence, and turbidity. Empty bars represent clear water conditions; bars with horizontal lines represent turbid water conditions. White represents a 1-m release distance; grey represents a 5-m distance. Turbidity treatments were not conducted with the late protolarval life stage due to rapid development and inadequate time to complete experiments. Error bars represent 95% confidence intervals.

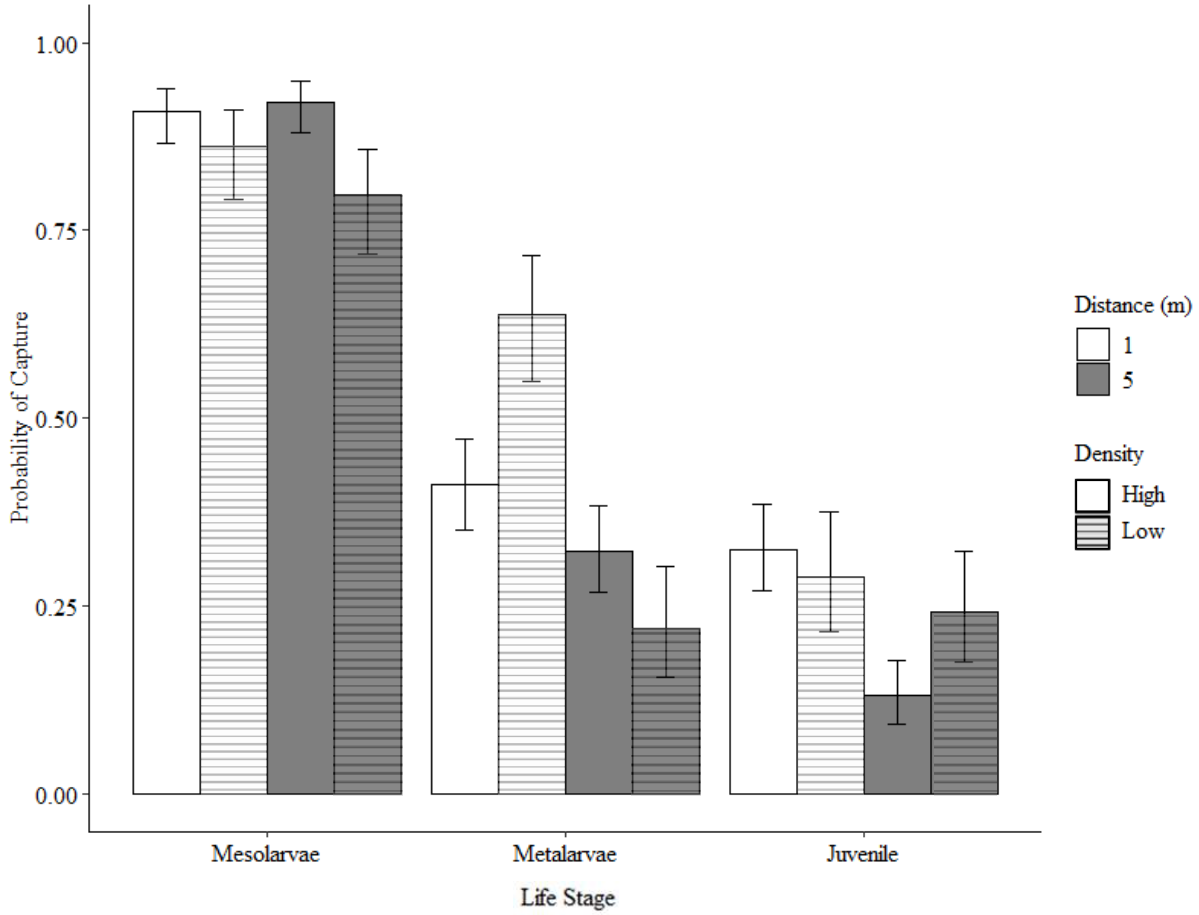

FIGURE 1.10. Probability of capture among various Razorback Sucker life stages, release distances, and densities. Empty bars represent high density; bars with horizontal lines represent low density. White represents a 1-m release distance; grey represents a 5-m distance. Error bars represent 95% confidence intervals.

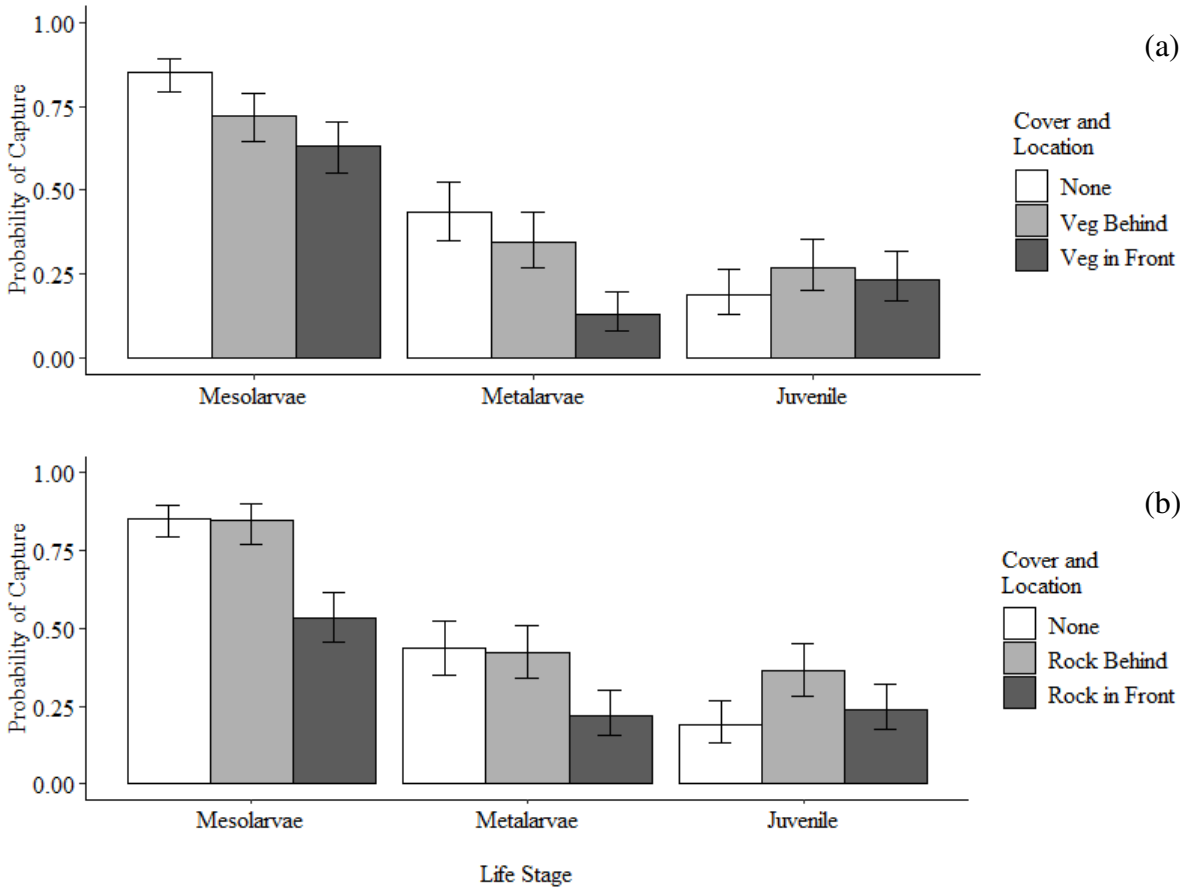

FIGURE 1.11. Probability of capture among various Razorback Sucker life stages, cover (vegetation (a), and simulated rock (b)) and location in relation to the light trap. Error bars represent 95% confidence intervals.

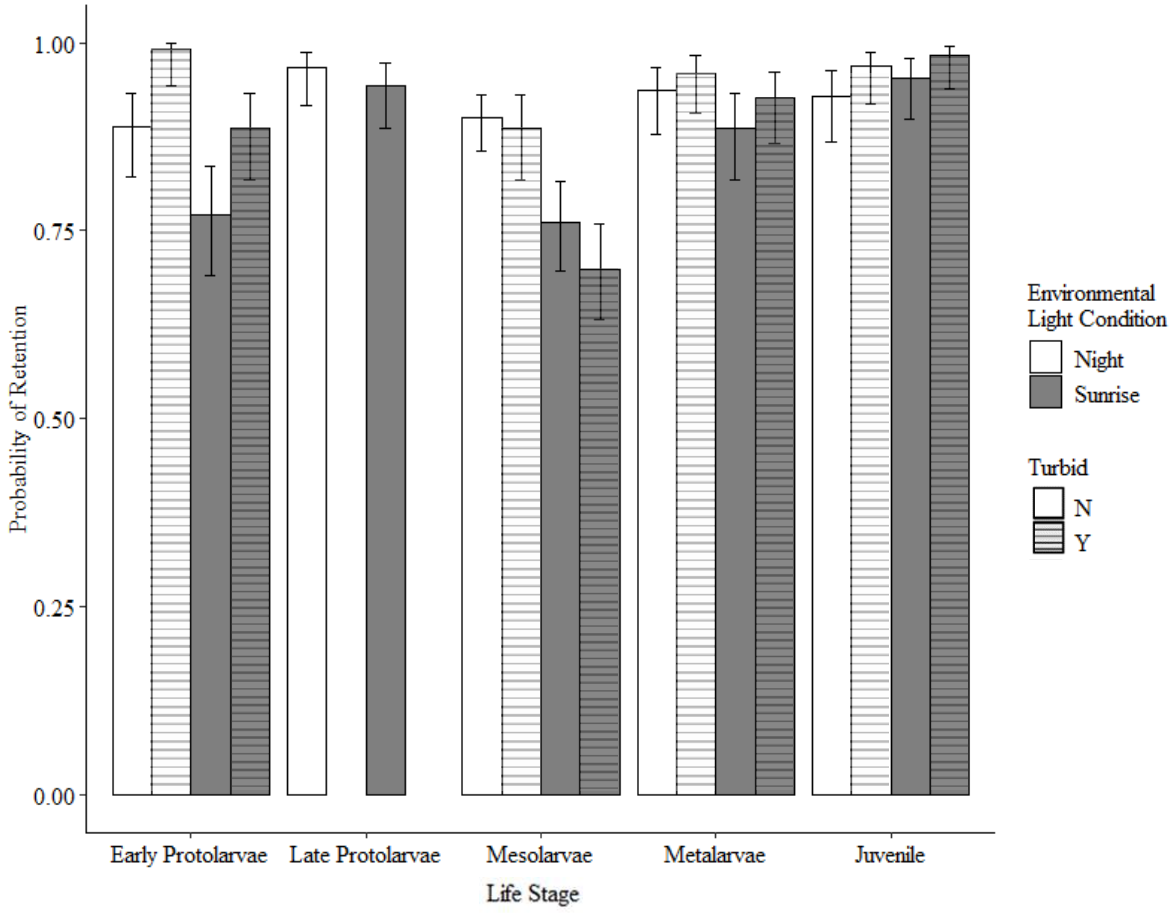

FIGURE 1.12. Probability of retention among various Razorback Sucker life stages, environmental light condition, and turbidity. Empty bars represent clear water conditions; bars with horizontal lines represent turbid water conditions. White represents a new moon night conditions; grey represents sunrise conditions. Turbidity treatments were not conducted with the late protolarval life stage due to rapid development and inadequate time to complete experiments. Error bars represent 95% confidence intervals.

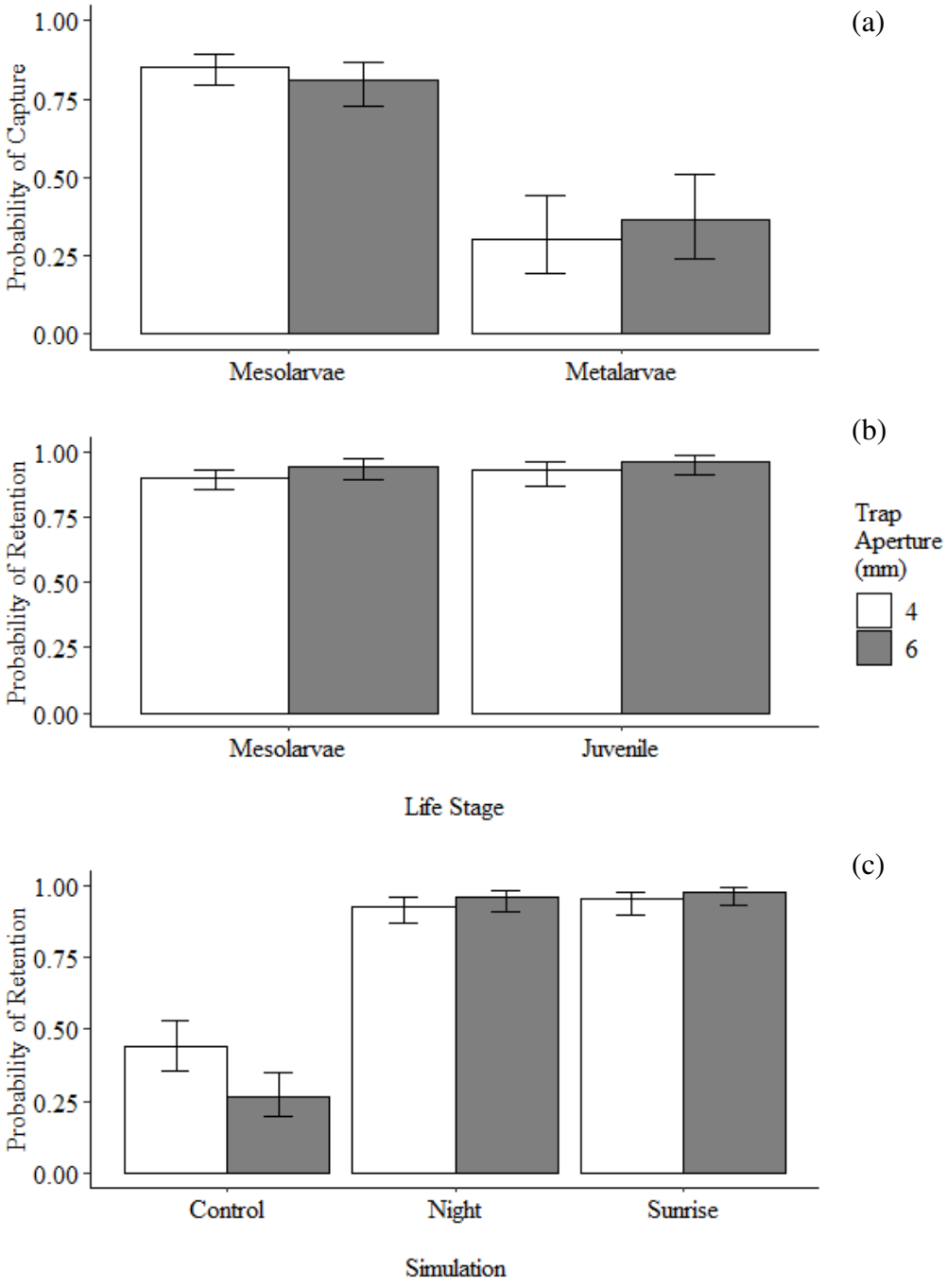

FIGURE 1.13. The probability of capture (a) and retention (b) among various Razorback Sucker life stages and trap aperture widths. Panel (c) shows probability of retention among various environmental light conditions and trap aperture widths for juvenile Razorback Sucker retention. Control consists of new moon night light condition and absence of light trap light source. Error bars represent 95% confidence intervals.

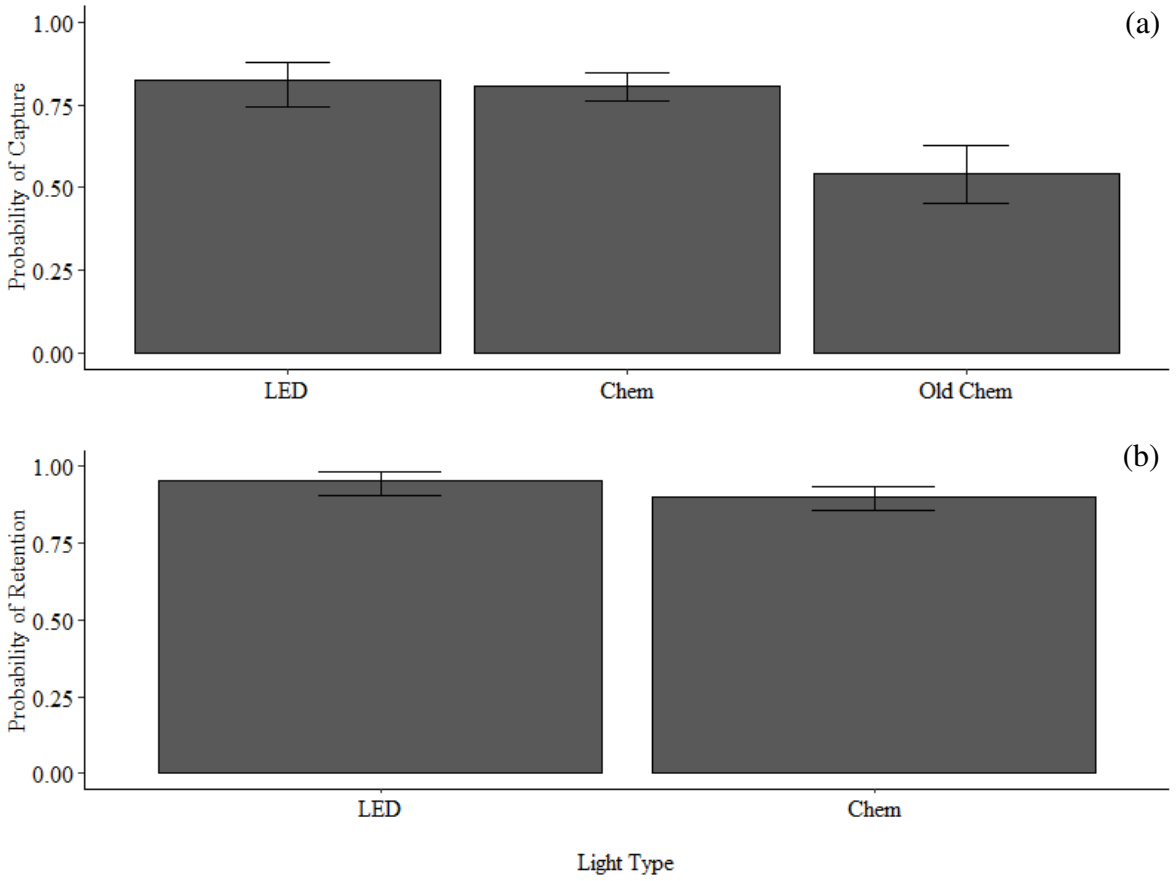

FIGURE 1.14. Probability of Razorback Sucker capture (a) and retention (b) among three light sources. Old Chem refers to a chemical light stick which had been activated about 16 h prior to the experiment. Error bars represent 95% confidence intervals.

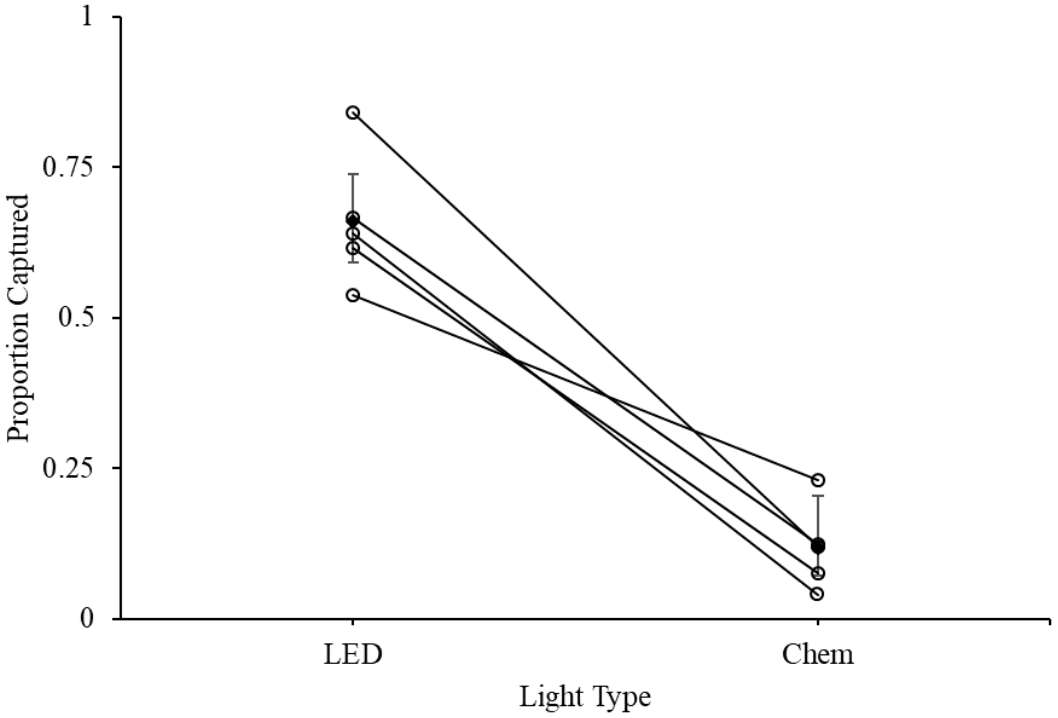

FIGURE 1.15. Proportion of mesolarval Razorback Sucker captured in LED and chemical light stick (Chem) lighted light traps in paired preference tests. The solid diamond represents the mean proportion of larvae captured in traps in each light source determined via conditional logistic regression analysis. Error bars represent 95% confidence intervals.

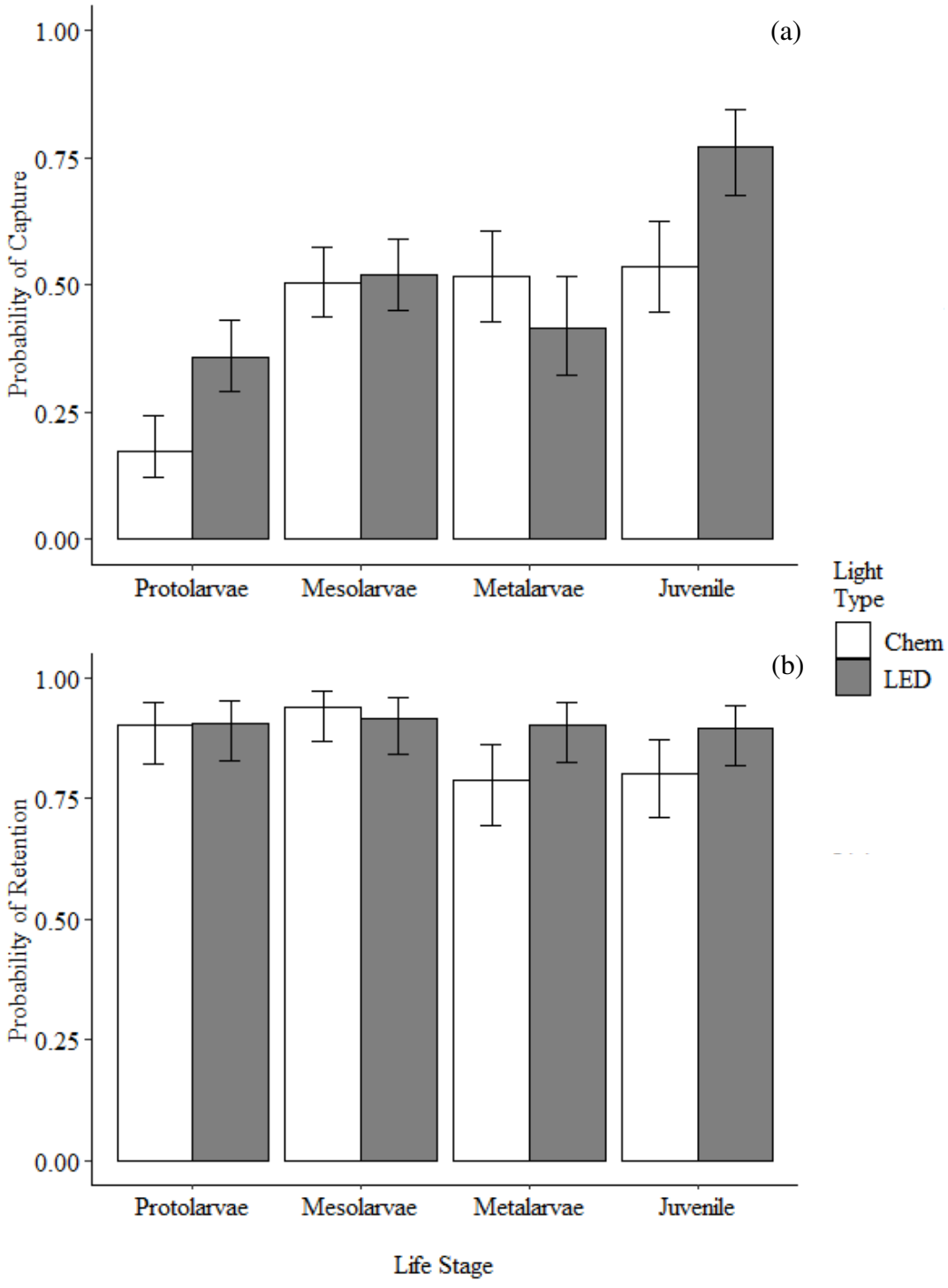

FIGURE 1.16. Probability of capture (a) and retention (b) of various life stages of Fathead Minnow and light source types. Chem refers to a chemical light stick light source. Error bars represent 95% confidence intervals.

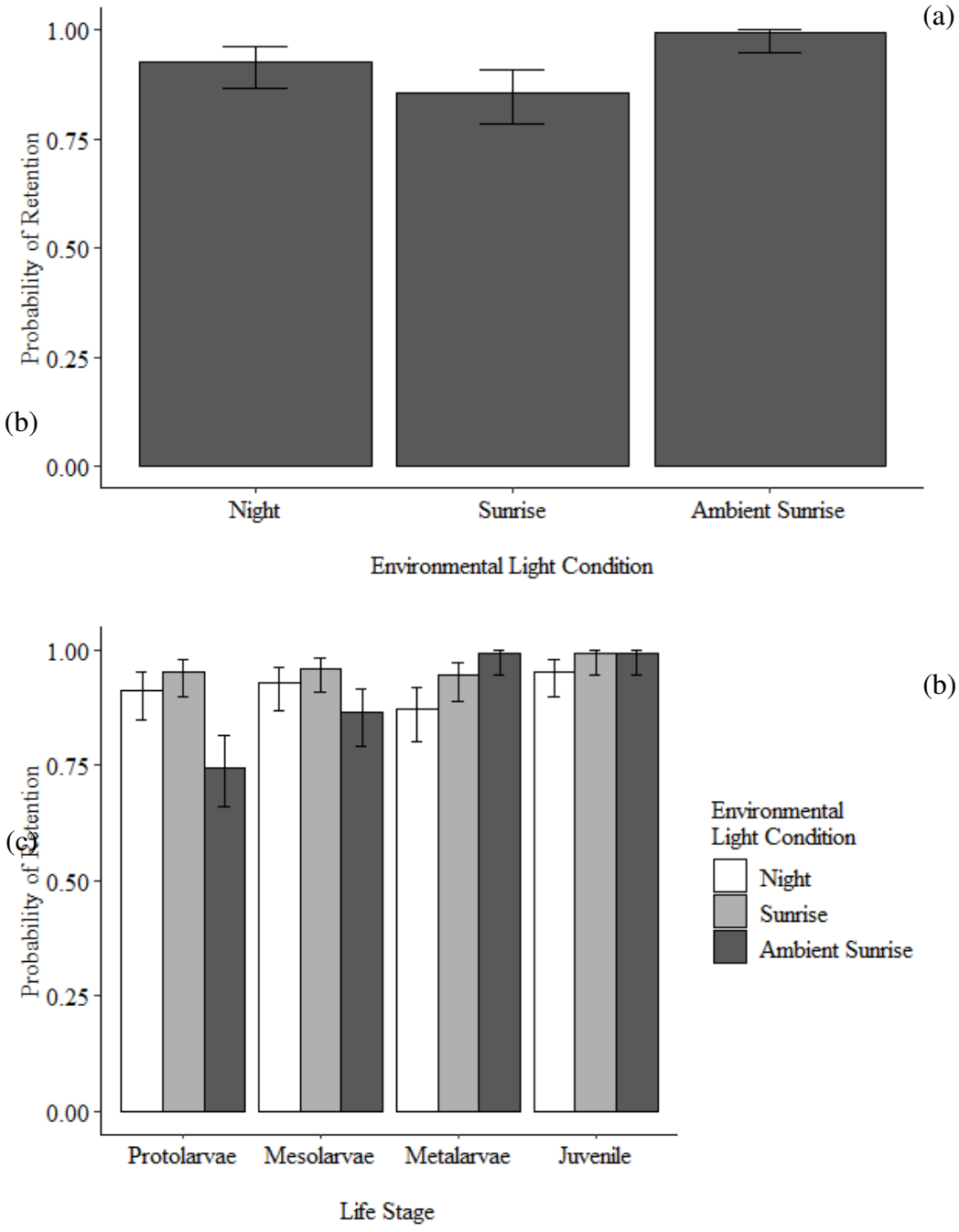

FIGURE 1.17. Probability of mesolarval Razorback Sucker (a) and early life stages of Fathead Minnow (b) retention and environmental light condition conducted in 50 L bucket experiments. Night and sunrise simulations were conducted in the laboratory, while ambient sunrise simulations were conducted outdoors in a shaded area. Error bars represent 95% confidence intervals.

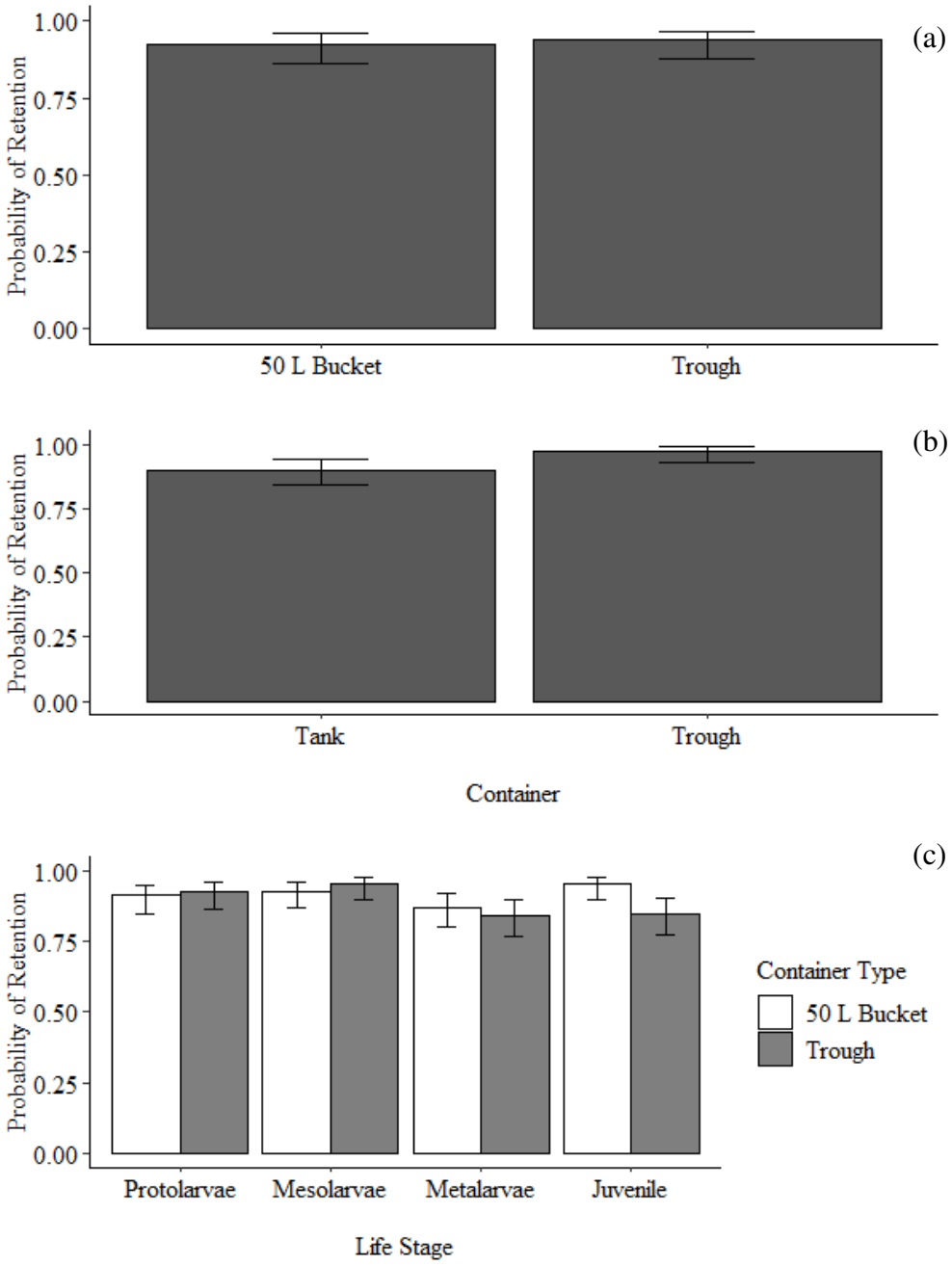

FIGURE 1.18. Probability of mesolarval Razorback Sucker retention and container type conducted in 1.5 h new moon night light conditions (a) and in overnight trials (b). Trials in troughs were conducted under new moon night light conditions while the tank trials were conducted outdoors. Probability of retention among various Fathead Minnow life stages and container types in new moon night light conditions (c). Error bars represent 95% confidence intervals.

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CHAPTER TWO:

FIELD EXPERIMENTS TO EVALUATE LIGHT TRAP SAMPLING FOR RAZORBACK SUCKER LARVAE

Current management strategies for improving status of wild Razorback Sucker rely on sampling of larvae in wetland and riverine backwater habitats to evaluate post-reproductive survival, spatial and temporal abundance patterns, and entrainment into wetlands. Light traps, a passive sampling gear which exploits the innate attraction of fish early life stages to light, are thought an effective gear type for sampling, but little is known on their efficacy to capture or retain larvae. We conducted experimental releases of unmarked, single-marked, and double-marked (immersion in oxytetracycline hydrochloride [OTC]) Razorback Sucker larvae over three nights in a managed wetland of the Green River, Utah, at the Ouray National Wildlife Refuge. Batches of released larvae were paired with 1 of 12 light traps each night in various densities (10, 50, 250, 1,000 fish per trap), 3 and 10-m release distances from light traps, light-emitting diode (LED) and chemical light stick light sources, and two release times to evaluate effects on larvae capture. In addition, batches of 25 single-marked larvae were placed in light traps and set on a fourth night in three environmental light conditions (night, sunrise, and sunlight) to evaluate effects on larvae retention. Light traps recaptured larvae each night even when low densities of fish were released in the 53.5 ha wetland. Recapture proportions for individual traps ranged from 0 to 0.68 over the three release nights. Recapture proportions in traps with either light source were not influenced by release distance. Results from ANCOVA indicated LED traps had consistently higher recapture proportions than chemical light stick traps. Further, recapture proportions were not substantially affected by release densities, indicating light trap captures

may be an index of larvae abundance. Inexplicably, retention was very low, which is inconsistent with previous laboratory tests. Recapture data suggest light traps can detect even low densities of Razorback Sucker larvae in large and open habitats, and capture proportions vary little as density increases. Thus, light traps are a useful tool to monitor presence and abundance of larvae. This information will aid management of the species and improve conservation status of Razorback Sucker in the Colorado River basin.

Introduction

The Razorback Sucker is a long-lived, large catostomid native to the Colorado River basin and has been federally listed as endangered since 1991 due to negative impacts of habitat and flow alteration and negative effects of widespread and abundant non-native fishes (Minckley 1983; U.S. Fish and Wildlife Service 1991; Poff et al. 1997; Bestgen et al. 2002; Bunn and Arthington 2002; Bestgen et al. 2011). Though historically widespread throughout the basin, wild populations were believed extirpated (Marsh 1994; Bestgen et al. 2002). However, hatchery stocking has restored populations in portions of its former range. In the upper Colorado River basin, stocking has occurred since 1995, and successful reproduction by wild or hatchery-released fish has occurred every year since monitoring began in 1992 (Zelasko et al. 2010; Bestgen et al. 2011). Although stocked adult fish survive and reproduce, and larvae are evident each year, the few juvenile Razorback Suckers detected indicates lack of recruitment of young fish to the adult life stage and a tenuous population status (Zelasko et al. 2018; Bestgen et al., in press).

In the upper Colorado River basin, Razorback Sucker typically spawn on the ascending limb of the hydrograph, maximizing dispersal of drifting larvae (Tyus and Karp 1990; Wydoski and Wick 1998). Reproduction timing coincident with flood flows increases access to wetland

habitats, which provide plentiful food and warm water temperatures (Modde 1996; Modde et al. 2001; Bestgen 2008) that are crucial for increased growth and survival. An example of the benefit of managed floodplain wetlands for rearing and recruitment of Razorback Sucker is Stewart Lake, where survival and fast growth to the juvenile stage has been documented (e.g., Schelly et al. 2016; Bestgen et al. 2017). Currently, spring flow releases from upstream Flaming Gorge Reservoir are triggered by the detection of larval Razorback Sucker to maximize larval entrainment into floodplain wetlands per the Larval Trigger Study Plan (LTSP) implemented by the Upper Colorado River Endangered Fish Recovery Program (Brower et al. 2001; Hedrick et al. 2009; Bestgen et al. 2011; LaGory et al. 2012).

Additional components of the LTSP include evaluating the entrainment, retention, relative abundance, and survival of larval and juvenile Razorback Sucker in floodplain wetlands along the Green River (LaGory et al. 2012). Due to habitat complexity and heavy macrophyte growth in wetlands, typical larval sampling techniques like seining are difficult and ineffective. Light traps, a passive gear commonly used for sampling larval fish in low velocity freshwater habitats (Secor et al. 1992; Mueller et al. 1993; Snyder and Meismer 1999; Marchetti et al. 2004; Hedrick et al. 2009; Naus and Adams 2016), are thought to be effective for monitoring these population characteristics (Gregory and Powles 1985; Hickford and Scheil 1999; Gyekis et al. 2006, Pierce et al. 2007; Catalán et al. 2014; Chapter 1). Despite widespread use, experimental studies to assess efficacy of light traps to detect presence of Razorback Sucker larvae or measure their abundance in riverine backwaters or wetlands are lacking (Snyder and Meismer 1999; Bestgen et al. 2012; Chapter 1). Here, we tested effects of larval density, release distance from traps, and release time as well as light trap light source type on capture and retention of

Razorback Sucker larvae. This information should improve monitoring efforts that will inform management to conserve Razorback Sucker in the Colorado River basin.

Methods

Field trials were conducted in the Leota-10 (L-10) wetland located at Ouray National Wildlife Refuge, Randlett, Utah, west of and adjacent to the Green River (Figure 2.1). The L-10 wetland was about 53 ha and had average depth of approximately 1.2 m (Dan Schaad, U.S. Fish and Wildlife Service, personal communication). Because no Razorback Sucker larvae were stocked in L-10 just prior to the study and wetland water was from an off-stream source (Pelican Lake), we were assured that all Razorback Sucker larvae captured were from our study releases.

Razorback Sucker larvae used in the study were reared at Ouray National Fish Hatchery located on Ouray National Wildlife Refuge (Figure 2.1). Ripe adults were stripped of gametes in paired matings in late April 2018 and embryos were incubated in hatching jars with a circulating water current. Embryos hatched from 2-5 May. Two separate batches of larvae were immersed in a solution of tris-buffered (pH 7) oxytetracycline hydrochloride (OTC; 350 mg/L) for 6 h to mark the otoliths (Muth and Bestgen 1991; Muth and Meismer 1995). One batch was then marked three days later using the same procedure. The 3-d interval is sufficient to produce two easily distinguishable marks on the otolith (Muth and Meismer 1995; Hedrick et al. 2009; Bestgen et al. 2011). The OTC marks fluoresce yellow-green under a UV microscope at 400x magnification; otolith marks in treated fish were easily visible in specimens preserved after marking. Use of unmarked, single-marked, and double-marked larvae allowed for recognition of batches of fish that were released into the L-10 wetland and sampled with light traps under different experimental conditions. Examination of otoliths from preserved samples of larvae showed batches were distinguishable. Batches of mesolarval Razorback Sucker (11 mm TL) for

experimental release were estimated volumetrically by weighing small volume samples and counting those, or were counted completely (small batches) and placed into sealable bags at the hatchery. Bags were transported to the study site where acclimation to wetland water began about 1 h prior to release.

The east bank levee of L-10 wetland was used as the experiment staging area (Figures 2.1 and 2.2). We marked 12 trap locations used throughout the study with reinforcement bars (also the retaining rod for floating traps), each about 30 m apart. That distance was assumed sufficient to ensure that the cone of light from traps would not overlap. All traps were placed 1-2 m from shore in water about 0.5 m deep.

Each batch of larvae released was paired with a specific light trap. The effect of fish release distance from the light trap was tested by alternating releases 3 and 10 m from the light traps each night. Release locations were perpendicular to and away from the levee, with the exception of the trap at location 12, where fish were released adjacent the levee and away from other traps because of heavy offshore vegetation (Figure 2.2).

A main study goal was to determine what proportion of fish released was detected by a nearby light trap, information not available in the literature for any species (Doherty 1987; Meekan et al. 2000). We used relatively high numbers of released fish (unmarked larvae) on the first night (Night 1, 14 May) because we wanted to increase the likelihood that some fish would be recaptured. We randomly designated half of the study area traps for either high (1,000 individuals, South) or low (250 individuals, North) density releases at either 3 or 10 m away from traps. Based on results from Night 1, we lowered releases for the second night (15 May). On this night we released 10 fish for each North trap and 50 fish for each South trap. All release batches on Night 3 (16 May) were an intermediate density of 100 fish per trap. We used both

chemical-light-stick-lit (CL) traps and LED-lit (LED) traps, which were used each night in a ratio of 2:1 because we did not have sufficient LED traps. The LED traps were evenly dispersed among the locations, so each treatment combination of distance and density or release time had two CL traps and one LED trap (Table 2.1; Figure 2.2). Each night chemical light sticks and LED's were activated less than an hour prior to sunset. On Nights 1 and 2, all larvae were released immediately after sunset, thought to be when light traps first become effective for sampling (Gehrke 1994; Vilizzi et al. 2008) to minimize larvae dispersal away from the traps. To understand if time to disperse from the release location affected the capture of larvae, half of the batches of fish on Night 3 were released about 3 h prior to sunset and the other half were released just after sunset, similar to releases on Nights 1 and 2 (Table 2.1). All trap samples were collected the morning following releases prior to sunrise. All samples, which included fishes other than Razorback Sucker, were preserved in ethanol and returned to the Larval Fish Laboratory, Colorado State University, for identification and otolith mark determination.

Larval Retention in Light Traps

To better understand if a light trap sample represents the surrounding density of larvae in backwater or wetland, it is crucial to determine the probability that once a fish enters a trap it remains. On 17 May (Night 4) we conducted a total of nine retention trials consisting of three replicates in three different environmental light scenarios (treatments) present at the completion of the light trap sample: overnight, sunrise, and daylight. We placed 25 single-marked larvae, acclimated to wetland conditions per previous nights, in the catch basin of the light trap, attached it to the trap, and placed it in the wetland. Single-marked larvae were used for retention tests because this batch had the lowest stocking abundance (360) compared to both unmarked and double-marked larvae (7,500 and 1,200 respectively), and thus, the lowest chance of resampling

fish released on Night 2. A single LED trap and two CL traps were used in each treatment. The three overnight replicates consisted of placing the larvae-filled trap just after sunset (trap locations 1-3), and pulling them just before sunrise, similar to previous experiments (approximately 8-h set times). The three sunrise replicates consisted of traps placed approximately 0.5 h prior to sunrise (trap locations 4-6) and pulling the traps 1 h after sunrise (1.5-h set times). The three sunlight treatments consisted of traps placed after sunrise (trap locations 7-9) and pulled after 1.5 h. The purpose of the sunrise and sunlight treatments was to determine if leaving traps in the water after exposure to ambient sunrise or direct sunlight conditions caused the attraction of larvae to the trap's light source to diminish, whereby fish would subsequently escape.

Tetracycline Mark Comparison Criteria

We collected a subset of unmarked larvae and larvae with 1 OTC mark from the hatchery and preserved them in ethanol on 14 May, prior to any larval releases in the wetland. Otoliths from a subset of those fish were extracted and observed with a UV light microscope at 200X and 400X magnification to determine mark presence, quality, and location. Samples of larvae which had 2 OTC marks were not preserved just prior to larval releases in the wetland, due to an oversight. However, a sample of larvae which had been marked twice by OTC was preserved immediately following the second mark. Due to the preservation schedule, only the first mark was visible, because the second mark did not have any subsequent otolith material deposited around it. However, the distance between the first mark and the edge of the otolith where the OTC would be deposited was measured. Thus, initial criteria for the appearance of 2 OTC-marked larvae captured in the wetland was partly determined by using measurements of otolith growth between the first OTC mark and the edge of the otolith of double OTC-marked larvae

made with a micrometer at 400X magnification. Further observation of the double-marked larvae from the hatchery indicated that the subsequent submersion in tetracycline caused an outward fading of OTC from the first mark, making the space between the marks glow as if it were weakly marked. This fading was not seen on otoliths from single-marked fish. The measured distance from the first mark to the second mark and the presence of the fading between the marks were characteristics used to discern 2 OTC-marked from 1 OTC-marked fish. Additional clarification of the appearance larvae with 2 OTC-marked otoliths was done by conducting an additional laboratory experiment marking a separate cohort of larval Razorback Sucker twice with OTC and comparing otoliths to ones collected in L-10.

Mark determination of captured larvae

All Razorback Sucker recaptured after release of marked larvae into the wetland were measured and at least two of four otoliths were removed and examined under a UV compound microscope at 400X magnification by two independent observers. Using the criteria detailed above, OTC mark presence, number, and quality (bright or faint) were determined for each otolith from each larva. Otolith mark presence, number, and quality were consistent between observers.

Environmental Conditions

Traps were set each night between 1955 and 2019 h. Turbidity at trap set ranged from 32 to 87 NTU and water temperature ranged from 21 to 24°C. Sunset ranged from 2027-2029 h and last light ranged from 2058-2100 h during the sampling period. Prior to trap retrieval the next morning turbidity ranged from 36 to 51 NTU and water temperature ranged from 15.5 to 18°C over the course of the study. All traps were retrieved between 0457 and 0545 after traps were set.

First light ranged from 0529-0531 h and sunrise ranged from 0600-0602 h for the duration of the study. On 16 May when half of the releases occurred 3 h prior to sunset, turbidity was 48 NTU and water temperature was 24°C upon release of the early-released batches of larvae. These were released between 1704-1714 h. On 16 May the LED lit trap at location 10 failed and was not emitting light so was omitted from subsequent analysis.

Various fishes, including Fathead Minnow *Pimephales promelas*, Red Shiner *Cyprinella lutrensis*, Common Carp *Cyprinus carpio*, Brook Stickleback *Culaea incontans*, and *Lepomis spp.,* were resident in L-10 during the study period due to prior-year connections to the main-stem Green River; adult Bonytail *Gila elegans* from Ouray National Fish Hatchery were also present (Dan Schaad, personal communication, U.S. Fish and Wildlife Service). During sampling invertebrates were observed in light traps including *Daphnia spp.* and Corixidae. Densities of *Daphnia spp.* in light trap samples were sometimes substantial, but observations determined that the traps were not full enough to hinder capture of larvae.

Results

A total of 9,060 larval Razorback Sucker were released into L-10 wetland from 14-16 May and 1,222 (14.35%) were recaptured by light traps (Table 2.2). On Night 1, 7,500 unmarked Razorback Sucker were released and 1,076 were recaptured. On Night 2, 360 single-OTC-marked Razorback Sucker larvae were released; of the 91 Razorback Suckers recaptured in light traps that night, 73 were from Night 1 releases (no OTC mark) and 18 (5.00%) were from the Night 2 releases (one OTC mark; Table 2.2).

On Night 3, 1,200 double-marked Razorback Sucker larvae were released, but only 55 larvae were recaptured in light traps. Twenty-nine were from Night 1 releases, 3 from Night 2,

and 23 from Night 3 (1.9%; Table 2.2); one trap accounted for approximately 60% of all Razorback Sucker recaptured (N = 33; 17 unmarked; 2 single OTC marked; 14 double OTC marked). Additionally, one LED trap had a short circuit, causing the light not to work, and a total of four traps caught no Razorback Sucker larvae. Based on large differences in capture proportions relative to nights 1 and 2, and other issues discussed later, we excluded Night 3 data from subsequent analyses.

To understand how release distance, release density, and light source affected capture rates of Razorback Sucker larvae by light traps, we compared the proportions of larvae recaptured in each trap. On Nights 1 and 2 the proportion of Razorback Sucker larvae recaptured ranged from 0 to 0.68 (Table C.1). Mean capture proportions in light traps paired with batches of larvae released at 3 and 10 m were similar (0.09 and 0.13, respectively; t-test: P = 0.54), suggesting that release distance did not affect recapture proportions, so data were pooled over distances.

We used ANCOVA to examine the pooled data of proportion of fish larvae recaptured in light traps as a function of release density, light source, and their interaction. The non-significant interaction effect of light source with density (P = 0.95; Table 2.4), and the subsequent reduced ANCOVA with only light type and density showed two important findings. First, release densities had no effect on recapture proportions of Razorback Sucker larvae in light traps (P = 0.42, Table 2.5, Figure 2.3), indicating that light traps will capture about equal proportions of the larvae present in these density ranges. Second, LED traps recaptured about 4X more larvae on average than CL traps over all densities (P = 0.01; Table 2.5; Figure 2.3).

Night 4 tests showed low retention of larvae, but also resulted in additional recaptures of fish that had been previously released. Of 25 fish placed in each trap, we recaptured an average

of one larva per trap in overnight treatments, four larvae per trap in sunrise treatments, and ten larvae in sunlight treatments. Of the overnight treatments, one trap also contained four unmarked larvae and another trap contained one double-marked larva. No unmarked or double-marked larvae were sampled in the sunrise treatments, and a single double-marked larva was sampled in one of the sunlight treatments (Table D.1). The low proportions of larvae retained differed substantially from laboratory work conducted previously (Chapter 1), and the low number of replications, and possible issues with fish health and environmental conditions led us to not consider these data further.

Discussion

Light traps set in L-10 wetland for 10 h were effective to capture Razorback Sucker larvae even when release densities varied from 10 to 1,000 larvae per trap. If one assumes that all larvae remained within 20 m of shore after releases, larvae may have occupied approximately 8,771 m^3 of water in the wetland. Even in that large volume, light traps were able to detect Razorback Sucker larvae at densities of 0.86 larvae/m^3 and 0.04 larvae/m^3 in sampling conducted on Nights 1 and 2, respectively. Furthermore, recapture proportions were invariant over the range of larvae densities released, and LED light traps were much more effective at capturing Razorback Sucker larvae than chemical glow stick traps.

Release density did not affect the proportion of larvae recaptured in light traps, in spite of releases that varied from 10 to 1,000 fish per trap (Figure 3). This finding has been corroborated in laboratory tests that found no effect of density on recapture probabilities when 25 or 50 fish were released into troughs (Chapter 1). This implies that even at very low or high densities, larvae would be captured in about the same proportions, which indicates light trap capture

proportions may be a useful index of abundance, a finding not previously tested or reported in the literature.

Another substantial finding was that light source had a large influence on recapture probabilities of Razorback Sucker larvae. The LED traps consistently recaptured a greater proportion of larvae than the CL traps over varying larval release densities (Table 2.3; Figure 2.3). Preliminary tests of our LED trap design suggested that light intensity is consistent over time and much greater than the chemical light sticks (Chapter 1). Because other variables such as light color type were accounted for in our sampling design, our results provided evidence that greater light intensities emitted from traps may be responsible for increased capture of larvae (Mueller et al. 1993; Snyder and Meismer 1999; Marchetti et al. 2004). A cause of concern with using LED traps is that they, like other gear types which require a power source, are prone to mechanical failure (Mueller et al. 1993; Snyder and Meismer 1999; Gyekis et al. 2006). For example, after exposure to windy and wet conditions on Night 1 and 2, one LED trap had a short circuit causing the trap to fail. Future work should include increasing the durability of LED traps to increase their effectiveness, should investigators wish to employ traps with this light type.

Our data indicate that the proportions of Razorback Sucker larvae recaptured in light traps did not vary with release distance from the light trap. These results provide supplemental information to previous laboratory tests run in troughs made to simulate backwater and side channel habitats (Chapter 1). Those experiments indicated that recapture probabilities of Razorback Sucker larvae did not vary at release distances up to 5 m, even when trap set times were short. In our field study, the larger floodplain environment and release distances up to 10 m apparently did not influence larval recapture by light traps. This provides additional evidence, supplemental to the lack of density effect observed on recapture proportion, that the abundance

of fish captured in light traps is correlated with larvae abundance. Additional field experiments with known numbers of released larvae should be conducted and specifically designed to increase our understanding of how light trap captures directly relate to surrounding backwater or wetland abundances of Razorback Sucker larvae. This knowledge will contribute to a more complete understanding of their reproductive success, timing, and spatial and temporal abundance estimates.

Capture of larvae released 10 m from traps caused us to examine the mechanisms of captures, given that the low light levels emitted may not even be detectable by larvae in turbid environments. In similar turbid conditions in laboratory studies (Chapter 1) we found that light from CL light traps does not travel further than 3 m. Thus, for a larva to be captured in a light trap, several key things have to occur. First, the larva had to swim in the direction of the light traps rather than away, a small likelihood given fish can swim any direction in a 360° circumference. The larva then has to navigate the release distance, in the sometimes windy, turbid, and predator-filled wetland. Finally, the larva had to come close enough to the trap to be attracted to the light, enter it, and then stay inside until the trap was pulled, an endpoint involving many probabilities subsequent to release. Despite these myriad factors which seemingly disadvantage larvae from being captured, light traps were able to capture larvae under a variety of environmental conditions. While we now know more about the factors that affect capture probabilities of larvae once they are in the cone of influence of a light trap (Chapter 1), to enhance efficient use of light traps to sample fish, additional studies aimed at understanding mechanisms of fish capture are needed. Minimally, these include light trap location in relation to the main-stem river, proximity to shore, and the surrounding three-dimensional water velocity profile.

Captures of larvae subsequent to Night 3 releases were very low relative to those for previous nights, which caused us to discard those data. Inconsistencies in recapture proportions may be due to a several reasons. First, because we wanted to test effects of an earlier release time, larvae used that night were held in bags for a longer time than those previously used, which may have stressed fish. Although all fish were alive prior to release, the day prior to Night 3 releases was the warmest recorded (air temperatures up to 28°C), and high water and air temperatures and perhaps reduced oxygen levels in bags may have induced mortality after release. Larvae released on Night 3 were also marked twice, another potential source of stress that may have weakened larvae and increased mortality after release. Unobserved differences in environmental conditions on Night 3 could also be responsible.

Retention rates of larvae in light traps in these field experiments were exceptionally low and inconsistent with previous laboratory experiments (Chapter 1). In our overnight tests only 0-2 fish (≤ 8%) of the 25 fish remained in the trap, while our laboratory tests regularly retained >77% of fish. This seems unrealistic given our field tests trapped over 200 larvae and in annual Green River light trap field sampling traps have captured 300 Razorback Sucker larvae or more in one night (Tildon Jones, personal communication, U.S. Fish and Wildlife Service). Video evidence from laboratory tests, recorded using a GoPro camera placed in the catch basin of a light trap, also revealed that placing a larvae-filled light trap in the water causes some fish to escape. Perhaps this action, along with the lack of containment of larvae near the trap that the laboratory containers provided, caused the escape and dispersal of larvae from the light traps in our field experiments. Additional experimental designs should be tested to better evaluate the retention of larvae in light traps, crucial information for understanding effectiveness of light trap sampling.

One factor we cannot evaluate is the degree of independence associated with a release of larvae and its adjacent trap. Clearly, larvae can swim any direction they choose after release, which during our overnight trials, may result in fish from different release batches mixing or moving such that larvae are exposed to one or more traps. Wind may also influence capture patterns, as we noted a pattern of increasing numbers of larvae recaptured from a North to South on Night 1; no directional patterns were noted on Night 2 but sample sizes were lower. Regardless of swimming patterns or potential mixing, we consider our analysis approach of trap and release independence to be valid because we grouped larvae in either high or low density releases on one or the other side of the levee-bounded sampling area. Thus, traps were capable of essentially sampling only low or high densities of fish, even though mixing or movement may cause more variation in the proportions recaptured due to varying availability of larvae to a particular trap. Additionally, we do not believe that fish movement and mixing was a factor influencing the higher numbers of larvae recaptured in LED traps because those light types were evenly interspersed among the release area and traps with each light source should have equal exposure to larvae. Thus, higher LED trap recapture proportions demonstrate a preference by larvae for that light source over chemical light sticks; additional tests may be needed to validate these findings more fully.

Our experiments in the large, variable, and open L-10 system demonstrated that light traps are a viable technique to capture Razorback Sucker larvae even at low densities, confirming our laboratory studies (Chapter 1). Further, consistent recapture probabilities over a wide range of release densities indicated light trap captures may be a useful index of larvae abundance for at least this life stage. This is important because the life stage we used in our field experiments is the one most commonly captured in annual field sampling for Razorback Sucker larvae (Bestgen

et al. 2011). We also found that LED traps in field applications sampled about 4X the number of Razorback Sucker larvae compared to CL traps over a range of release densities. The LED traps may be an especially effective tool for first detection of larvae, especially when larvae are in low abundance in backwaters of the Green River early in the reproductive season. LED traps may also be a useful capture technique to trigger conservation flows from Flaming Gorge Reservoir in spring.

Differences in capture probabilities should be considered if LED traps replace chemical light stick traps in monitoring efforts, due to potential capture probability differences that may reflect gear type rather than changes in annual or inter-annual abundances. This is important because all historical seasonal monitoring data based on captures per trap were collected only with traditional CL traps. Both laboratory and field experiments indicated light traps, regardless of light source, are a useful gear to monitor distribution and abundance of larvae and will expand the ecological understanding of early life stages of Razorback Sucker needed for conservation of the species in the Colorado River basin.

TABLE 2.1. Experimental design to assess recapture probabilities of Razorback Sucker larvae released into Leota-10 wetland, Ouray National Wildlife Refuge, Utah. Density refers to the number of fish counted or approximated in a single batch, matched with a light trap, and released into the wetland. The CL refers to traps with a chemical-light-stick light source, while LED (Light-Emitting Diode) refers to traps with an LED light source. Of the 12 traps set each night, eight were CL traps and four were LED traps. Thus, there was one LED trap and two CL traps in every night, density, and release distance treatment combination. On Night 3, fish in the afternoon were released about 3 h prior to sunset.

Release Night	Density		Distance		Light source		Release Time	
Night 1	250	1000	3	10	CL	LED	Sunset	
Night 2	10	50	3	10	CL	LED	Sunset	
Night 3	100		3	10	CL	LED	Afternoon	Sunset

TABLE 2.2. Number of Razorback Sucker larvae released and recaptured throughout the first three nights of the study period in Leota-10 wetland, Ouray National Wildlife Refuge, Utah. Recapture is the percent of larvae captured by light traps that had been released the previous night. For example, on Night 2, 360 single-marked larvae were released and 18 were recaptured (5%).

	Number Released			Number Recaptured/Retained			
Release Night	Unmarked	Single-mark	Double-mark	Unmarked	Single-mark	Double-mark	Recapture (%)
Night 1	7,500			1,076			14.4
Night 2		360		73	18		5.0
Night 3			1,200	29	3	23	1.9

TABLE 2.3. Mean proportion of Razorback Sucker larvae recaptured in light traps for each light source as a function of density of larvae (Number of Larvae per Batch). CL refers to traps with a chemical-light-stick light source, and LED (Light-Emitting Diode) refers to traps with a LED light source. Fish from 3 and 10-m release distances were pooled because there was no significant difference in recapture proportions.

Larvae per Batch	LED	CL
1,000	0.21	0.01
	(0.16-0.27)	(0.08-0.11)
250	0.40	0.07
	(0.12-0.68)	(0.01-0.13)
50	0.10	0.01
	(0.00-0.20)	(0.00-0.02)
10	0.15	0.08
	(0.01-0.20)	(0.00-0.20)

TABLE 2.4. Results of a Type III ANCOVA test for equality of slopes for the relationships of fish recapture proportion as a function of fish density with two different light sources; the assumption of slope similarity is evidenced by the non-significant interaction term.

Variable	*df*	*SS*	*MSS*	*F*	*P*
Density	1	0.01	0.01	0.60	0.45
Light Source	1	0.07	0.07	4.29	0.05
Density X Light Source	1	0.000082	0.000082	0.01	0.95

TABLE 2.5. Results of a Type III ANOCOVA examining the difference in the proportion of Razorback Sucker larvae recaptured in light traps with chemical-light-stick and LED light sources as a function of density. The LED recapture probability estimate is the intercept. The non-significant *Density* coefficient can be used to estimate the change in the proportion of fish recaptured as density increases (N = 10 to 1,000) using traps with each light type.

Variable	*Estimate*	*SE*	*t*	*P*
Intercept	0.199	0.05	4.00	0.0006
Density	0.000053	0.000065	0.82	0.42
Chemical Light Stick	-0.154	0.05	-2.80	0.01

FIGURE 2.1. A satellite image of Ouray National Wildlife refuge, which lies along the Green River near Randlet, UT. The red line outlines Leota 10 (L-10) wetland, the location of field experiments. All light traps were placed along the East levee. Nearby Ouray National Fish Hatchery provided Razorback Sucker larvae for the study.

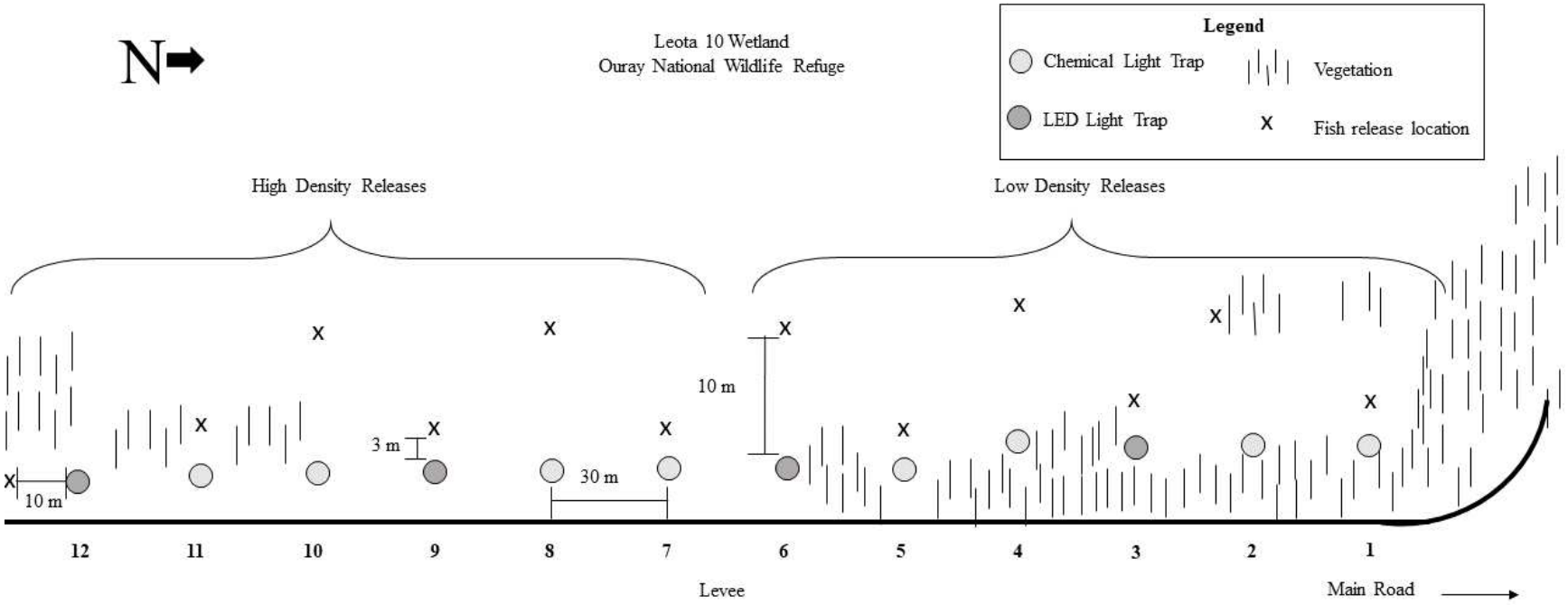

FIGURE 2.2. Diagram showing the experimental design of releases of Razorback Sucker larvae into Leota 10 (L-10) wetland. The higher and lower density batches of larvae on Nights 1 and 2 were released on the same side of the wetland. On Night 3, early release batches were released on the low density side of the wetland, and batches released just prior to sunset were released on the high density side. Release distances of either 3 or 10 m alternated at each trap location each night. Trap locations were the same throughout the study and were placed at least 30 m apart. The specific trap location of each LED trap was alternated each night. LED refers to Light-Emitting Diode. Figure not to scale.

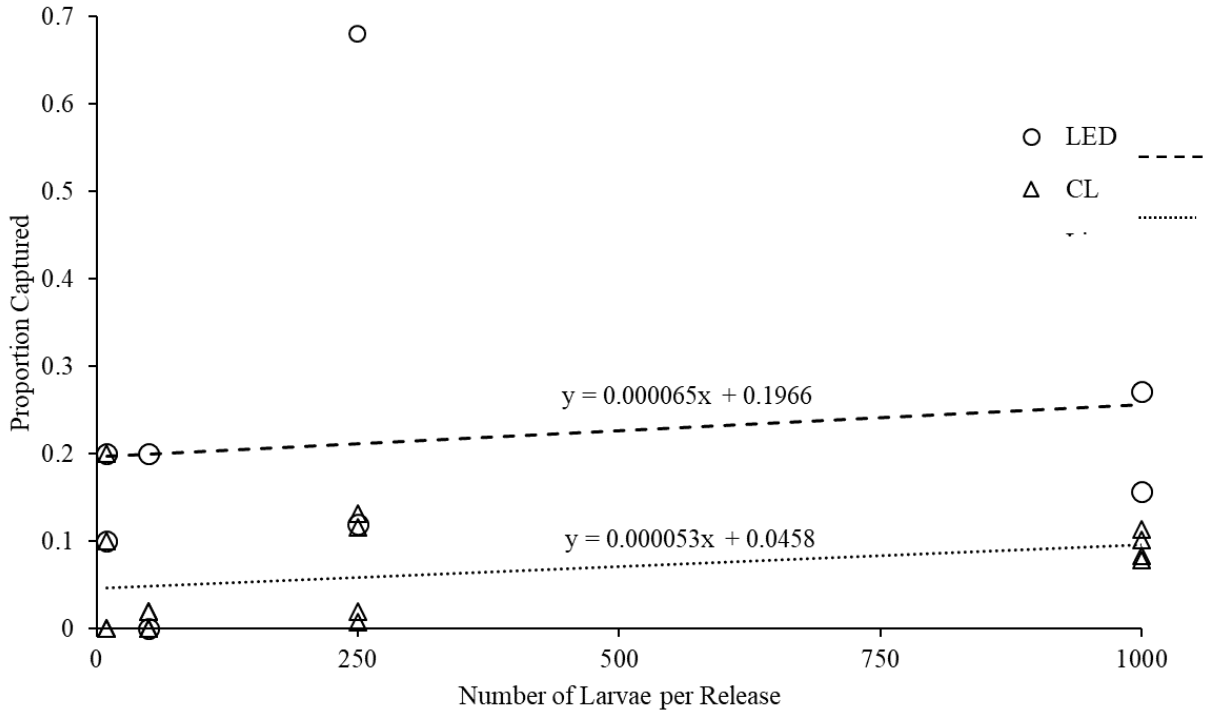

FIGURE 2.3. Relationships of the proportion of larvae recaptured in each light trap light source as a function of release density of Razorback Sucker larvae (Number of Larvae per Release). CL refers to traps with a chemical-light-stick light source, and LED (Light-Emitting Diode) refers to traps with a LED light source.

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APPENDIX A

TABLE A.1. Logit response, capture probability, and other statistics from logistic regression models examining effects of distance, set time, and their interaction on capture probabilities for five life stages of Razorback Sucker. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Distance (m)	Set Time (h)	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Early Protolarvae	1	0.5	-2.56	0.35	0.07	0.04	0.13
	3	0.5	-4.80	1.00	0.00	0.00	1.00
	5	0.5	-4.80	1.00	0.00	0.00	1.00
	1	1	-1.94	0.27	0.13	0.08	0.20
	3	1	-1.72	0.25	0.15	0.10	0.23
	5	1	-2.70	0.37	0.06	0.03	0.12
	1	2	-0.95	0.18	0.28	0.21	0.36
	3	2	-0.58	0.18	0.36	0.28	0.45
	5	2	0.22	0.18	0.55	0.47	0.64
	1	4	0.03	0.18	0.51	0.42	0.59
	3	4	0.38	0.18	0.59	0.51	0.67
	5	4	0.13	0.18	0.53	0.44	0.62
Late Protolarvae	1	0.5	-1.13	0.21	0.24	0.18	0.33
	3	0.5	-0.72	0.19	0.33	0.25	0.41

	5	0.5	-1.86	0.26	0.13	0.09	0.21
	1	1	0.62	0.19	0.65	0.56	0.73
	3	1	1.28	0.22	0.78	0.70	0.85
	5	1	0.93	0.20	0.72	0.63	0.79
	1	2	1.15	0.22	0.76	0.67	0.83
	3	2	1.12	0.21	0.75	0.67	0.82
	5	2	1.44	0.23	0.81	0.73	0.87
	1	4	1.62	0.24	0.83	0.76	0.89
	3	4	2.14	0.29	0.89	0.83	0.94
	5	4	2.99	0.42	0.95	0.90	0.98
Mesolarvae	1	0.5	-0.47	0.18	0.38	0.30	0.47
	3	0.5	-0.91	0.20	0.29	0.21	0.37
	5	0.5	-0.70	0.18	0.33	0.26	0.42
	1	1	-0.19	0.18	0.45	0.37	0.54
	3	1	-0.33	0.18	0.42	0.33	0.51
	5	1	0.02	0.18	0.50	0.42	0.59
	1	2	1.83	0.25	0.86	0.79	0.91
	3	2	1.74	0.20	0.85	0.79	0.89
	5	2	1.37	0.22	0.80	0.72	0.86
	1	4	2.11	0.29	0.89	0.82	0.94
	3	4	2.44	0.33	0.92	0.86	0.96
	5	4	1.99	0.28	0.88	0.81	0.93
Metalarvae	1	0.5	-0.49	0.19	0.38	0.30	0.47

	3	0.5	-1.37	0.22	0.20	0.14	0.28
	5	0.5	-3.41	0.51	0.03	0.01	0.08
	1	1	-0.53	0.18	0.37	0.29	0.46
	3	1	-1.46	0.23	0.19	0.13	0.27
	5	1	-1.56	0.23	0.17	0.12	0.25
	1	2	0.56	0.19	0.64	0.55	0.72
	3	2	-0.26	0.18	0.44	0.35	0.52
	5	2	-1.26	0.22	0.22	0.16	0.30
	1	4	1.32	0.22	0.79	0.71	0.85
	3	4	2.33	0.32	0.91	0.85	0.95
	5	4	1.18	0.21	0.77	0.68	0.83
Juvenile	1	0.5	-1.05	0.21	0.26	0.19	0.34
	3	0.5	-2.72	0.37	0.06	0.03	0.12
	5	0.5	-3.38	0.51	0.03	0.01	0.08
	1	1	-1.58	0.24	0.17	0.11	0.25
	3	1	-1.53	0.23	0.18	0.12	0.25
	5	1	-2.70	0.37	0.06	0.03	0.12
	1	2	-0.90	0.20	0.29	0.22	0.38
	3	2	-1.45	0.22	0.19	0.13	0.27
	5	2	-1.14	0.21	0.24	0.18	0.32
	1	4	0.02	0.18	0.50	0.42	0.59
	3	4	-0.36	0.18	0.41	0.33	0.50
	5	4	-0.06	0.18	0.48	0.40	0.57

TABLE A.2. Logit response, capture probability, and other statistics from logistic regression models examining the effects of set time on capture probabilities for each life stage of Razorback Sucker. All trials were conducted with 3-m distances. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Set Time (h)	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Early Protolarvae	0.5	-4.80	1.00	0.01	0.00	0.06
	1	-1.72	0.25	0.15	0.10	0.23
	2	-0.58	0.18	0.36	0.28	0.45
	4	0.38	0.18	0.59	0.51	0.67
	8	0.50	0.19	0.62	0.53	0.70
Late Protolarvae	0.5	-0.72	0.19	0.33	0.25	0.41
	1	1.28	0.22	0.78	0.70	0.85
	2	1.12	0.21	0.75	0.67	0.82
	4	2.14	0.29	0.89	0.83	0.94
	8	1.80	0.25	0.86	0.79	0.91
Mesolarvae	0.5	-0.91	0.20	0.29	0.21	0.37
	1	-0.33	0.18	0.42	0.33	0.51
	2	1.74	0.20	0.85	0.79	0.89
	4	2.44	0.33	0.92	0.86	0.96
	8	4.82	1.00	0.99	0.95	1.00
Metalarvae	0.5	-1.37	0.22	0.20	0.14	0.28
	1	-1.46	0.23	0.19	0.13	0.27
	2	-0.26	0.18	0.44	0.35	0.52

	4	2.33	0.32	0.91	0.85	0.95
	8	2.70	0.37	0.94	0.88	0.97
Juvenile	0.5	-2.72	0.37	0.06	0.03	0.12
	1	-1.53	0.23	0.18	0.12	0.25
	2	-1.45	0.22	0.19	0.13	0.27
	4	-0.36	0.18	0.41	0.33	0.50
	8	1.57	0.24	0.83	0.75	0.89

TABLE A.3. Logit response, capture probability, and other statistics from logistic regression models examining the effects of distance, turbidity, and their interaction on capture probabilities for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Turbidity	Distance (m)	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Early Protolarvae	Clear	1	-0.95	0.18	0.28	0.21	0.36
	Turbid	1	1.30	0.22	0.79	0.71	0.85
	Clear	5	0.22	0.18	0.55	0.47	0.64
	Turbid	5	-1.01	0.20	0.27	0.20	0.35
Mesolarvae	Clear	1	1.83	0.25	0.86	0.79	0.91
	Turbid	1	0.99	0.20	0.73	0.64	0.80
	Clear	5	1.37	0.22	0.80	0.72	0.86
	Turbid	5	1.06	0.20	0.74	0.66	0.81
Metalarvae	Clear	1	0.56	0.19	0.64	0.55	0.72
	Turbid	1	0.47	0.18	0.62	0.53	0.70
	Clear	5	-1.26	0.22	0.22	0.16	0.30
	Turbid	5	0.03	0.18	0.51	0.42	0.59
Juvenile	Clear	1	-0.90	0.20	0.29	0.22	0.38
	Turbid	1	-0.18	0.18	0.46	0.37	0.54
	Clear	5	-1.14	0.21	0.24	0.18	0.32
	Turbid	5	-0.55	0.19	0.37	0.29	0.45

TABLE A.4. Logit response, capture probability, and other statistics from logistic regression models examining the effects of light source presence and absence on capture probabilities for each life stage of Razorback Sucker tested. All trials were conducted at 1-m distances. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Light Source	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Early Protolarvae	Absent	-3.13	0.46	0.04	0.02	0.10
	Present	-0.95	0.18	0.28	0.21	0.36
Late Protolarvae	Absent	-3.00	0.42	0.05	0.02	0.10
	Present	1.15	0.22	0.76	0.67	0.83
Mesolarvae	Absent	-4.84	1.00	0.01	0.00	0.05
	Present	1.83	0.25	0.86	0.79	0.91
Metalarvae	Absent	-2.67	0.37	0.06	0.03	0.12
	Present	0.56	0.19	0.64	0.55	0.72
Juvenile	Absent	-1.26	0.21	0.22	0.16	0.30
	Present	-0.90	0.20	0.29	0.22	0.38

TABLE A.5. Logit response, capture probability, and other statistics from logistic regression models examining the effects of light source presence, turbidity, and their interaction on retention probabilities for each life stage of Razorback Sucker tested.

Life Stage	Light Source	Turbidity	Logit Response	SE	Retention Probability	95% LCL	95% UCL
Early Protolarvae	Absent	Clear	-0.43	0.18	0.39	0.31	0.48
	Present	Clear	1.59	0.17	0.83	0.78	0.87
	Absent	Turbid	-2.94	0.42	0.05	0.02	0.11
	Present	Turbid	2.72	0.27	0.94	0.90	0.96
Late Protolarvae	Absent	Clear	-0.82	0.20	0.31	0.23	0.39
	Present	Clear	3.07	0.31	0.96	0.92	0.98
Mesolarvae	Absent	Clear	-2.15	0.29	0.10	0.06	0.17
	Present	Clear	1.64	0.13	0.84	0.80	0.87
	Absent	Turbid	-2.56	0.35	0.07	0.04	0.13
	Present	Turbid	1.21	0.13	0.77	0.72	0.81
Metalarvae	Absent	Clear	-0.41	0.18	0.40	0.32	0.49
	Present	Clear	2.33	0.22	0.91	0.87	0.94
	Absent	Turbid	-0.73	0.19	0.33	0.25	0.41
	Present	Turbid	2.81	0.28	0.94	0.91	0.97
Juvenile	Absent	Clear	-0.24	0.18	0.44	0.36	0.53
	Present	Clear	2.76	0.27	0.94	0.90	0.96
	Absent	Turbid	-0.24	0.18	0.44	0.36	0.53
	Present	Turbid	3.71	0.41	0.98	0.95	0.99

TABLE A.6. Logit response, capture probability, and other statistics from logistic regression models examining the effects of distance, larval density, and their interaction on capture probabilities for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Density	Distance (m)	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Mesolarvae	High	1	2.29	0.22	0.91	0.87	0.94
	Low	1	1.83	0.25	0.86	0.79	0.91
	High	5	2.45	0.23	0.92	0.88	0.95
	Low	5	1.37	0.22	0.80	0.72	0.86
Metalarvae	High	1	-0.36	0.13	0.41	0.35	0.47
	Low	1	0.56	0.19	0.64	0.55	0.72
	High	5	-0.74	0.14	0.32	0.27	0.38
	Low	5	-1.26	0.22	0.22	0.16	0.30
Juvenile	High	1	-0.73	0.14	0.33	0.27	0.39
	Low	1	-0.90	0.20	0.29	0.22	0.38
	High	5	-1.90	0.19	0.13	0.09	0.18
	Low	5	-1.14	0.21	0.24	0.18	0.32

TABLE A.7. Logit response, capture probability, and other statistics from logistic regression models examining the effects of cover (vegetation and simulated rock) presence and location on capture probabilities for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Cover Presence and Location	Logit Response	SE	Capture Probability	95% LCL	95% UCL
		Vegetation				
Mesolarvae	None	1.74	0.20	0.85	0.79	0.89
	Veg Behind	0.96	0.18	0.72	0.65	0.79
	Vegetation in Front	0.54	0.17	0.63	0.55	0.70
Metalarvae	None	-0.26	0.18	0.44	0.35	0.52
	Vegetation Behind	-0.63	0.19	0.35	0.27	0.43
	Vegetation in Front	-1.92	0.26	0.13	0.08	0.20
Juvenile	None	-1.45	0.22	0.19	0.13	0.27
	Vegetation Behind	-1.00	0.20	0.27	0.20	0.35
	Vegetation in Front	-1.19	0.21	0.23	0.17	0.32
		Rock				
Mesolarvae	None	1.74	0.20	0.85	0.79	0.89
	Rock Behind	1.70	0.25	0.85	0.77	0.90
	Rock in Front	0.14	0.16	0.53	0.45	0.61
Metalarvae	None	-0.26	0.18	0.44	0.35	0.52
	Rock Behind	-0.32	0.18	0.42	0.34	0.51
	Rock in Front	-1.26	0.21	0.22	0.16	0.30
Juvenile	None	-0.26	0.18	0.19	0.13	0.27

Rock Behind	-0.32	0.18	0.36	0.28	0.45
Rock in Front	-1.26	0.21	0.24	0.17	0.32

TABLE A.8. Logit response, capture probability, and other statistics from logistic regression models examining the effects of environmental light condition, water condition, and their interaction on retention probabilities for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Environmental Light Condition	Turbidity	Logit Response	SE	Retention Probability	95% LCL	95% UCL
Early Protolarvae	Night	Clear	2.08	0.28	0.89	0.82	0.93
	Sunrise	Clear	1.22	0.21	0.77	0.69	0.84
	Night	Turbid	4.77	1.00	0.99	0.94	1.00
	Sunrise	Turbid	2.06	0.28	0.89	0.82	0.93
Late Protolarvae	Night	Clear	3.40	0.51	0.97	0.92	0.99
	Sunrise	Clear	2.81	0.39	0.94	0.89	0.97
Mesolarvae	Night	Clear	2.20	0.21	0.90	0.86	0.93
	Sunrise	Clear	1.16	0.17	0.76	0.70	0.82
	Night	Turbid	2.05	0.28	0.89	0.82	0.93
	Sunrise	Turbid	0.84	0.15	0.70	0.63	0.76
Metalarvae	Night	Clear	2.68	0.37	0.94	0.88	0.97
	Sunrise	Clear	2.06	0.28	0.89	0.82	0.93
	Night	Turbid	3.16	0.46	0.96	0.91	0.98
	Sunrise	Turbid	2.55	0.35	0.93	0.87	0.96
Juvenile	Night	Clear	2.56	0.35	0.93	0.87	0.96
	Sunrise	Clear	3.00	0.42	0.95	0.90	0.98

Night	Turbid	3.42	0.51	0.97	0.92	0.99
Sunrise	Turbid	4.12	0.71	0.98	0.94	1.00

TABLE A.9. Logit response, capture probability, and other statistics from logistic regression models examining the effects of light trap aperture width on capture probabilities for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Trap Aperture Width (mm)	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Mesolarvae	4	1.74	0.20	0.85	0.79	0.89
	6	1.44	0.23	0.81	0.73	0.87
Metalarvae	4	-0.85	0.31	0.30	0.19	0.44
	6	-0.57	0.30	0.36	0.24	0.51

TABLE A.10. Logit response, capture probability, and other statistics from logistic regression models examining the effects of trap aperture width, environmental light condition, and their interaction on retention probabilities for each life stage of Razorback Sucker tested. Mesolarvae was only tested in new moon night environmental light conditions. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Environmental Light Condition	Trap Aperture Width (mm)	Logit Response	SE	Retention Probability	95% LCL	95% UCL
Mesolarvae						
Night	4	2.20	0.21	0.90	0.86	0.93
Night	6	2.79	0.34	0.94	0.89	0.97
Juvenile						
Control	4	-0.24	0.18	0.44	0.36	0.53
Night	4	2.56	0.35	0.93	0.87	0.96
Sunrise	4	3.00	0.42	0.95	0.90	0.98
Control	6	-1.01	0.20	0.27	0.20	0.35
Night	6	3.19	0.46	0.96	0.91	0.98
Sunrise	6	3.74	0.58	0.98	0.93	0.99

TABLE A.11. Logit response, capture probability, and other statistics from logistic regression models examining the effects of light trap light source on capture probabilities for each life stage of Razorback Sucker and Fathead Minnow tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Light source	Logit Response	SE	Capture Probability	95% LCL	95% UCL
		Razorback Sucker				
Mesolarvae	Chemical light stick	1.44	0.14	0.81	0.76	0.85
	LED	1.53	0.24	0.82	0.75	0.88
	Old chemical light stick	0.16	0.18	0.54	0.45	0.63
		Fathead Minnow				
Protolarvae	Chemical light stick	-1.56	0.22	0.17	0.12	0.24
	LED	-0.59	0.16	0.36	0.29	0.43
Mesolarvae	Chemical light stick	0.02	0.14	0.51	0.44	0.57
	LED	0.09	0.15	0.52	0.45	0.59
Metalarvae	Chemical light stick	0.07	0.18	0.52	0.43	0.61
	LED	-0.34	0.21	0.42	0.32	0.52
Juvenile	Chemical light stick	0.15	0.18	0.54	0.45	0.63
	LED	1.22	0.25	0.77	0.68	0.85

TABLE A.12. Logit response, capture probability, and other statistics from logistic regression models examining the effects of light trap light source on retention probabilities for each life stage of Razorback Sucker and Fathead Minnow tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Light source	Logit Response	SE	Retention Probability	95% LCL	95% UCL
		Razorback Sucker				
Mesolarvae	Chemical light stick	2.20	0.21	0.90	0.86	0.93
	LED	3.04	0.42	0.95	0.90	0.98
		Fathead Minnow				
Protolarvae	Chemical light stick	2.21	0.35	0.90	0.82	0.95
	LED	2.27	0.35	0.91	0.83	0.95
Mesolarvae	Chemical light stick	2.72	0.42	0.94	0.87	0.97
	LED	2.40	0.37	0.92	0.84	0.96
Metalarvae	Chemical light stick	1.32	0.26	0.79	0.69	0.86
	LED	2.23	0.35	0.90	0.82	0.95
Juvenile	Chemical light stick	1.40	0.26	0.80	0.71	0.87
	LED	2.15	0.33	0.90	0.82	0.94

TABLE A.13. Logit response, capture probability, and other statistics from logistic regression models examining the effects environmental light condition tested in a 50 L bucket on retention probabilities for each life stage of Razorback Sucker and Fathead Minnow tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Environmental Light Condition	Logit Response	SE	Capture Probability	95% LCL	95% UCL
		Razorback Sucker				
Mesolarvae	Night	2.53	0.35	0.93	0.86	0.96
	Sunrise	4.81	1.00	0.99	0.95	1.00
	Sunlight	1.78	0.25	0.86	0.78	0.91
		Fathead Minnow				
Protolarvae	Night	2.35	0.32	0.91	0.85	0.95
	Sunrise	2.99	0.42	0.95	0.90	0.98
	Sunlight	1.07	0.20	0.74	0.66	0.81
Mesolarvae	Night	2.56	0.35	0.93	0.87	0.96
	Sunrise	3.18	0.46	0.96	0.91	0.98
	Sunlight	1.85	0.26	0.86	0.79	0.91
Metalarvae	Night	1.91	0.27	0.87	0.80	0.92
	Sunrise	2.82	0.39	0.94	0.89	0.97
	Sunlight	4.82	1.00	0.99	0.94	0.99
Juvenile	Night	2.98	0.41	0.95	0.89	0.97
	Sunrise	4.82	1.00	0.99	0.94	0.99
	Sunlight	4.82	1.00	0.99	0.94	0.99

TABLE A.14. Logit response, capture probability, and other statistics from logistic regression models examining the effects of treatment container location on retention probabilities for each life stage of Razorback Sucker and Fathead Minnow tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Life Stage	Container	Logit Response	SE	Capture Probability	95% LCL	95% UCL
		Razorback Sucker				
Mesolarvae	50 L Bucket	2.53	0.35	0.93	0.86	0.96
	Trough	2.71	0.37	0.94	0.88	0.97
		Fathead Minnow				
Protolarvae	50 L Bucket	2.35	0.32	0.91	0.85	0.95
	Trough	2.54	0.35	0.93	0.87	0.96
Mesolarvae	50 L Bucket	2.56	0.35	0.93	0.87	0.96
	Trough	3.01	0.42	0.95	0.90	0.98
Metalarvae	50 L Bucket	1.91	0.27	0.87	0.80	0.92
	Trough	1.69	0.25	0.84	0.77	0.90
Juvenile	50 L Bucket	2.99	0.42	0.95	0.90	0.98
	Trough	1.72	0.25	0.85	0.78	0.90

TABLE A.15. Logit response, capture probability, and other statistics from logistic regression models examining the effects of treatment container location on retention probabilities tested overnight for each life stage of Razorback Sucker tested. SE refers to standard error. LCL refers to lower confidence limit. UCL refers to upper confidence limit.

Container	Logit Response	SE	Capture Probability	95% LCL	95% UCL
Tank	2.20	0.27	0.90	0.84	0.94
Trough	3.60	0.51	0.97	0.93	0.99

APPENDIX B

TABLE B.1. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of turbidity, distance, and their interaction on the capture probabilities of each life stage of Razorback Sucker in light traps. The "X" indicates an interaction between variables. X^2 refers to the likelihood chi-square statistic.

Life Stage	Variable	X^2	*df*	*P*
Early Protolarvae	Distance	21.78	1	<0.01
	Turbidity	73.32	1	<0.01
	Distance X Turbidity	87.17	1	<0.01
Mesolarvae	Distance	1.91	1	0.17
	Turbidity	6.86	1	0.01
	Distance X Turbidity	1.43	1	0.23
Metalarvae	Distance	44.89	1	<0.01
	Turbidity	0.12	1	0.73
	Distance X Turbidity	13.11	1	<0.01
Juvenile	Distance	0.71	1	0.40
	Turbidity	7.36	1	<0.01
	Distance X Turbidity	0.12	1	0.73

TABLE B.2. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of density, distance, and their interaction on the capture probabilities of each life stage of Razorback Sucker in light traps.

Life Stage	Variable	X^2	*df*	*P*
Mesolarvae	Density	1.89	1	0.17
	Distance	0.24	1	0.62
	Density X Distance	1.79	1	0.18
Metalarvae	Density	17.17	1	<0.01
	Distance	4.09	1	0.04
	Density X Distance	18.59	1	<0.01
Juvenile	Density	0.50	1	0.48
	Distance	27.26	1	<0.01
	Density X Distance	6.26	1	0.01

TABLE B.3. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of environmental light condition on the retention probabilities of each life stage of Fathead Minnow.

Life Stage	Variable	X^2	*df*	*P*
Protolarvae	Environmental Light Condition	26.01	2	<0.01
Mesolarvae	Environmental Light Condition	7.84	2	0.02
Metalarvae	Environmental Light Condition	17.27	2	<0.01
Juvenile	Environmental Light Condition	5.94	2	0.05

TABLE B.4. Logistic regression analysis (Type-III likelihood ratio tests) estimating effects of treatment container type on the retention probabilities of each life stage of Fathead Minnow.

Life Stage	Variable	X^2	*df*	*P*
Protolarvae	Container	0.17	1	0.68
Mesolarvae	Container	0.72	1	0.40
Metalarvae	Container	0.36	1	0.55
Juvenile	Container	7.74	1	0.01

APPENDIX C

TABLE C.1. Proportion of Razorback Sucker larvae captured in each light trap. CL refers to light traps with a chemical-light-stick light source and LED (Light-Emitting Diode) refers to traps with an LED light source. Proportion captured is based on the number of fish released per batch paired with the light trap the night of its release. Previous larval marking using oxytetracycline hydrochloride allowed for differentiation of larvae released each night.

Night	Number of Larvae Released	Release Distance (m)	Light source	Proportion Captured
1	250	3	CL	0.02
		10	CL	0.01
		3	LED	0.12
		10	CL	0.13
		3	CL	0.12
		10	LED	0.68
	1000	3	CL	0.08
		10	CL	0.10
		3	LED	0.27
		10	CL	0.08
		3	CL	0.11
		10	LED	0.16
2	10	10	CL	0.00
		3	LED	0.10
		10	CL	0.00
		3	CL	0.10

	10	LED	0.20
	3	CL	0.20
50	10	CL	0.00
	3	LED	0.00
	10	CL	0.02
	3	CL	0.02
	10	LED	0.20
	3	CL	0.00

APPENDIX D

TABLE D.1. Number of larvae, mark presence, and proportion retained in each light trap as per the retention treatments. Proportion retained is the number of single-marked larvae present at the end of the treatment out of 25. Overnight sampling duration was approximately 10 h. Traps in the sunrise treatment were placed 0.5 h prior to sunrise and pulled 1 h after sunrise (1.5-h set). Traps in the sunlight treatment were set for 1.5 h after sunrise. Light traps had chemical-light-stick (CL) and light-emitting diode (LED) light sources.

Trap Location	Light Source	Treatment	*N*: Total	Unmarked	Single-marked	Double-marked	Proportion Retained
1	CL	Overnight	3	0	2	1	0.08
2	CL	Overnight	5*	4	0	0	0
3	LED	Overnight	1	0	1	0	0.04
4	CL	Sunrise	4	0	4	0	0.16
5	CL	Sunrise	4	0	4	0	0.16
6	LED	Sunrise	5	0	5	0	0.2
7	CL	Sunlight	9	0	8	1	0.32
8	CL	Sunlight	12	0	12	0	0.48
9	LED	Sunlight	12	0	12	0	0.48

*One larva sampled had an indistinguishable mark.