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Identifying Optimal Stocking Strategies to Support Recovery of an Endemic Lake Sucker

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IDENTIFYING OPTIMAL STOCKING STRATEGIES TO SUPPORT RECOVERY

OF AN ENDEMIC LAKE SUCKER

by

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ABSTRACT

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Utah State University, 2022

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Anthropogenic alterations to freshwater ecosystems have been associated with decreased biodiversity and extinction of native species, and endemic fishes are particularly vulnerable to extinction due to their limited native range. Native species recovery programs have employed a suite of methods to reduce extinction risk, but perhaps the most prominent is artificial propagation (i.e., stocking) to increase the abundance of spawning adults, as natural recruitment is often limited for imperiled populations. Thus, identifying stocking strategies that most effectively augment adult abundance is a critical aspect of successful adaptive management. The threatened June sucker (*Chasmistes liorus*), endemic to Utah Lake, Utah, USA, is emblematic of many endemic fish species in degraded ecosystems. Over 800,000 June suckers have been stocked from various hatcheries, grow-out-ponds, and refuge populations since artificial propagation began in the mid-1990s. In addition to source variability, fish have been stocked at differing sizes and seasons, raising questions of efficacy among stocking methods. Here, I evaluated post-stocking survival of June suckers using a Cormack-Jolly-Seber model with three covariates: stocking origin, stocking size, and stocking season.

Survival was positively correlated with stocking size, with a possible size-selective predation threshold occurring around 300mm, and survival of spring-stocked fish appeared to be higher than summer or fall cohorts regardless of origin. Additionally, as the goal of stocking programs is not simply to increase survival, but to maximize spawning adults while minimizing costs, I analyzed costs and benefits of different stocking strategies. In doing so, I identified that stocking larger individuals produces more adult spawners than stocking smaller individuals at the same operational cost. By identifying biotic and abiotic variables which affect survival, along with costs, I highlight operational changes that can help maximize efficacy of hatchery programs, a critical component of native fish recovery programs throughout the intermountain west.

(42 pages)

PUBLIC ABSTRACT

IDENTIFYING OPTIMAL STOCKING STRATEGIES TO SUPPORT RECOVERY OF AN ENDEMIC LAKE SUCKER

Dale R. Fonken

Endemic fishes in the intermountain west experienced significant population declines in the 20th century due to a variety of disturbances, including habitat fragmentation, water development, and the introduction of non-native, predatory fish species. The combination of habitat degradation with increased predation risk can severely limit natural recruitment for native fish species, and in response, fisheries managers have employed a variety of recovery strategies to prevent extinction. Among the most prominent strategies is artificial propagation and subsequent release of individuals into the natural environment (i.e., stocking). Artificial propagation is an expensive endeavor, and when not coupled with a research component, can lead to poor post-stocking survival and inefficient use of limited recovery resources. The June sucker, an imperiled species endemic to Utah Lake, UT, has been supplemented through artificial propagation since the 1990s. Approximately 800,000 June suckers have been stocked from multiple sources at varying sizes and across different seasons. Here, I analyzed the effects of stocking origin, size, and season on post-stocking survival for June suckers. Additionally, because the goal of hatchery programs is to maximize efficiency, I examined costs and benefits of stocking different sizes of fish. In doing so, I highlight operational changes that will more effectively augment adult abundance, which in turn will reduce extinction risk for the June sucker and other imperiled fish species in the intermountain west.

ACKNOWLEDGMENTS

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Dale R. Fonken

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INTRODUCTION

Freshwater ecosystems are hotbeds of biodiversity, yet are becoming increasingly imperiled due to anthropogenic disturbances, as overexploitation, pollution, flow modification, habitat degradation, and introduction of exotic species all pose major threats to freshwater biodiversity (Dudgeon et al. 2006; Reid et al. 2019). Fifty-seven of North America's 1,200 known freshwater fish went extinct between 1989 and 2006, and 80 more extinctions are expected to occur by 2050 (Burkhead 2012). Several endemic fishes in the intermountain west are currently facing extinction, largely due to size-selective predation of juveniles by an abundance of invasive fish species (Schooley and Marsh 2007; Tyus 2000). Propagating and rearing fish in an artificial environment, or refuge environments devoid of predators, can mitigate size-selective predation of juveniles, and is used as a management tool for many endangered fishes, including Razorback sucker (*Xyrauchen texanus*), Bonytail chub (*Gila elegens*), Colorado pikeminnow (*Ptychocheilus lucius*), and Rio Grande silvery minnow (*Hybognathus amarus* Hutson 2012; Nesler 2003). While generally a stopgap measure until threats driving population declines can be addressed, artificial propagation has likely prevented extinction of native fish species (Marsh et al. 2015). However, optimization of stocking programs is difficult, as many variables can affect post-stocking survival and funding is often limited (Cowx 1999). Artificial propagation requires significant financial investment, and if a robust research component is not included to guide stocking practices, survival of stocked fish can suffer, causing limited resources to be used inefficiently (Schooley and Marsh 2007; Steffensen et al. 2019).

The June sucker (*Chasmistes liorus*), an adfluvial lake sucker endemic to Utah Lake, UT, USA, is emblematic of many endemic fish species in degraded ecosystems. Flow modification, nutrient loading, river channelization, and introduction of invasive species transformed Utah Lake from a mesotrophic, macrophyte-dominated ecosystem into a hyper-eutrophic system with sparse aquatic vegetation (King 2019). The loss of predator refugia historically present in macrophyte habitats coinciding with the establishment of multiple exotic piscivores led to a precipitous decline in the June sucker population (USFWS 1999). Recruitment failure occurred in the mid-1900s, and by the 1980s the population was reduced from numbers that once supported a commercial fishery to around 1,000 senescent individuals (Keleher et al. 1998). In 1986, the species was listed as endangered under the Endangered Species Act (USFWS 1999). Early efforts to recover the June sucker centered around supplementing the population through artificial propagation (Anderson et al. 2007), and approximately 800,000 June suckers have been released into Utah Lake since stocking began.

June suckers are raised in hatcheries, grow-out ponds, and refuge populations, and have been stocked at differing sizes and seasons since the stocking program began. A diverse stocking portfolio can mitigate for unknown environmental limitations and ensure some level of success (Cowx 1999). However, survival is a function of biotic and abiotic conditions which can shift over time. Post-stocking survival analysis can identify conditions that maximize survival, which in turn can further enhance productivity of stocking programs by highlighting operational changes which maximize survival to adulthood (Steffensen et al. 2019). However, in addition to survival, investment needs to be considered, as changes in hatchery operations which increase survival may be offset by additional costs.

Previous studies have found that post-stocking survival of June suckers is positively correlated with size-at-stocking and highest for individuals stocked in June (Billman et al. 2011; Ehlo et al. 2019; Rasmussen et al. 2009). However, these studies either occurred 10-15 years ago, when PIT tag antenna data from spawning tributaries were not available or examined short-term survival of juveniles. Since publication of these studies, applications of statistical models for survival have developed to incorporate antenna data. By including antenna data from spawning tributaries, I was able to analyze a much larger data set, which will provide stronger inference into the effect of size, season, and origin on survival to adulthood. Additionally, substantial management actions resulting in ecosystem-level changes have occurred in the past 10 years that may have altered observed survival rates from previous studies. Removal of Common carp (hereafter "carp") reduced carp biomass by 73% since 2009 (Walsworth et al. 2020), and Hobble Creek, one of three main spawning tributaries for June sucker, was restored in 2011. Periodic survival analyses, especially in dynamic ecosystems such as Utah Lake, can improve understanding of biotic and abiotic conditions that maximize survival. Beginning in 2013, a portion of stocked June suckers have been implanted with 134Hz PIT Tags, allowing for mark-recapture analysis. Here, I examined the effect of size-at-stocking, stocking season, and stocking origin on survival to adulthood of stocked June suckers. Additionally, I analyzed costs and benefits for different stocking strategies using survival results from my primary objective, thus providing fisheries managers with a blueprint for optimizing hatchery production. Insights about the factors influencing survival of June sucker will likely be applicable to other native fish recovery programs.

METHODS

Study Area

Utah Lake is a large, shallow, remnant of Pleistocene Era Lake Bonneville located in central Utah (Figure 1). At full pool, the surface area of Utah Lake is 388 km^2, with an average depth of 2.9 meters and a maximum depth of 4.2 meters. Utah Lake was historically a mesotrophic, macrophyte-dominated system, but shifted to a hyper-eutrophic state in the mid-1900s. This sudden shift coincided with the establishment of carp as a dominant species, as well as increased nutrient loading associated with urban and agricultural development (King 2019).

Historically, the fish community in Utah Lake was comprised of 14 native species. A series of introductions in the 19th and 20th centuries resulted in the establishment of 16 non-native fish species and the extinction of an endemic species, the Utah Lake sculpin (*Cottus echinatus* Heckmann et al. 1981). Now, just three native species remain: Utah sucker (*Catostomus ardens*), Utah chub (*Gila atraria*), and the endemic June sucker.

Six tributaries flow into Utah Lake: the Provo River, Hobble Creek, Spanish Fork, American Fork, Battle Creek, and Spring Creek. All tributaries contain June sucker spawning habitat, which is characterized by gravel-cobble substrate in shallow water (<1 meter) with high velocity (1m/second) (Modde and Muirhead 1994). The vast majority (98%) of spawning activity occurs in the Provo River, Spanish Fork, and Hobble Creek (Unpublished Data, Utah Division of Wildlife Resources). Over-allocation of flows, particularly in the American Fork River, prohibit consistent spawning activity in other tributaries. The three main spawning tributaries have been the focus of intensive monitoring using Passive Integrated Arrays (PIAs) since 2011. PIAs are permanent structures that span the channel in shallow areas near the stream-lake interface and detect spawning June suckers with high efficiency as they migrate upstream. Detection range for PIAs is approximately 0.9m and they are able to scan majority of the water column in most water years. The propensity of June suckers to spawn in shallow riffles also contributes to high detection efficiency.

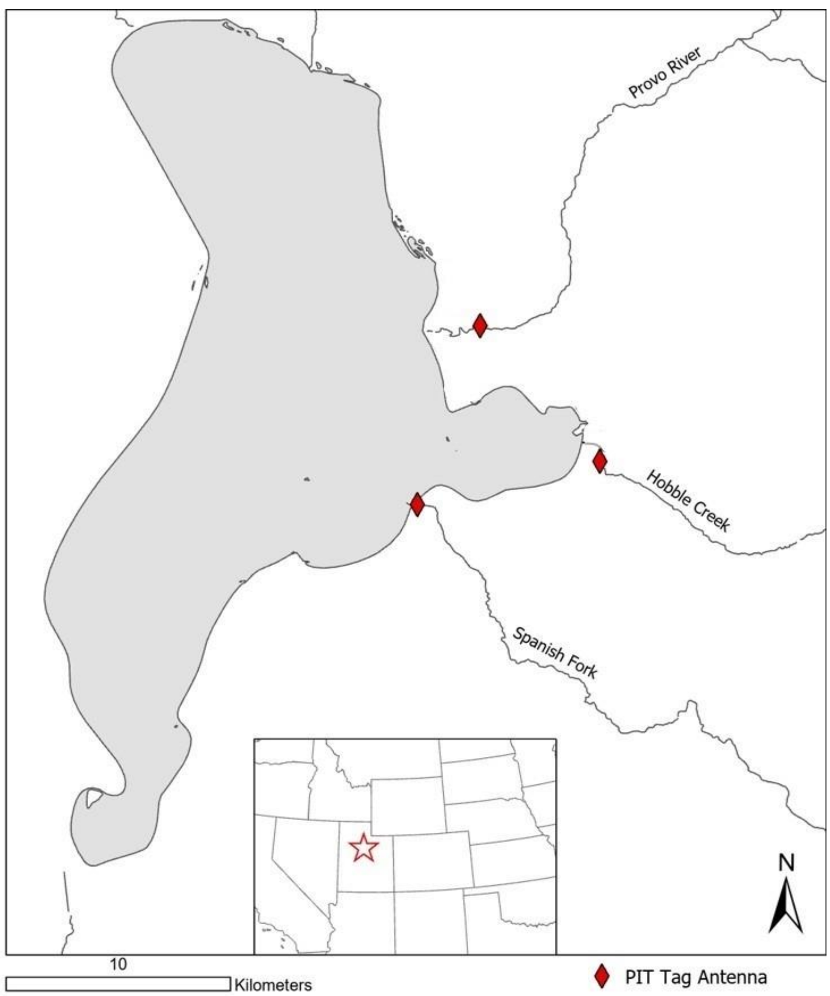

Figure 1. The location of Utah Lake, Utah, and its major tributaries. Diamonds indicate the location of PIT tag scanning antennae.

June suckers are stocked from four different locations which can be categorized into three distinct environments: hatcheries, grow-out ponds, and refuge populations. June suckers from the Logan Hatchery are raised in an artificial environment for two years before stocking into Utah Lake. Rosebud Ponds contain June suckers which are raised in a hatchery environment for one year before being transported to the grow-out ponds, where they rear for an additional year before being stocked into Utah Lake. Red Butte Reservoir (hereafter “Red Butte), near Salt Lake City, Utah, USA, was stocked with June suckers in the 1990s and currently supports a wild, self-sustaining refuge population. Camp Creek Reservoir (hereafter “Camp Creek”), in Box Elder County, Utah, USA, had an additional self-sustaining refuge population of June suckers and was used as a stocking source until 2013, when a fire and subsequent landslide extirpated the population. For my analyses, Red Butte and Camp Creek were pooled into a single origin (refuge populations).

Data Collection

Approximately 5% of June suckers stocked from the Logan Hatchery and Rosebud Ponds and all fish captured at Camp Creek and Red Butte were implanted with 12mm, 134kHz PIT tags beginning in 2013. Stocking size (total length in mm), date, and origin were recorded for each PIT-tagged fish. The Logan Hatchery primarily stocked June suckers in spring (May/June), while cohorts from Rosebud Ponds were stocked exclusively in the fall (September/October; Table 1; Figure 2). Refuge populations contributed one spring cohort from Camp Creek, and summer (July/August) and fall cohorts from Red Butte. No stocking events occurred between November-April across the entire study period.

Table 1. Number, origin, and stocking season for PIT-tagged (134Hz) June Suckers stocked from 2013-2019 in Utah Lake, Utah.

	Logan Hatchery			**Red Butte Reservoir**			**Rosebud Ponds**			**Camp Creek Reservoir**		
Year	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall
2013	0	551	600	0	0	0	0	0	0	215	0	0
2014	584	583	0	0	0	0	0	0	499	0	0	0
2015	599	598	0	0	0	0	0	0	496	0	0	0
2016	2930	0	0	0	0	0	0	0	498	0	0	0
2017	1978	0	0	0	714	14	0	0	494	0	0	0
2018	1892	0	0	0	223	166	0	0	479	0	0	0
2019	1972	0	0	0	0	803	0	0	1868	0	0	0

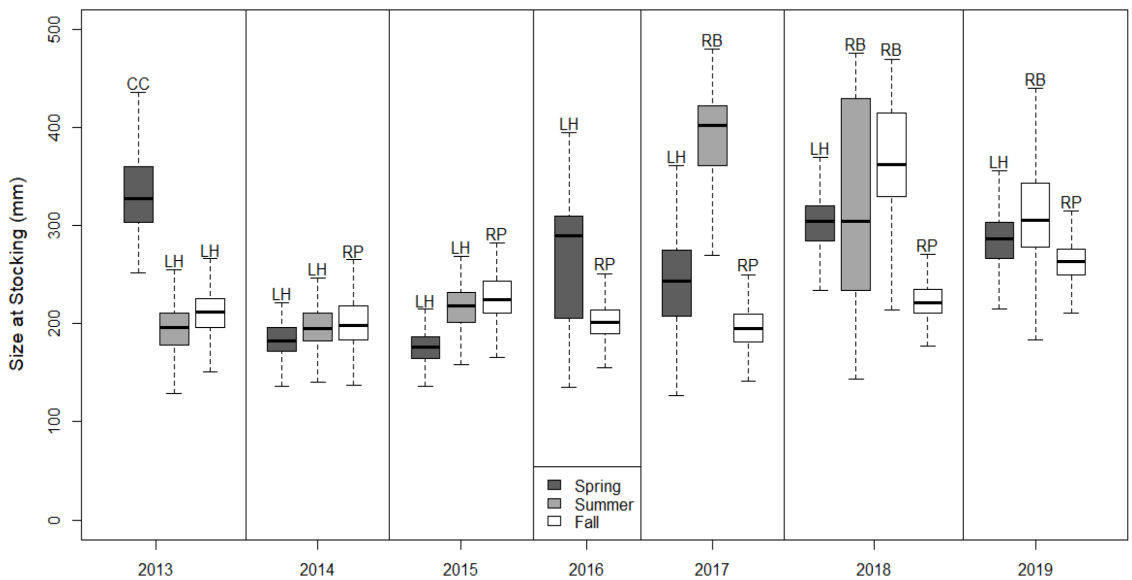

Figure 2. Size-at-stocking for all PIT-tagged (134Hz) June sucker cohorts stocked in Utah Lake, Utah from 2013-2019 (CC=Camp Creek, LH = Logan Hatchery, RP=Rosebud Ponds, and RB = Red Butte).

Reencounter data for stocked June suckers were collected through active and passive methods during a defined closed-capture period (1 May – 30 June) when 97% June suckers spawn (unpublished data, Utah Division of Wildlife Resources). Active capture methods consisted of trammel netting (36 x 1.5m, 38mm mesh), electrofishing, and spotlighting, a technique in which handheld LED lights and dipnets are used to temporarily stun and capture spawning June suckers. Passive methods consisted of PIAs in the Provo River, Hobble Creek, and Spanish Fork, and accounted for the vast majority of reencounters (96.7%). PIAs functioned properly throughout close-capture periods with the exception of 2017, when significant flooding damaged the PIA in the Provo River, and 2015, when two weeks of data from the Provo River PIA were inadvertently deleted. Extracted records included all PIT-tagged stocked fish and subsequent reencounters in the Provo River, Spanish Fork, and Hobble Creek during the closed-capture period.

Data Analysis

I constructed capture histories from stocking and reencounter data from the June Sucker Recovery Implementation Program Database. Using these data, I estimated apparent survival (ϕ) and detection probability (p) of stocked June suckers using a Cormack-Jolly-Seber model in Program Mark (Cormack 1964; Jolly 1965; Seber 1965; White and Burnham 1999). Annual apparent survival (ϕ_i) is the probability that a stocked June sucker survived from year t to t+1, given that individual was available for capture (i.e., moved into one of the 3 main tributaries during the sampling period). Recapture probability (p) is the probability of recapture in year t. Beyond CJS model assumptions (e.g., tagged individuals are representative of all stocked June suckers, tagging does not affect survival, etc.; Burnham et al. 1987), an additional assumption is that detection of June suckers in a tributary is indicative of recruitment to adulthood.

I used Akaike's Information Criterion adjusted for small sample sizes (AICc) and normalized AICc weights (w_i) to rank models (Burnham and Anderson 2002). I could not estimate overdispersion ($\hat{c}$) to determine goodness-of-fit using the recommended procedures for CJS models because all models included the individual covariate for size (Cooch and White 2019). Moreover, $\hat{c}$ for the global model (with size) was 0.71. Cooch and White (2019) recommend leaving $\hat{c} = 1$ when $\hat{c} < 1$. Because the observed $\hat{c}$ of the global model was <1.0, I did not use $QAIC_c$ for model selection or inflate variances of parameter estimates by $\hat{c}$ (Burnham and Anderson 2002).

To reduce the total number of models considered, model development was a sequential process (Nichols et al. 1997), wherein I first constructed models with different temporal effects. I modeled ϕ and p with year (time; t) modeled as a categorical effect, constant, and with a linear trend (ϕ and p increased or decreased through time). I then focused on modeling p, using the best model for ϕ. Model structures for p included stocking size modeled individually, additively, and interactively with the best temporal structure for p.

For the final phase of modeling, I used the model with the best temporal structure for ϕ and the top model for p as a base model. I constructed models for ϕ which included stocking size, stocking season, and stocking origin as covariates. Each stocking covariate was included by itself in the model individually (no temporal structure), and then additively and interactively with the best temporal structure for ϕ. Finally, I used combinations of the 3 stocking covariates together for modeling ϕ, based on the best model structure (i.e., the model with lowest AIC_c) when only a single covariate was used. I also included interactions between stocking covariates and between stocking covariates and time that were hypothesized to be relevant (see appendix for the full models set).

I assessed the cost and benefit of stocking 200mm and 300mm spring-stocked fish using my survival estimates and budget information from the Logan Hatchery. Across my study period (2013-2019), the Logan Hatchery has reared June Suckers for one year (median size 200mm) or two years (median size 300mm); thus, the reasoning for analyzing two size classes. The cost of producing one 200mm and 300mm fish was estimated to be \$5.50 and \$12.50 (USD) (Unpublished data, Utah Division of Wildlife Resources), respectively, and the following equations were used to estimate the cost per recruit for both sizes classes and their associated confidence intervals:

$$\beta = \frac{\text{Cost per Stocked Fish}}{\phi}$$

$$\text{Cost} = S^{*}\,\beta + \alpha$$

where, ϕ = apparent survival, β = the cost per spawner produced, S = the number of spawners produced, and α represents the fixed cost of operating a hatchery. Cost-benefit tradeoffs were analyzed using Program R (R Core Team 2020).

RESULTS

Model selection revealed strong interactive and time-varying effects from covariates (size, season, and origin; Table 2). The top model, {ϕ(Origin x Size+Origin x Season+*t* x Size+*t* x Season+*t* x Origin) *p*(*t* x Size)}, was 23.9 ΔAIC_c lower than the second best model, {ϕ(Origin x Season+*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}, which did not have an interactive effect of stocking size. Interactive and time-varying size parameters had strong effects on survival (Figure 3).

Table 2. Top 4 models for estimation of apparent survival (ϕ) and detection probability (*p*) of June suckers stocked into Utah Lake, Utah, from 2013-2019. Models are ranked by AIC_c

Model	Parameters	AIC_c	ΔAIC_c	Deviance
{ϕ(Origin x Size+Origin x Season+*t* x Size+*t* x Season+*t* x Origin) *p*(*t**Size)}	62	13416.5	0.0	13292.1
{ϕ(Origin x Season+*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	60	13440.4	23.9	13320.0
{ϕ(Origin x Size +*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	58	13519.8	103.3	13403.5
{ϕ(*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	56	13542.8	126.2	13430.5

Note: *t*, time-varying effect of covariate; AIC, Akaike Information Criterion

Size had the strongest relationship with survival of the three stocking covariates. Post-stocking survival was positively related to stocking size across all stocking origins (Figure 4). Survival of spring-stocked June suckers from the Logan Hatchery increased four-fold from 200mm (ϕ =0.12, [95% CI=0.08, 0.17]) to 300mm (ϕ =0.50, [95% CI=0.45, 0.58]). The pattern was similar for Camp Creek spring stocking and similar but offset (occurred between 300mm and 400mm) for Red Butte summer stocking (Figure 4).

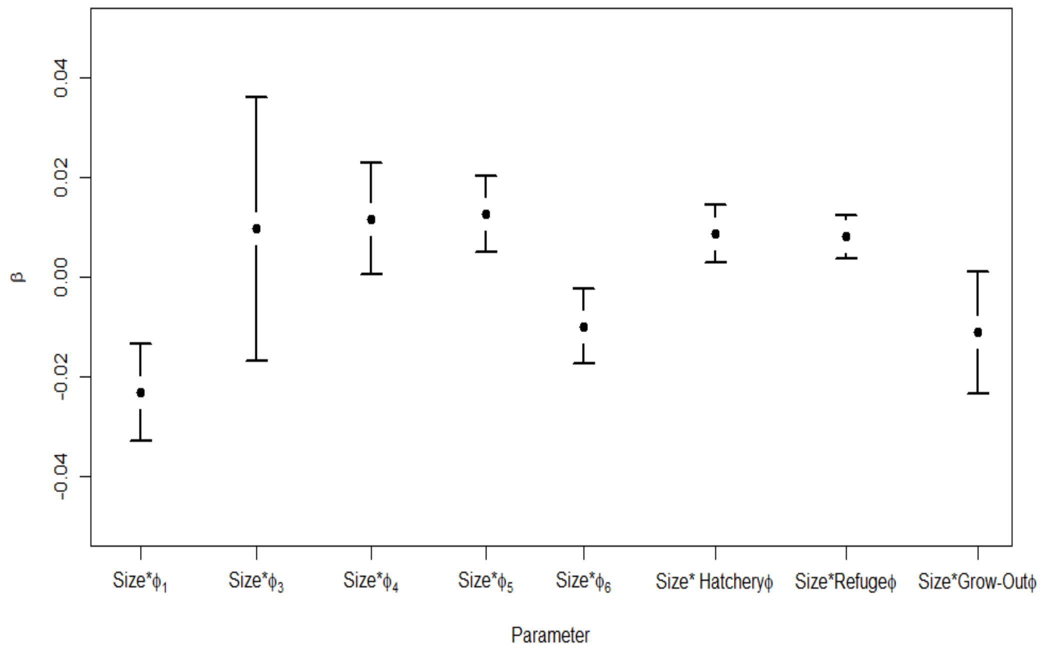

Figure 3. LOGIT link function parameter estimates from the highest performing model. Size* ϕ_i is the effect of size on apparent survival for interval (year) *i*. Size* ϕ_2 could not be estimated, presumably due to a lack of reencounter data from interval 2. Size*Hatchery ϕ, Size*Refuge ϕ, and Size*Grow-out ϕ represent the interactive effect of size and origin on apparent survival.

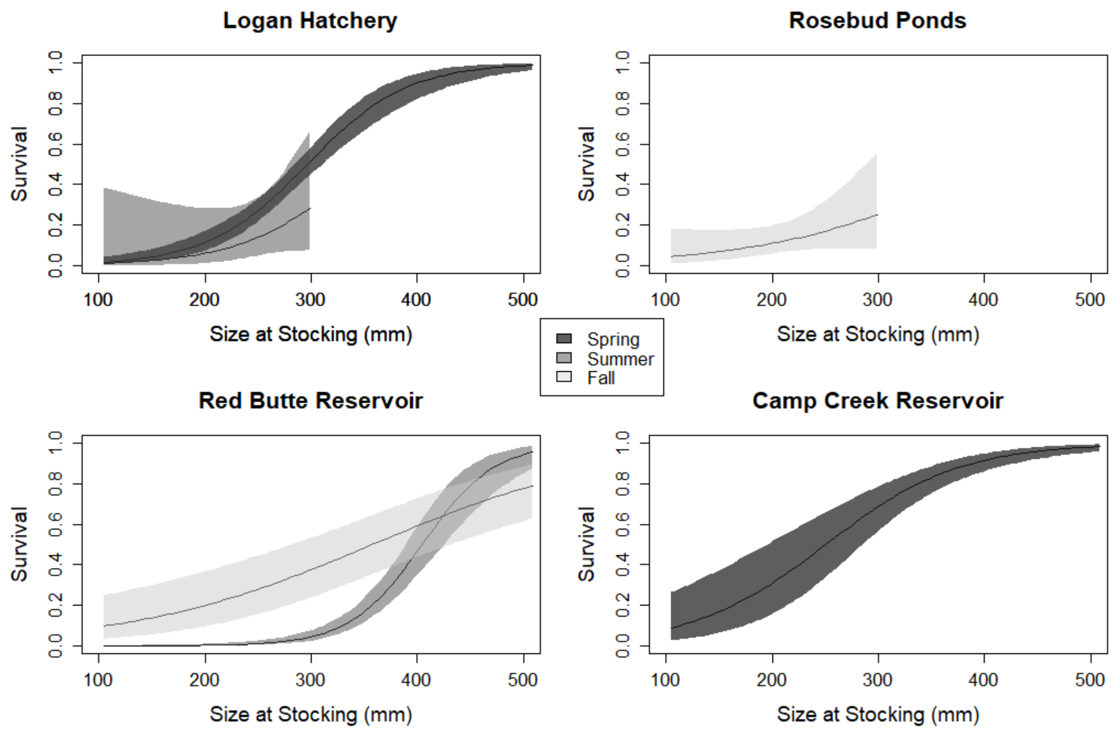

Figure 4. Apparent annual survival (with 95% CI) versus length of stocked June suckers in Utah Lake, Utah. Survival estimates are for fish stocked from the Logan Hatchery, Rosebud Ponds, Red Butte include fish stocked between 2015-2018, and fish stocked from Camp Creek in 2013. Since they are both refuge populations, Red Butte and Camp Creek were modeled as one origin. Survival estimates for Logan Hatchery summer cohorts and Rosebud Ponds were not plotted at sizes greater than 300mm, as those cohorts did not contain fish >300mm. Fall cohorts from the Logan Hatchery are not plotted, as they have near-zero survival with CI [0,1] across all size classes.

Survival curves for June suckers from Red Butte varied seasonally, and there was an interaction between size and season. Near-zero survival was estimated for summer-stocked fish less than 300mm from Red Butte, while survival of fall-stocked 300mm fish was substantially higher (ϕ =0.38, [95% CI=0.24, 0.54]). However, survival of summer cohorts was similar to fall cohorts at 400mm and greater at 500mm (Figure 4). Although comparisons between spring and summer occurred across a reduced size range (100-300mm), spring stocking appears more favorable to survival than summer. Survival of spring-stocked 250mm June suckers from Logan Hatchery was estimated to be twice as high as summer-stocked fish. In addition, although there may be a difference due to origin, survival of spring-stocked June suckers from Camp Creek (ϕ =0.50, [95% CI=0.34, 0.66]) was three times higher than fall-stocked cohorts from Rosebud Ponds (ϕ =0.17, [95% CI=0.08, 0.32]). However, season and origin were confounded because only Red Butte had fish stocked in two seasons across a wide size range (i.e., 100mm to >400mm) and only Logan Hatchery and Camp Creek stocked in spring across a wide size range (Figure 4).

Survival of stocked June suckers at small size classes differed by stocking origin. Non-zero survival was estimated for 100mm fall-stocked June suckers from Red Butte (ϕ =0.10 [95% CI=0.03, 0.25]) and spring-stocked June suckers from Camp Creek (ϕ =0.08 [95% CI= 0.03,0.26]), both refuge populations where June suckers reproduce naturally. Post-stocking survival estimates for cohorts from the Logan Hatchery and Rosebud grow-out ponds demonstrated lower survival at 100mm and the 95%CI included zero.

Stocking sizes necessary to achieve specified survival rates from 0.1 to 0.5 varied considerably among origin-season combinations. Stocking sizes were lowest for spring-stocked June suckers from Camp Creek and highest for summer-stocked June suckers from Red Butte (Figure 5). To achieve survival of 0.3, estimated stocking size for June suckers from Camp Creek was 198mm [95%CI= 154mm, 275mm], while for summer-stocked June suckers from Red Butte it was 376mm [95%CI= 359mm, 394mm], which is 1.8 times larger. Stocking sizes needed to achieve survival of 0.3 were similar for spring-stocked June suckers from Logan Hatchery and fall-stocked from Red Butte (258mm and

263mm) and were intermediate between Camp Creek and summer stocked Red Butte cohorts.

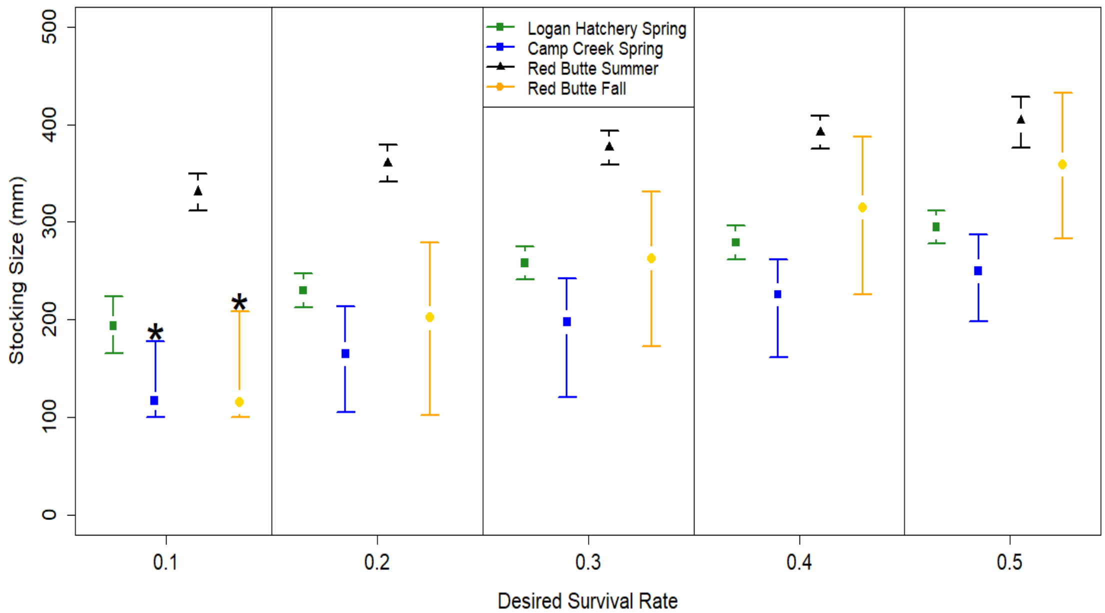

Figure 5. Stocking sizes necessary to achieve desired survival rates (0.1-0.5) for June suckers stocked into Utah Lake, UT from 2013-2019. Asterisks indicate cohorts whose lower CI was less than 100mm and therefore could not be estimated by my model. Summer cohorts from the Logan Hatchery and fall cohorts from Rosebud Ponds were not included in this analysis due to prohibitively wide confidence intervals.

A cost-benefit analysis for hatchery-reared spring cohorts revealed a significant advantage for stocking 300mm June suckers compared to 200mm fish across all budgets (Figure 6). For example, a budget of $150,000 produced nearly twice as many recruits (i.e., spawning June suckers) when fish were stocked at 300mm versus 200mm. That is, an estimated 3,327 recruits were produced when fish were stocked at 200mm compared to 5,693 recruits when stocked at 300mm.

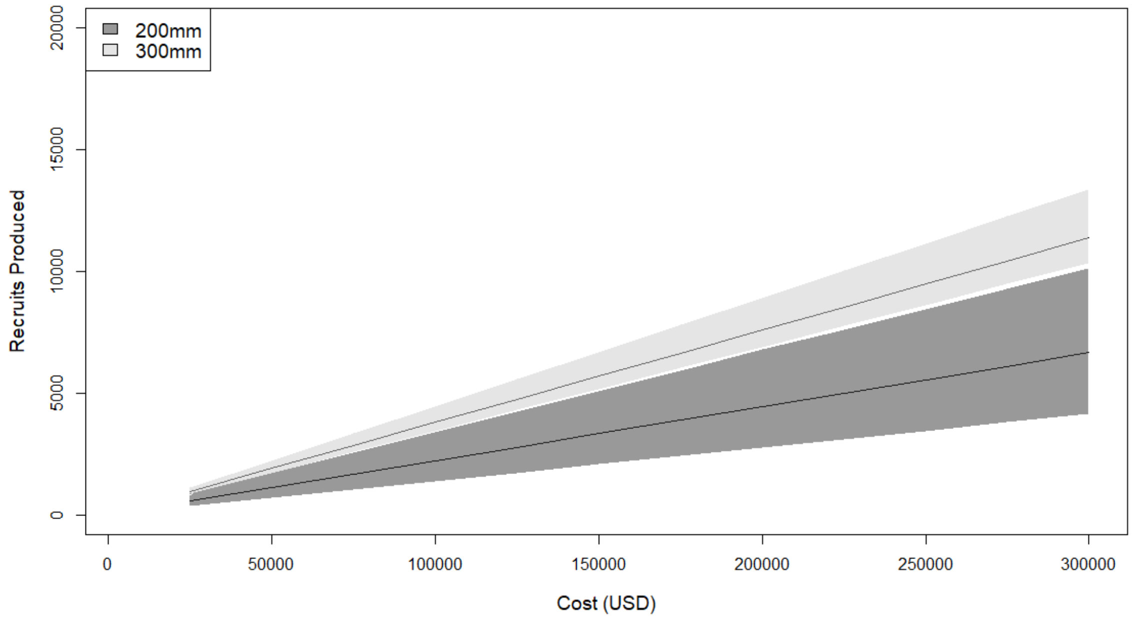

Figure 6. Cost/benefit analysis for spring-stocked hatchery June sucker cohorts.

DISCUSSION

Stocking fishes for conservation often requires significant investment, and robust research designed to evaluate stocking programs is a critical aspect of adaptive management (Clark et al. 1999; Hunt et al. 2017; Johnson et al. 1995; Mohsin et al. 2012). My analysis of long-term mark recapture data for stocked June suckers showed a strong positive relationship between size-at-stocking and apparent survival, with a large increase in survival between 200mm and 300mm. For spring-stocked fish from Logan hatchery, the largest sample size, survival was four times higher for 300mm fish than 200mm fish. For summer stocked fish from Logan Hatchery, increased survival for 300mm fish was less drastic than spring, but still more than twice as high.

My survival analysis was congruent with previous research showing demonstrably higher survival for larger individuals (Billman 2011; Ehlo et al.2019). However, it is important to consider the cost of rearing fish for an extended period, as it may be more cost effective to stock higher abundances of small fish. Cost benefit analyses are commonly used to evaluate stocking programs (Hunt et. al 2018; Rutledge et al. 2000; Stickney 1986) and should be coupled with post-stocking survival studies to ensure efficient use of financial resources. I found that stocking 300mm June suckers produced more recruits at a given investment (cost) than stocking 200mm individuals. This result is consistent with most cost benefit analyses for stocked fishes, which have shown distinct advantages for stocking larger fish (Eggold and Horms 2001). Although it is more expensive to raise June suckers to 300mm, it appears the survival advantage conferred by additional rearing time outweighs the elevated cost, perhaps by reducing susceptibility to predation. This analysis is specific to hatchery-reared June suckers, but is relevant to most stocking programs, especially where predatory fish are abundant in the environment.

Substantial increases in survival were observed between 200-300mm spring-stocked fish and 300-400mm summer-stocked fish, indicating an interaction between size and season. Such increases may be the result of size-selective predation. Utah Lake is home to many non-native piscivores, including Walleye (*Sander vitreus*), White bass (*Morone chrysops*), and Channel catfish (*Ictalurus punctatus*). Quantitative predator-prey analysis for Walleye in the midwestern United States demonstrated a propensity to consume prey less than 250mm (Gaeta et al. 2018), and white bass rarely consume prey items greater than 200mm, with an observed increase in piscivory in autumn (Hartman 1998). Additionally, Channel catfish rarely consume prey items greater than 300mm, but frequently consume native Bluehead sucker (*Catostomus discobolus*) in the San Juan River, a tributary of the Colorado River in the southwestern United States (Hedden et al. 2018). The temporal shift in survival between spring and summer-stocked fish is peculiar, as gape limitation should remain constant through time. However, increased metabolic rates during warmer months and changes in forage abundance can cause seasonal shifts in size-selective predation (Montaña et al. 2011). Feeding ecology of non-native predators appears to be driving survival rates of stocked June sucker in Utah Lake. Given the similar climate and predator assemblage in aquatic ecosystems throughout the intermountain west, size-selective predation of stocked fishes is likely similar on a regional level.

Predation by gape-limited, non-native piscivores appears to be impacting survival of stocked June suckers. However, avian predation may have a significant effect on survival as well. American White pelicans (*Pelecanus erythrorhynchos*), Double-Crested cormorants (*Phalacrocorax auritus*), and Western grebes (*Aechmophorus occidentalis*) are fish-eating birds which inhabit Utah Lake. Predation by all three species on newly-stocked fish can be extreme, especially in confined environments with little structure (Derbe 1997; Ebner et al. 2007; Kloskowski 2011). June sucker are stocked near the confluence of the Provo River and Utah Lake. Availability of refuge habitat in this area is largely dependent on lake level and discharge from the Provo River. When water levels are high, an abundance of submerged aquatic vegetation is accessible to newly-stocked June suckers, and may facilitate avoidance from avian predators. Conversely, when lake level and discharge are low, newly-stocked June suckers have little or no refuge habitat, and avian predation has been observed. Predation risk associated with refuge habitat availability may partially explain the seasonal effect on survival of stocked June suckers. Lake level and stream discharge are highest in spring and may provide newly-stocked June suckers with adequate habitat to avoid predation. In summer and fall, when water levels are low, avian predation may significantly affect survival of stocked individuals.

Another plausible explanation for size and season interaction may be elevated water temperatures during summer stocking events. For stocking events from refuge populations, fish are captured via gill net, tagged, and placed in holding tanks before being loaded into a hatchery truck and stocked into Utah Lake. This process can be very stressful, especially when water temperatures exceed 22°C. Metabolic rates of Northern Crayfish increase dramatically when water temperatures reach 22°C (*Faxonius virilis*; USFWS 2015), which can lead to predation attempts on fish captured in gill nets. Temperatures exceeded 22°C during summer stocking events from Red Butte, resulting in descaling and partial fin loss from crayfish predation, especially on fish less than 300mm. Stress induced by crayfish predation may have been exacerbated by low dissolved oxygen associated with high water temperatures, which in turn may have affected post-stocking survival of summer-stocked fish. Temperatures ranged from (15-19 °C) during spring and fall stocking events from refuge populations, and little visible signs of stress were observed.

Hatchery supplementation may have prevented extinction of the June sucker; however, complete recovery of imperiled species requires restoration of their natural life cycle. While I did not analyze survival of naturally-produced June sucker, analysis of wild-origin fish (i.e., fish from refuge populations) may be a proxy for Utah Lake origin June suckers, especially at small size classes. For example, survival of hatchery-reared fish is zero at 100mm, but non-zero for two refuge population cohorts: fall-stocked fish from Red Butte and spring-stocked fish from Camp Creek. These differences in apparent survival at small size classes may be attributed to stark contrasts in rearing environments. Hatchery fish are reared in an artificial environment without predators and where food is provided. Alternatively, June suckers from Red Butte and Camp Creek compete for scant food resources and coexist with piscivorous Bonneville Cutthroat trout (*Oncorhynchus clarkii utah*) and avian predators. Simulating natural environments is a common strategy for stocking programs and can improve post-stocking survival (Ward et al. 2004). For example, flow conditioning has been shown to significantly improve post-stocking survival of Razorback sucker and Bonytail chub in the Colorado River (Franssen et al. 2021). For June sucker, learned foraging and predator avoidance behaviors likely contribute to higher survival of diminutive fish stocked from refuge populations.

Hatchery-reared fish need to be stocked at sizes exceeding gape limitations of non-native predators, while fish from refuge populations can be stocked as small as 100mm with some expectation of survival. This effect provides some insight into natural recruitment in Utah Lake, the limiting factor for June sucker. If June suckers stocked from natural environments are able to survive in Utah Lake at small sizes, then native Utah Lake June suckers may be recruiting naturally if they are able reach a size of 100mm. Natural recruitment has been documented through stable isotope analysis of otoliths (Wolff 2013), but further quantitative analysis is needed to ascertain survival and recruitment of wild-origin June suckers at a population scale.

My survival analyses identified variables which currently affect survival of stocked June suckers. However, aquatic ecosystems are dynamic, and the effect of stocking size, season, and origin on survival may change over time. For example, a commercial-scale carp removal program reduced carp biomass in Utah Lake by 72% from 2009-2019 (Walsworth et al. 2020), resulting in a shift in dominant zooplankton taxa from small to large-bodied individuals (Landom and Walsworth 2021). Zooplankton are an important food source for catostomids (May et al. 2021; Welker and Scarneccia 2003), and a shift to larger taxa may expedite growth and improve survival of stocked fishes, particularly zooplanktivores such as the June sucker. Additionally, as carp biomass decreases, establishment of aquatic macrophytes may increase and provide refuge habitat from predators. Thus, recent management actions may be related to increased survival of June suckers.

Commercial-scale removal of invasive species (i.e., carp) may increase post-stocking survival of June suckers. However, introductions of other invasive species are becoming more common across the intermountain west (Rahel and Smith 2018) and may deleteriously affect survival of stocked fishes. Northern pike (*Esox lucius*), a highly piscivorous non-native predator, was illegally introduced into Utah Lake within the past 10 years (Reynolds 2017). Given the recency of this introduction, abundance of Northern pike is currently low, but may increase to levels observed within their native range, which could threaten the existence of June sucker (Reynolds 2017). Northern pike are less gape limited than Utah Lake's other non-native predators and routinely consume prey items up to 400mm (Gaeta et al. 2018). Therefore, if Northern pike abundance increases to predicted levels, a shift to stocking June suckers larger than 300mm may be needed to mitigate for the increased gape of this introduced predator. To this end, post-stocking survival for hatchery programs should be analyzed frequently to monitor efficacy of current stocking strategies and identify adjustments needed to maintain adequate survival in changing environments.

My study adds to the library of research on stocking survival for imperiled fish species in the intermountain west, but also presents novel results. Previous work identified stocking size and season to be a very important predictors of survival. However, these studies were smaller in scale and did not incorporate antenna data from spawning tributaries. I utilized a much larger sample size to analyze the effect of size, season, and origin over a longer time period, and in doing so, I solidified results from previous studies. These results will improve decision making of managers when planning stocking programs, especially with respect to origin. Hatcheries, grow-out ponds, and refuge populations are very different environments which require disparate levels of funding. As such, it is imperative to identify which sources should be prioritized. Finally, cost and benefit analysis also added a novel aspect to my study. Survival analyses alone, while useful, do not directly address the issue of limited funding for native species recovery programs. Investment in conservation for non-game fishes is often reduced compared to more economically important game species (Mangun and Shaw 1984). Therefore, native species recovery programs are constrained financially and need to make the most of limited resources. The cost-benefit analysis presented herein identifies stocking strategies that result in the greatest return for a given cost.

While my survival analysis identified variables that can be adjusted to increase survival of stocked June suckers, there are still important data gaps that need to be addressed. For example, I was unable to fully analyze survival of cohorts from grow-out ponds because no fish were stocked from this source in spring. It appears that spring stocking events produce the highest survival, as has been found in Razorback suckers (Zelasko et al. 2010). However, without spring cohorts from grow out ponds, the effect of season is confounded with origin. Fortunately, June suckers from grow out ponds were stocked in spring 2020. These fish will not reach maturity until 2022 and were therefore not included in my analysis; however, future survival analysis of this cohort will address the confounding effect of origin and season.

In addition to size, season, and origin, other biotic and abiotic variables may have an effect on post-stocking survival. Availability of predator refugia in Utah Lake is driven by lake level (Landom and Walsworth 2021). As lake level recedes, shoreline vegetation is exposed, desiccating habitat which newly-stocked fish may use to avoid predation. The effect of lake level may be captured by season, as spring is associated with higher water. However, Utah Lake can fluctuate as much as 7 feet of elevation between years, and these substantial environmental changes should be investigated in subsequent modeling.

My results indicate stocking larger fish can improve post-stocking survival, and more specifically, that stocking hatchery-origin June suckers at 300mm is the most cost-effective method for producing spawning adults. By identifying cost-effective stocking methods, my research will guide optimization of stocking programs, which in turn will augment adult abundance and reduce extinction risk for native fishes on a regional level. Many North American endemic fishes are in imminent danger of local extirpation or extinction (Burkhead 2012), but strategic supplementation from alternative sources can improve long-term viability of threatened species. Additionally, as the goal of recovery programs is not only to increase adult abundance through supplementation, but to restore natural life cycles of native species, I identify potential impediments to natural reproduction, such as size-selective predation from non-native fishes and avian predators.

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APPENDIX

Table A.1. Full model set for estimation of survival (ϕ) and detections probability (p) of June suckers stocked into Utah Lake, UT from 2013-2019.

Model	Parameters	AIC_c	ΔAIC_c	Deviance
{ϕ(Origin x Size+Origin x Season+*t* x Size+*t* x Season+*t* x Origin) *p*(*t* x Size)}	62	13416.5	0.0	13292.1
{ϕ(Origin x Season+*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	60	13440.4	23.9	13320.0
{ϕ(Origin x Size +*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	58	13519.8	103.3	13403.5
{ϕ(*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	56	13542.8	126.2	13430.5
{ϕ(Size x Season+*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	58	13545.2	128.7	13428.8
{ϕ(Origin x Size+*t* x Size+*t* x Origin+*t* x Season) *p*(*t* x Size)}	46	13688.9	272.3	13596.7
{ϕ(*t* x Size+*t* x Origin+*t* x Season) *p*(*t*+Size)}	35	13740.0	323.4	13669.8
{ϕ(Origin x Size+*t* x Size+*t* x Origin+*t* x Season) *p*(*t*+Size)}	52	13767.4	350.9	13663.1
{ϕ(*t* x Size+*t* x Origin+*t* x season) *p*(*t*+Size)}	50	13770.1	353.6	13669.8
{ϕ(*t* x Size+Origin+*t* x season) *p*(*t*+Size)}	32	13789.2	372.7	13725.1
{ϕ(Origin x Size+*t* x Size+*t* x Origin+Season) *p*(*t*+Size)}	40	13891.0	474.5	13810.8
{ϕ(*t* x Size+*t* x Origin+Season) *p*(*t*+Size)}	50	13927.7	511.2	13827.5
{ϕ(Origin x Size+*t* x Size+Season) *p*(*t*+Size)}	28	13933.6	517.1	13877.5
{ϕ(Origin x Size+Origin x Season+*t* x Size+*t* x Season+*t* x Origin) *p*(*t*)}	55	13948.3	531.8	13838.0
{ϕ(*t**Size+Origin+Season) *p*(*t*+Size)}	26	13948.3	531.8	13912.1
{ϕ(*t*+Size+Season+Origin) *p*(*t*+Size)}	20	14019.2	602.7	13979.2
{ϕ(*t**Size+Origin+Season) *p*(*t*)}	24	14470.7	1054.1	14422.6
{ϕ(*t**Size+Origin) *p*(*t*)}	22	14504.1	1087.6	14460.1
{ϕ(*t*+Size+Season) *p*(*t*)}	16	14668.9	1252.4	14636.9
{ϕ(*t*+Size+Origin+Season) *p*(*t*)}	18	14674.2	1257.6	14638.1
{ϕ(*t*+size) *p*(*t*+Size)]}	13	14686.1	1269.6	14660.1
{ϕ(*t**Size) *p*(*t*)}	20	15065.4	1648.9	15025.3
{ϕ(*t**Origin) *p*(*t*)}	28	15121.4	1704.9	15065.3
{ϕ(*t*+Size) *p*(*t*)}	15	15229.7	1813.1	15199.6

{ϕ(t*Season) p(t)}	28	15518.5	2102.0	15462.5
{ϕ(t) p(t)}	14	16806.1	3389.6	16778.1

Note: t, time-varying effect of covariate**;** AIC, Akaike Information Criterion