Weber River metapopulation and source-sink dynamics of native trout and nongame fishes

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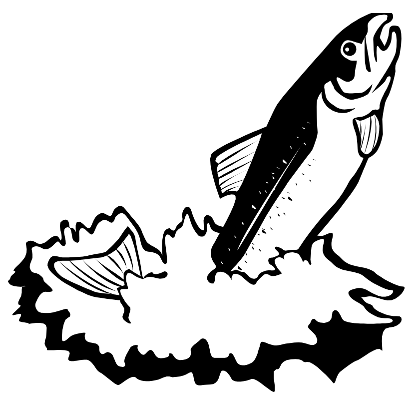

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TABLE of CONTENTS

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EXECUTIVE SUMMARY

Bonneville cutthroat trout (*Oncorhynchus clarkii utah*) presently occupy a variety of habitats from small streams to larger rivers and lakes that drain into the Bonneville Basin. As a result of continued threats to the subspecies and its habitat, the Bonneville cutthroat trout is designated by the State of Utah as a "conservation species" managed under a formal conservation agreement intended to preclude the need for listing under the federal Endangered Species Act. The Weber River in northern Utah is somewhat unusual for the intermountain west in that it is still home to native and endemic Bonneville cutthroat trout and bluehead sucker (*Catostomus discobolus*), yet is highly regulated and connectivity has been significantly reduced due to barriers to movement and migration. Despite the prevalence of these factors in the Weber River, both resident and fluvial Bonneville cutthroat trout as well as large, mature bluehead sucker were thought to be relatively common, highlighting the potential of this watershed for native fish conservation and restoration. The overall goal of this study was to identify the historical and contemporary importance of mainstem connectivity and tributaries to maintaining the population viability and persistence of these two species. To meet that goal, we used a multifaceted approach to describe the metapopulation structure and the importance of the tributaries in providing connectivity among subpopulations, at the watershed scale. This project was initiated in 2011 and the field work was completed in 2013.

In order to describe potential subpopulation structure and the overall and relative abundance in the tributaries, we collected fish using electrofishing, angling, and a picket weir. To obtain information on PIT-tagged fish and aid in estimating survival, we opportunistically used passive instream arrays (PIA) consisting of PIT-tag antenna(s) anchored to the stream bottom at the mouth of tributaries to detect PIT-tagged fish moving into and out of tributaries. In sum, we tagged 1671 trout (including cutthroat trout, rainbow trout [*O mykiss*], and hybrids) from 2 June 2011 to 13 June 2013; we actively recaptured 234 fish (at least one time) and detected (i.e., resighted) 260 unique fish at PIAs at least once. In the mainstem Weber River, there are likely six to seven age classes of cutthroat trout, and across the tributaries, there were four to six age classes, with age-0 fish captured only in 2011 (a high flow year) in Peterson, Jacobs, and Strawberry creeks. Based on mark recapture, we estimated subpopulations of cutthroat trout across the Weber River mainstem sections and years ranging from a low of 139 (Section 02 in 2012) to a high of 1296 (Section 04 in 2012). We estimated a population of bluehead sucker in the Weber River mainstem Section 02 of 175 (95% CI = 115 - 305). In general, across years, mean catch per unit effort (CPUE) for cutthroat trout was highest in tributaries compared to the mainstem Weber River. Survival was high and 95% confidence intervals were very narrow indicating high confidence in this estimate (S = 84%, 95 CI = 81 - 86%). Recapture probability was unsurprisingly highest in summer (p = 0.30, 95% CI = 0.16 - 0.47; August – October), when active sampling occurred, and was generally low in

April – July and November – March. The probability of being resighted (detected on a PIA) was greatest in spring and early summer (R = 0.15, 95% CI = 0.09 - 0.26) and was much lower in the other two later time periods.

To evaluate movement and potential tributary use, we combined information above and also identified 10 potential barriers to fish movement: three in the mainstem Weber River, and seven potential tributary barriers. In tributaries, these were primarily culverts with steep drops, lack of a plunge pool, and velocity blocking fish passage, and in the Weber River mainstem, there is a diversion at the mouth, a set of hydraulic gates for power diversion, and a dam and reservoir. Despite these barriers, in 2011, an extremely high water year, we captured large (> 400 mm TL) cutthroat trout in all tributaries excluding Dry Creek. When in operation, we captured adult cutthroat trout in the weir trap (as well as all other species in the Weber River) moving upstream. Across the years, we captured seven juvenile bluehead sucker moving upstream, and up to 13 and 7 cutthroat trout moving upstream and downstream, respectively. In addition, fluvial cutthroat trout detected at PIAs in the tributaries came primarily from the Weber River Section 04, totaling 21 in 2012 and 156 in 2013. Some individuals were sampled or re-sampled in multiple tributaries in the same year. Patterns of movement within the four streams with multiple PIAs in 2013 varied from detections by only one PIA to detections by both PIAs, with movement in both directions. The PIAs revealed heaviest use by tagged fish in Peterson, Jacobs, and Cottonwood creeks, which detected 67, 65, and 62 unique tags in the respective streams in 2013. The majority (88%) of the PIT tags resighted in those three streams were categorized as fluvial cutthroat trout, ranging from 76% fluvial in Cottonwood Creek to 97% in Peterson Creek. Data collected by the PIAs indicate that some of the suspected migration barriers are not complete barriers. Passage at some “barriers” likely depends on flow conditions, and other structures may only impede a portion of the fish attempting passage, depending on fish size or strength.

To identify natal origin (e.g., where a fish spawned or was born), we collected water samples in 2011 from each tributary at base-flow conditions to determine elemental levels of strontium. Analysis of mass spectrometry from laser ablation of cutthroat trout otoliths allowed us to determine trace elemental composition (e. g., 87Sr:86Sr ratios) which can be an indicator of natal origin when compared to the isotopic signature of water samples from each tributary. Analysis of strontium elemental signature on cutthroat trout otoliths indicates that cutthroat trout captured in the Weber River originated or make extensive use of tributary streams. Of the five ablated “mainstem cutthroat trout derived” otoliths, analyses indicate that all five cutthroat trout originated from or visited streams outside the mainstem, likely to spawn.

Similarly, to identify potential subpopulation structuring, we collected tissue from an adipose fin and/or lower caudal fin between 2003 and 2011 from 212 individual Bonneville cutthroat trout representing the seven potential subpopulations or stream reaches in the Weber River drainage. A series of genes in the mitochondria (mtDNA) were sequenced and a series of microsatellite regions in the nuclear (nDNA) genome were genotyped. The number of mtDNA haplotypes in the seven populations (i.e., stream reaches) ranged from 1 to 9 and only the Weber River and Peterson Creek contained haplotypes of Yellowstone cutthroat trout (*O. c. bouvieri*) and/or nonnative rainbow trout. Microsatellite data indicated that Gordon and Strawberry creeks showed significant differentiation in gene frequencies relative to the Weber River.

Summary and Management Implications

In sum, a relatively large and still intact population of Bonneville cutthroat trout resides in the Weber River and its tributaries. Given the range-wide reduction of Bonneville cutthroat trout and their protected status under a Conservation Agreement, conservation and enhancement of this population should be a top priority. In addition, our size structure, movement, and otolith analysis of natal origin results all collectively indicate the population of cutthroat trout in the Weber River makes frequent use of almost all the tributaries for spawning and rearing. While Yellowstone cutthroat trout haplotypes are present within the Weber River cutthroat trout population, we do not know if this has resulted from past stockings of nonnative trout or represents what was historically in the Weber River. Regardless, all populations (i.e., mainstem and tributaries) still largely represent the native genetic composition of cutthroat trout and some genetic mixing between the mainstem and tributary populations occurs, except within Strawberry and Gordon creeks, where full barriers exist. In addition, these fish attempt, likely with mixed success, to move upstream in both the mainstem Weber River (and this is also true for native and protected bluehead sucker) and into the tributaries in spring. Their migrations are partially blocked by barriers of mixed permeability, depending on water year. In addition, some individual fish appear to use multiple tributaries across their lifespan. Clearly, the importance of maintaining or restoring connectivity cannot be ignored if sustaining viable populations is a conservation goal. The agenda for the restoration of connectivity basin-wide could be informed not only by these fish population and movement data, but also by the permeability analysis.

Further, in contrast to other large, remnant populations of Bonneville cutthroat trout (e.g., Logan River), the larger fluvial life-history expression still remains and is frequently expressed in the Weber River. As the larger, fluvial individuals in a migratory population can play a disproportionate role in maintaining diversity and expression of its life history and population viability, maintaining and restoring connectivity in the Weber River is also of high priority.

The spawning tributaries that have not been identified, but are known to exist given the otolith microchemisty, should be discovered, to help prioritize restoration. This population should also be closely monitored into the future, given its now proven overall importance to the range-wide status of Bonneville cutthroat trout.

INTRODUCTION

Modern human activity has dramatically altered landscapes at both spatial and temporal scales greater than which many organisms have adapted (Vitousek et al. 1997; Fullerton et al. 2011). Alterations to river landscapes in the form of habitat fragmentation are especially pervasive, with a large majority of streams world-wide fragmented by dams or diversions (Ward and Stanford 1983). Riverine fishes are some of the most highly imperiled due, in part, to habitat alteration and degradation that has disrupted life histories adapted to high discharge, habitat heterogeneity, and long distance migratory corridors (Lenhardt et al. 2006 (in Pracheil); Pracheil et al. 2013). As a consequence of these anthropogenic alterations, many species of stream-dwelling fish face extinction or extirpation throughout their range (Pringle et al. 2000).

In response to a long evolutionary history of habitat heterogeneity and natural disturbance (e.g., drought, flood), many riverine fishes including almost all salmonids are structured to some degree as metapopulations (Rieman and Dunham 2000), a population structure that may no longer be viable under current riverine degradation. Low frequency dispersal among subpopulations, migratory behavior between rearing and spawning habitat, and a wide variation in life history expression are all critical in maintaining metapopulation structure in salmonids (Muhlfield and Marotz 2005; Nyce et al. 2013). However dispersal, which links subpopulations over a range of temporal and spatial scales, is frequently limited by connectivity or habitat fragmentation, especially in rivers, where all dispersal occurs in a linear (upstream or downstream) pattern. Further, habitat fragmentation and the loss of connectivity among riverine metapopulations not only prevents access to preferred spawning habitat and other spatially discrete resources (Vanicek et al. 1970; Chart and Bergersen 1992; Osmundson 2002; Muhlfield and Marotz 2005) but also increases extinction risk through stochastic events (Dunham and Rieman 1999; Fagan 2002; Fausch et al. 2006). As such, connectivity can influence several levels of biological organization (from genes to populations) and thus plays a fundamental role in conservation (Morita and Yamamoto 2002; Wiens 2002; Neville et al. 2006; Fullerton et al. 2011).

In addition to their role in maintaining genetic variation (Cegelski et al. 2006; Neville et al. 2006) fluvial fish are dispersers that ultimately decrease the extinction probability of the meta-population as a whole (Schlosser and Angermeier 1995; Hanski and Simberloff 1997). Fluvial fish that demonstrate medium to long-distance migrations between mainstem and tributary habitats are especially vulnerable to habitat fragmentation that commonly occurs at this scale (e.g., small dams and diversions) and isolates them from spawning areas (Dunham and Rieman 1999). Fluvial fish are typically larger, more fecund, and thus can have a greater proportional contribution to reproductive potential (Peterson and Fausch 2003). Large, fluvial individuals are also important due to their greater fecundity and ability to rescue populations from extinction (Power 2002). Therefore, conserving the larger, fluvial individuals in a migratory population can play a disproportionate role in maintaining diversity and expression of its life history and population viability.

Understanding the magnitude and extent of dispersal of individuals within a watershed, both historically and contemporary, is important for scientists and resource managers charged with protecting imperiled species, a task that is especially difficult in rivers (Dunham and Rieman 1999; Fausch et al. 2002). Traditionally, much fish population research has been conducted on a small (10 - 1000 m) reach scale or on a large (10^5 – 10^6 m), basin scale. However, many important life-history aspects of stream-dwelling fishes occur at an intermediate scale, in both temporal (5 – 50 yr) and spatial (1 – 100 km) terms. Dispersal of individuals at this scale can be difficult to detect with traditional sampling designs (Fausch et al. 2002), yet it is vital that research addressing metapopulation dynamics encompasses a range of habitats used by fish throughout their life history. The range of habitats at which many salmonids express their full life-history potential occur at this intermediate scale (Thurow et al. 1997), and this is the scale at which species management is most feasible and common (Fausch et al. 2002). At present, highly connected riverine systems and intact native fish assemblages are rare (Ricciardi and Rasmussen 1999; Dudgeon et al. 2006; Jelks et al. 2008). And, this loss of connectivity is especially significant in the Intermountain West, where dams and water withdrawals fragment river systems and fish populations. Compounding risks associated with isolation is the increased risk of extirpation due to small population size (Dunham et al. 1997; Cegelski et al. 2006; Williams et al. 2009). Thus, the importance of maintaining or restoring connectivity cannot be ignored if sustaining viable populations is a conservation goal.

The cutthroat trout (*Oncorhynchus clarkii*) has the widest distribution of any species of native trout in western North America (Behnke 1992), and is comprised of several subspecies that occupy the major river drainages and basins of the West, including the intermountain region. The Bonneville cutthroat trout (*O. c. utah*) is the only trout native to the Bonneville Basin, both named for ancient Lake Bonneville, the prehistoric glacial lake that once covered much of what is now western Utah. Owing to descriptions of its great abundance shortly after modern settlement (Cope and Yarrow 1875), coupled with subsequent reported declines in abundance (Tanner 1936), the Bonneville cutthroat trout was once thought to be extinct (Sigler and Miller 1963). Although knowledge of its distribution at that time was undoubtedly incomplete as a result of limited recent survey data, declines were real and attributed to such factors as habitat alteration and fragmentation, pollution, non-native species interactions, and over-harvest (Sigler and Miller 1963). Bonneville cutthroat trout presently occupy a variety of habitats from small streams to larger rivers and lakes that drain into the Bonneville Basin. As a result of continued threats to the subspecies and its habitat, the Bonneville cutthroat trout is designated by the State of Utah as a “conservation species” (UDWR 2005) managed under a formal conservation agreement intended to preclude the need for listing under the federal Endangered Species Act. Although a fluvial life history is no longer expressed in the majority of interior subspecies of cutthroat trout (Young 1995), largely due to habitat fragmentation that prevents fluvial fish from both accessing spawning areas and maintaining metapopulations through dispersal, recent studies have identified fluvial populations of Bonneville cutthroat trout in multiple drainages (e.g., Colyer et al. 2005).

The Weber River in northern Utah is somewhat unusual for the intermountain west in that it is still home to native and endemic Bonneville cutthroat trout and bluehead sucker (*Catostomus discobolus*), yet is highly regulated and connectivity has been significantly reduced due to barriers to movement and migration. Across their range, both species have declined broadly in abundance and distribution, likely in response to the combined effects of flow alteration, habitat loss and alteration, and the introduction of nonnative fishes. Despite the prevalence of these factors in the Weber R., both resident and fluvial Bonneville cutthroat trout as well as large, mature bluehead sucker were thought to be relatively common, highlighting the potential of this watershed for native fish conservation and restoration.

Goals, objectives, approach

The overall goal of this study was to identify the historical and contemporary importance of mainstem connectivity and tributaries to maintaining the population viability and persistence of these two species. To meet that goal, we used a multifaceted approach to describe the metapopulation structure and the importance of the tributaries in providing connectivity among sub-populations, at the watershed scale. Our specific objectives were to 1) identify source-sink populations, 2) determine the role and extent of barriers to movement, and 3) identify opportunities for conservation in the Weber River Basin. Our research will be applicable to developing effective conservation plans for native salmonids in this and other fragmented western rivers.

STUDY AREA

The Weber River, Utah, is a high gradient river with headwaters in the Uinta Mountains and a terminus in the Great Salt Lake, draining 6,413 km^2 with a mean daily discharge of 15.5 m^3/s. The study area encompasses the lower Weber River Sections 02, 03, and 04, between the cities of Ogden and Peterson, and six tributaries: Cottonwood Creek, Dry Creek, Gordon Creek, Jacobs Creek, Peterson Creek, and Strawberry Creek (Figure 1). In our study area, the Weber River is highly altered and stream flow is regulated by five upstream reservoirs and the Stoddard Diversion, which is capable of withdrawing 700 cfs (about 21 m^3/s) from the mainstem Weber River directly upstream from the study area.

The Weber River in the project area is fragmented by three mainstem diversion structures and at least seven barriers in the five tributaries with extant populations of Bonneville cutthroat trout (hereafter cutthroat trout), although the permeability of all potential barriers has not been firmly established. Tributary barriers in the study area are primarily culverts and diversion structures that impede fish movement in either an upstream or downstream direction seasonally and perhaps permanently.

Along with cutthroat trout and bluehead sucker, the river hosts more than a dozen species of fish including nonnative brown trout (*Salmo trutta*), nonnative rainbow trout (*Oncorhynchus mykiss*) and rainbow trout × cutthroat trout hybrids, nonnative common carp (*Cyprinus carpio*), mountain whitefish (*Prosopium williamsoni*), mountain sucker (*Catostomus platyrhynchus*), Utah sucker (*Catostomus ardens*), longnose dace (*Rhinichthys cataractae*), speckled dace (*Rhinichthys osculus*), mottled sculpin (*Cottus bairdii*), Paiute sculpin (*Cottus beldingii*), Utah chub (*Gila atraria*), and redside shiner (*Richardsonius balteatus*). Additional species are occasionally sampled in the study area, including nonnative yellow perch (*Perca flavescens*) and nonnative green sunfish (*Lepomis cyanellus*).

METHODS

Subpopulation structure and abundance

From 2011 to 2013, we collected fish using electrofishing (backpack, raft, and canoe-mounted units according to standard methods in Bonar et al. 2009), angling, and a picket weir. We recorded the total length (TL, mm), weight (body mass in g), and spawning condition, if known, of all captured cutthroat trout and bluehead sucker. We inserted a uniquely-numbered passive integrated transponder (PIT) tag (full-duplex, FDX; 134.2 kHz) into the peritoneal cavity of captured cutthroat trout and bluehead sucker (12-mm PIT tag for fish ≥ 120 mm TL; 23-mm PIT tag for most cutthroat trout ≥ 150 mm TL), and we clipped the adipose fin on tagged cutthroat trout to analyze PIT-tag loss. All fish were returned to slow-water habitat near individual capture locations. We geo-referenced targeted fish catch data using Global Positioning System (GPS) devices. In the mainstem Weber River, we also conducted a 2-pass mark-recapture population estimate of brown trout, a potential predator and competitor of cutthroat trout. We marked brown trout by clipping the caudal fin with a hole-punch.

Further, to obtain information on PIT-tagged fish, we opportunistically used passive instream arrays (PIA) consisting of PIT-tag antenna(s) anchored to the stream bottom at the mouth of tributaries to detect PIT-tagged fish moving into and out of tributaries. In 2012, we installed and operated PIAs in each of the following five tributaries: Cottonwood, Gordon, Jacobs, Peterson, and Strawberry creeks. In 2013, some streams had PIAs placed downstream and upstream of suspected fish barriers to determine the permeability of barriers as well as stream distance traveled within tributaries (Figure 1).

Abundance

We estimated trout abundance using multiple pass mark-recapture electrofishing in the mainstem Weber River and two-pass depletion electrofishing in some tributaries. In the mainstem Weber River, we calculated a Lincoln-Peterson population estimate (*see* Van Den Avyle 1993) for two-pass electrofishing sampling events and used a modified Schnabel method to estimate abundance (*see* Krebs 1999) for sampling events consisting of three and four electrofishing passes. When the total number of recaptures was < 50, we treated the Σr_t as a Poisson variable and used Appendix 2 of Ricker (1975) to obtain 95% confidence intervals. We calculated two-pass depletion abundance estimates and 95% confidence intervals using a modified Zippin formula (Zippin 1958).

Catch per unit effort

In the six primary tributaries and two mainstem sections (03 and 04), Utah Division of Wildlife Resources biologists conducted multiple single-pass raft electrofishing surveys to determine catch per unit effort (CPUE) as an index of abundance for cutthroat trout. We did this in order to make comparisons between the mainstem and tributary streams.

Movement

We used mark and recapture of PIT-tagged fish to describe magnitude and frequency of fish movement, habitat use, and distribution of target species. Using GPS units, we mapped the location of all potential mainstem and tributary barriers in the study area in 2011. We also measured velocity at select barriers.

To evaluate the success of a fish-passage channel that was constructed at the lowermost mainstem diversion barrier (lower limit of Section 03) in 2011, we installed and maintained a picket weir in the side-channel during 2011 (n = 1 month), 2012 (n = 6 months), and 2013 (n = 8 months). We quantified the number of all fish attempting to pass in either direction.

Survival

We estimated annual survival probabilities from encounter histories generated for each individual PIT-tagged fish using Program MARK (Cooch and White 2011). Encounters were from active marking and recapturing and passive detections at PIT-tag arrays (i.e., PIA). Because the data from arrays is continuously collected, we used the Barker model (Barker 1997) rather than a Cormack-Jolly-Seber (CJS) model to estimate survival. The Barker model is a re-parameterization of the CJS model that can accommodate continuously collected resight and recovery data between sampling occasions (Barker et al. 2004). There are 7 parameters in the Barker model (from Cooch and White 2011): S_i = the probability an animal alive at i is alive at i +1, p_i = the probability an animal at risk of capture at i is captured at i, r_i = the probability an animal that dies in interval i to i +1 is found dead and the band reported, R_i = the probability an animal that survives from i to i + 1 is resighted (i.e., alive) sometime between i and i +1, R'_i = the probability an animal that dies in i, i +1 without being found dead is resighted alive in i, i + 1 before it died, F_i = the probability an animal at risk of capture (i.e., on study area) at i is at risk of capture at i +1, and $F'i$ = the probability an animal not at risk of capture at i is at risk of capture at i + 1 (this differs from the definition in Barker, 1997). We did not evaluate model fit or estimate the over-dispersion parameter ($\hat{c}$) because, based on 10 bootstrap simulations, we calculated it would take well over a week and there is not a verified procedure for evaluating the fit of Barker Models (Cooch and White 2011).

The MARK input file consisted of individual records for each cutthroat trout and rainbow trout (including suspected hybrids) captured during mainstem or tributary sampling. In all, there were seven unequal encounter periods roughly corresponding to spawning (April-July 2011, 2012, and 2013), summer-autumn (August-October 2011 and 2012), and winter (November-March 2012 and 2013). A species code was designated for each individual based on identification (i.e., cutthroat trout or rainbow trout, including hybrids) by the sampling crew. A life-history code was assigned to each fish based on the size of the individual, where it was initially captured, and where it was subsequently recaptured or resighted; a "fluvial" fish was tagged in the Weber River and re-sampled in a tributary, tagged in tributary at greater than 300 mm TL, or tagged in tributary and re-sampled in another tributary regardless of size; an "unknown" individual was one that was tagged in the Weber River at less than 300 mm TL and never seen again or recaptured in the Weber River at less than 300 mm TL, tagged in a tributary at less than 300 mm TL and never seen again or only resighted in the same tributary; a fish was designated "unknown fluvial" if it was tagged in the Weber at greater than 300 mm TL and never seen again or only recaptured in the Weber River , trapped in the picket weir at the mouth of Weber River Canyon moving upstream at greater than 300 mm TL, or tagged in the Weber River at less than 300 mm TL and later recaptured in the Weber River at greater than 300 mm TL. The total length (mm) at tagging was included for each individual.

We developed a suite of models for two species (groups), three life-history expression groupings (groups), and time (three uneven intervals per year; *t* in model notation). We evaluated additive and multiplicative effects for *S*, *p*, *R*, *R'*, *F* and *F'*. We set r and R' as constant for all models to maintain parsimony and because these rates were extremely low (e.g., < 0.001). Our main goal was to estimate annual survival by species and life history expression and assess the impacts of a suite of individual. To keep the number of models from becoming too great, we used a two-phase approach in the model selection process. First, we used just species and life-history expression groupings for the model parameters to determine the best structure for the data. We then used the top model (or models if within 2 ΔAICc of top model) and added the individual covariates where appropriate (e.g., size of fish at tagging). We used Akaike's Information Criterion corrected for small sample size (AICc) and AICc compared using AICc (Lebreton et al. 1992; Burnham and Anderson 2002) and normalized AICc weights (Burnham and Anderson 2002). Models with the lowest AICc values were most supported by the data and generally, models < 2 AICc units of the best model were considered competing models.

Determining natal origin of cutthroat trout

Otolith microchemistry

To determine elemental levels of strontium, and likely natal-stream origins of cutthroat trout, we collected water samples in 2011 from each tributary at base-flow conditions. Water samples were analyzed at the Woods Hole Oceanographic Institute. In 2013, we had three additional water samples from two more tributaries (Dalton and Smith creeks) and the mainstem Weber River analyzed. Analysis of mass spectrometry from laser ablation of cutthroat trout otoliths allowed us to determine trace elemental composition (e. g., ^{87}Sr:^{86}Sr ratios) which can be an indicator of natal origin when compared to the isotopic signature of water samples from each tributary (*as per* Kalish 1989; Wells et al. 2003) and can also provide additional insight to contemporary movement patterns when coupled with mark-recapture movement analysis.

Genetic analysis of cutthroat trout

We collected tissue from an adipose fin and/or lower caudal fin between 2003 and 2011 from 212 individual Bonneville cutthroat trout representing the seven populations or stream reaches in the Weber River drainage (Figure 1). We placed tissues from individual fish in 1.5 mm sealable vials containing 95% ethanol. Processing and analyses were performed at the fish genetics lab at Brigham Young University (BYU; see Houston et al. 2013). Ultimately, a series of genes in the mitochondria (mtDNA) were sequenced and a series of microsatellite regions in the nuclear (nDNA) genome were genotyped. Analyses of genetic structure and variability included assessment of Hardy-Weinberg equilibrium, estimates of genetic distance using F_{ST} pairwise population statistics, and tests to assess whether potential sub-populations exhibited local genetic structure, had undergone genetic bottlenecks, or both.

RESULTS and DISCUSSION

Subpopulation structure and abundance

We tagged 1671 trout (including cutthroat trout, rainbow trout, and hybrids) from 2 June 2011 to 13 June 2013; we actively recaptured 234 fish (at least one time) and detected (i.e., resighted) 260 unique fish at PIAs at least once. Of the total number of trout tagged, 1630 were cutthroat trout (Table 1).

Size structure

Over the 3-yr study period, via electrofishing, we encountered age-0, young-of-year (about 40 – 60 mm TL) cutthroat trout in Peterson, Jacobs, and Strawberry creeks in 2011 only (Figures 2 – 8). However, we note that effort was greatest in 2011. In Peterson and Gordon creeks, there appeared to be five age classes of cutthroat trout sampled, and in Jacobs and Strawberry creeks there were likely five to six age classes (Figures 2, 5, and 6). In Cottonwood Creek, it appears there were only four age classes of cutthroat trout, as we never collected age-0 trout (Figure 3). In the mainstem Weber River, there are likely six to seven age classes of cutthroat trout (Figure 7).

Table 1. Number of cutthroat trout tagged in the Weber River and its tributaries by year. Stream length represents the distance from the Weber River confluence upstream to the uppermost sampling site.

	Year				
Stream section	2011	2012	2013	Total	Stream length (km)
Weber River, section 02	7	54	8	69	20.4
Weber River, section 03	184	28	22	234	4.4
Weber River, section 04	306	340	5	651	14.5
Strawberry Creek	71	11	22	104	2.9
Jacobs Creek	111	40	7	158	2.3
Gordon Creek	52	61	5	118	4.7
Cottonwood Creek	41	96	11	148	11.9
Peterson Creek	139	9	0	148	2.8
Total	911	639	80	1630	63.9

Abundance

In 2011, we estimated cutthroat trout abundance in two sections of the Weber River mainstem: sections 03 and 04 (Table 2). In Section 03 (0.5 km reach from the Rest Stop Dam to Scrambled Eggs and 1.3 km reach from the Power Plant to the diversion at the mouth of the canyon), we estimated 405 cutthroat trout (95% CI = 310 – 584) and in Section 04 (11.7 km reach from the Red Barn to the Rest Stop Dam), we estimated 877 (684 – 1124). In 2012, we conducted 2-pass surveys and estimated 139 (95% CI = 66 – 672) in Section 02 (19 km reach from U.S. Highway 89 to Marriott-Slaterville Diversion; Table 2), and 1296 (911 – 2069) cutthroat trout in Section 04 (9.5 km reach from the Red Barn to the Mountain Green bridge; Table 2). In 2012, we estimated there to be 175 (95% CI = 115 – 305) bluehead sucker in Section 02 of the Weber River mainstem (Table 3).

Catch per unit effort

We conducted electrofishing surveys from June - December 2011, March - October 2012, and March - June 2013. In general, across years, mean CPUE was highest in tributaries (combined tributary mean = 20 fish/hr) compared to mainstem Weber River (Section 03 and 04 mean = 8 fish/hr). Relative abundance (as CPUE) of cutthroat trout across the five tributaries ranged from 42 fish/hr (± 2 SE = 46) in Cottonwood Creek in 2012 to 10 fish/hr (± 7) in Cottonwood

Creek in 2011 (Figure 13). In the two mainstem sections, mean CPUE ranged from a low of 7 fish/hr (± 0.3) in Section 03 in 2013 up to 15 fish/hr (± 8) in Section 04 in 2011 and 15 fish/hr (± 4) Section 03 in 2012 (Figure 13).

Table 2. Population estimates (with 95% confidence intervals) of cutthroat trout in three mainstem sections of the Weber River, Utah, in 2011 and 2012.

Year and Weber River section	Distance	Number of passes	Dates of sampling	Population estimate (N hat)	95% confidence intervals
2011 Section 03	Combined 1.8 km of 4.4 km	2 and 3 (combined)	15 Nov, 17 Nov, 29 Nov, 14 Dec	405	310 – 584
2011 Section 04	11.7 km	4	20 Jul, 21 Jul, 26 Jul, 12 Aug	877	684 – 1124
2012 Section 02	Lower 19 km of 20 km reach	2	19 Jun, 21 Jun	139	66 – 672
2012 Section 04	9.5 km	2	8 Aug, 16 Oct	1296	911 – 2069

Table 3. Populations estimate (with 95% confidence intervals) of bluehead sucker in mainstem section 02 of the Weber River, Utah, in 2012.

Year and Weber River section	Distance	Number of passes	Dates of sampling	Population estimate (N hat)	95% confidence intervals
2012 Section 02	Lower 19 km of 20 km reach	2	19 Jun, 21 Jun	175	115 – 305

Movement

Barriers and weir trap

In 2011, we identified 10 potential barriers to fish movement in the study area: three in the mainstem Weber River, and seven potential tributary barriers (Figure 2). In tributaries, these were primarily culverts with steep drops, lack of a plunge pool, and velocity blocking fish passage. In the Weber River mainstem, there is (1) a diversion at the mouth of Weber Canyon,

(2) a set of hydraulic gates for power diversion in Weber Canyon, and (3) a dam and reservoir at the head of Weber Canyon that supply water to the power plant. Despite these barriers, in 2011, an extremely high water year, we captured large (> 400 mm TL) cutthroat trout in all tributaries (Figure 8), excluding Dry Creek.

In 2011, permeability analysis of the lowermost mainstem diversion structure (*see* Figure 1) indicated that no cutthroat trout or bluehead sucker were successful in utilizing the fish ladder installed in 2011. That year, during a month of weir operation from mid-June to mid-July, we captured four cutthroat trout attempting to move upstream, three of which were captured only days later attempting to move back downstream, and four additional cutthroat trout were captured attempting to move downstream through the fish ladder (Table 4). The fourth cutthroat trout that was released upstream of the weir trap was not trapped subsequently. Many native fish species and 10 brown trout were captured moving downstream through the fish ladder in 2011 (Table 4).

We operated the weir trap from 9 March to 1 September 2012, and captured three cutthroat trout and three bluehead sucker attempting to move upstream. In addition, brown trout and multiple native fishes were captured in the weir trap. Permeability analysis indicated that all species were successful in passing upstream via the fish ladder in 2012.

We also operated the weir trap from 13 March to 21 November 2013. During that period, we captured 13 cutthroat trout, including one recapture and 12 new cutthroat trout, all of which were moving upstream. Four bluehead sucker were captured moving upstream. Several other species, most of them native nongame fishes, were captured moving in both directions (Table 2). Five non-native fish species, including brown trout and rainbow trout, were trapped, most moving upstream through the fish ladder (Table 4).

The mainstem Weber River diversion structure at the mouth of Weber Canyon and the boundary of sections 02 and 03 functions periodically as a barrier, depending on discharge in the river and volume limitations of the bypass channel. Because 2011 flows were very high and sustained over a longer than normal period and since discharge capacity of the bypass channel is limited, the intake structure at the head of the channel required installation of a temporary deflector (i.e., a set of wooden planks placed to limit the amount of water entering the bypass channel) to avoid negative impacts to the integrity of the channel. As a result, a substantial vertical drop of four to five feet was created and no successful passage of any fish was verified during weir trap operations and associated sampling in 2011. Given this configuration, coupled with periodic breaches in the weir trap resulting from structural malfunctions that were observed in 2011, it is unlikely that the fourth cutthroat trout that attempted to move upstream actually achieved passage but instead evaded trapping while moving back downstream. In 2012 and 2013, passage was likely achieved as a result of lower flows that were more manageable for fish and allowed the bypass channel to remain unaltered. Data from the weir trap show that most of the fish using the ladder in 2011 were moving in the downstream direction, likely being pushed downstream by high flows, and most of the movement was in the upstream direction in 2013, a year of lower flows. Regardless, the diversion structure no longer acts as a permanent barrier, the bypass channel providing connectivity between those two sections of the Weber River (i.e., Section 02 is no longer a sink for fish moving or being flushed downstream across the diversion).

Table 4. Fish species captured in the picket weir moving through the fish ladder below the diversion at the mouth of the canyon, 2011-2013. Note: No downstream trap was deployed in 2012; the trapping period was not equal between years (i.e., one month in 2011, three months in 2012, and eight months in 2013).

	2011		2012	2013	
Fish species	Up	Down	Up	Up	Down
Bluehead sucker	0	0	3	4	0
Bonneville cutthroat trout	4	7	3	13	0
Brown trout	35	10	2	123	17
Common carp	0	0	0	1	0
Green sunfish	0	0	0	1	0
Longnose dace	2	272	7	88	25
Mountain sucker	14	25	36	189	24
Mountain whitefish	2	2	0	8	3
Rainbow trout	0	0	0	1	0
Redside shiner	2	85	1	133	34
Sculpin	0	11	0	14	35
Speckled dace	9	527	8	342	130
Utah sucker	0	0	0	10	5
Yellow perch	0	0	0	0	16

The hydraulic gates at the power plant in Weber River Canyon are yet unknown in terms of allowing upstream fish passage. However, the dam at the head of Weber River Canyon appears to only be a barrier when the gates are closed, and likely allowed passage to tagged cutthroat trout that were resighted in Jacobs, Cottonwood, and Peterson creeks in 2013, although the timeframe of passage is unknown. This dam would be a partial barrier, depending on operation of the gates and flow conditions. Incidentally, the cutthroat trout tagged in Section 03 that were detected in tributaries in 2013 moved up to 16.8 km, the distance from Devils Gate (Scrambled Eggs) to the upper antenna in Cottonwood Creek.

Passive detections of cutthroat trout at PIA

We operated PIAs in five primary tributaries in 2012 and 2013 (Table 5). PIT-tagged cutthroat trout classified as fluvial were detected (i.e., resighted) in each of the five tributaries at PIAs in both 2012 and 2013, except for Strawberry Creek in 2012, due to equipment malfunctions. Fluvial cutthroat trout detected in the tributaries came primarily from the Weber River Section 04, totaling 21 in 2012 and 156 in 2013. Seven cutthroat trout PIT tagged in Section 03 in 2011 downstream of the Rest Stop barrier delineating sections 03 and 04 (Figure 1) were detected in Cottonwood, Jacobs, or Peterson creeks in 2013. Other cutthroat trout resighted in the tributaries were tagged in that same tributary and were categorized as either fluvial or unknown, depending on length at tagging or whether they had been re-sampled elsewhere, as described in Methods.

The PIAs in Peterson Creek detected 67 unique PIT tags in 2013, 65 of which were associated with fluvial individuals, and 19 unique resights in 2012, 14 of them fluvial. Jacobs Creek had 65 unique PIT tags detected by its PIAs in 2013, 58 of which were fluvial, and 31 in 2012, 12 of them fluvial. There were 62 unique PIT tags, of which 47 were fluvial, resighted by PIAs in Cottonwood Creek in 2013 and five in 2012, four of them fluvial. The Gordon Creek PIAs logged nine unique PIT tags in 2013, six of them fluvial, and four in 2012, two of them fluvial, although some tag data in 2012 near the peak of the run were inadvertently deleted from the tag reader prior to data download; consequently, the total number of uniquely tagged cutthroat trout that actually utilized Gordon Creek in 2012 is unknown. The PIA in Strawberry Creek detected 15 unique PIT tags in 2013, 11 of them fluvial, and as noted previously, no data were successfully collected in 2012.

Some individuals were sampled or re-sampled in multiple tributaries in the same year. Each of 10 individual cutthroat trout sampled or re-sampled in more than one tributary in the same year had a link to Jacobs Creek, having been sampled in Jacobs Creek and then detected in another tributary later, or detected in Jacobs Creek after being sampled or resighted in another tributary. Five cutthroat trout were sampled/re-sampled in multiple tributaries in different years (e.g., tagged in a tributary in 2012 and re-sampled in a different tributary in 2013, or resighted in one tributary in 2012 and resighted in a different tributary in 2013).

Table 5. Cutthroat trout detections at PIAs during spring and summer 2012-2013. "Unknown" indicates we could not determine whether the trout was resident or fluvial.

Stream, PIA location	Dates of operation	Fluvial detections (resights)	"Unknown" detections (resights)
Cottonwood Creek, lower	4 May – 7 June 2012	4	1
	5 April – late June 2013	33	7
Cottonwood Creek, upper	19 April – late June 2013	38	14
Gordon Creek, lower	14 April – 11 July 2012	2	2
	11 March – late June 2013	4	1
Gordon Creek, upper	11 March – late June 2013	5	3
Jacobs Creek, lower	13 April – 17 August 2012	12	19
	6 March – late June 2013	57	7
Jacobs Creek, upper	19 April – late June 2013	42	1
Peterson Creek, lower	20 April – 7 June 2012	14	5
	6 March – late June 2013	62	2
Peterson Creek, upper	19 April – late June 2013	49	2
Strawberry Creek	5 May – 5 June 2012	0	0
	6 March – late June 2013	11	4

Patterns of movement within the four streams with multiple PIAs in 2013 varied from detections by only one PIA to detections by both PIAs, with movement in both directions. The PIAs in Jacobs Creek recorded 41 fluvial tags that were resighted by both PIAs, 40 of which hit the lower PIA then hit the upper PIA, in succession; the remainder was detected by the upper PIA, then the lower PIA. Of the 40 PIT-tagged fluvial cutthroat trout with the "lower-upper" pattern, 15 were subsequently detected again by the lower PIA (i.e., lower-upper-lower). In Peterson Creek, 46 fluvial tags were detected by both PIAs, 38 of them following the lower-upper pattern, with five of the 38 detected at the lower PIA again later. The PIAs in Cottonwood Creek picked up 24 tagged fluvial cutthroat trout, 23 of which exhibited the lower-upper pattern, with the remaining fluvial tag detected by the upper PIA, then the lower PIA. Only three of the 23 tags detected by the lower PIA then upper PIA were detected again later by the lower PIA. The Gordon Creek PIAs detected three fluvial cutthroat trout that hit both PIAs, two of them with a lower-upper movement pattern and one with the upper-lower pattern; no PIT tags followed the lower-upper-lower pattern of movement (however, there were probable issues with equipment function at the lower Gordon PIA, indicated by fluvial cutthroat trout detected by the upper PIA but not the lower).

The PIAs revealed heaviest use by tagged fish in Peterson, Jacobs, and Cottonwood creeks, which detected 67, 65, and 62 unique tags in the respective streams in 2013. The majority (88%) of the PIT tags resighted in those three streams were categorized as fluvial cutthroat trout, ranging from 76% fluvial in Cottonwood to 97% in Peterson. Although the antenna in Strawberry Creek resighted 15 tagged cutthroat trout, the amount of fluvial use is likely less than potential levels and may be reduced from former levels as the segment of the cutthroat trout population utilizing Strawberry Creek has likely dwindled based on lack of access to more than the lower 0.2 km of stream. Evidence that the Strawberry Creek PIA malfunctioned in 2013 included numerous undetected tags from two occasions of sampling upstream of the PIA but below the Interstate-84 culvert, a distance of less than 0.03 km; only five of 21 tags were resighted by the PIA, and at least three of the 21 vacated Strawberry Creek very soon after tagging because they were resighted in another tributary only two days later. The suspected malfunction of the PIA in lower Gordon Creek could explain the apparently suppressed numbers of fluvial cutthroat trout that utilized this tributary in 2013. However, a compounding factor is the late March 2014 discovery of a large, established (e.g., old cuttings, heavily silted on the upstream side), possibly impassable beaver dam just upstream of the confluence with the Weber River, which may limit fluvial fish from accessing the majority of Gordon Creek.

The use of multiple tributaries in the same year by several individuals seems to suggest that if a fish does not find what it is looking for in one tributary, it will seek out another tributary. As an example, three fish tagged in Strawberry Creek on 14 May 2013 in the pool directly below the interstate-highway culvert (i.e., the point at which upstream migration is impeded) were resighted two days later by the lower PIA in Jacobs Creek; all three were able to pass upstream beyond the suspected culvert barrier and were resighted by the upper Jacobs PIA. Several other cutthroat trout tagged in 2012 in the Weber River were resighted in 2013 at the lower PIA in one of the tributaries and subsequently resighted by both PIAs in a different tributary.

Data collected by the PIAs indicate that some of the suspected migration barriers are not complete barriers. Passage at some "barriers" likely depends on flow conditions, and other structures may only impede a portion of the fish attempting passage, depending on fish size or strength. The upper culvert in Jacobs Creek was suspected of being impassable due the cascading waterfall on the downstream end, but PIA data showed otherwise, with 42 of 65 PIT tags detected by the lower and upper PIAs in succession. The difference in mean length at tagging was 55 mm (lower) for those fish that were resighted by the lower PIA only, but without handling the fish, it is impossible to know length at resighting. Regardless, fish length is likely a factor in determining whether a structure is a complete or partial barrier or not a barrier at all. The PIAs above and below the irrigation diversion in lower Peterson Creek showed results similar to Jacobs Creek, with approximately two-thirds of the fish that hit the lower PIA also making it to the upper PIA, again suggesting that the Peterson Creek diversion is only a partial migration barrier. Without having a PIA above the irrigation diversion in Cottonwood Creek, assessment of barrier status was not possible; however, spot electrofishing just upstream produced one cutthroat trout approximately 400 mm in length, likely a fluvial fish that had successfully passed above the diversion. The distance up Cottonwood Creek from the confluence with the Weber River mainstem to the upper PIA (immediately downstream of the diversion) is approximately 11 km, the farthest of any of the PIAs in any of the tributaries, and 52 out of 62 tagged cutthroat trout were detected at the upper PIA in 2013, with 38 of the 52 classified as fluvial. Much like surmounting the culvert in Jacobs Creek, use of Cottonwood Creek is suggestive of the internal "drive" of fluvial Weber River cutthroat trout to return to natal spawning areas, given that the stream channel is essentially dry from the diversion to the Weber River following spring runoff, the fairly long distance to perennial flows, and the potential risk of becoming stranded in a dry channel following spawning. The bridge structure in Gordon Creek (lower barrier in Figure 1) is thought to be a nearly complete migration barrier, although electrofishing in 2011 produced one large, suspected fluvial cutthroat trout that may have breached the barrier; however, no PIA has been deployed above the structure to determine whether tagged fish are able to achieve passage. The tagged fish detected by the upper PIA in Gordon Creek that were recorded multiple days each had an average "stay" at the PIA of 12.7 days (range 4 – 27 days), suggesting the fish are not able to pass the barrier but are holding below the structure and probably making repeated attempts at passage. By comparison, the PIA below the Jacobs Creek culvert detected tagged fish for an average of 3.7 days before those fish were detected by the PIA upstream of the culvert. Coincidentally, tagged fish in Jacobs Creek that were detected only by the lower PIA and presumably were not able to achieve passage were at the lower PIA an average of four days. The Strawberry Creek culvert is suspected of being a complete barrier to upstream migration, as no large fish have been sampled upstream of the culvert and fish observed attempting to pass through the culvert have not succeeded, only swimming a short distance into the culvert before encountering a combination of swift (due to steep gradient, > 5% slope) and shallow (due to culvert width) flow conditions.

Bluehead sucker movement

Using information from six PIT tagged (in 2009), recaptured (one in 2009, five in 2012), and handled bluehead sucker, we determined movement of bluehead sucker in the mainstem Weber River (Table 6).

Table 6. Size, growth, and movement distance and direction of six PIT-tagged bluehead sucker in the Weber River, Utah.

Tagging date (2009)	Recapture date	Length (mm) at tagging	Length (mm) at recapture	Mass (g) at tagging	Mass (g) at recapture	Distance moved (km) and direction
13 Jan	8 Jul 2009	257	281	184	223	15 km downstream
8 July	19 Jun 2012	227	392	137	720	1.7 km upstream
13 July	18 Jun 2012	345	421	475	916	8.3 km downstream
13 July	19 Jun 2012	204	375	100	813	7.0 km upstream
22 July	19 Jun 2012	161	370	54	796	9.8 km upstream
22 July	19 Jun 2012	227	407	144	796	5.2 km upstream

Survival of cutthroat trout

We tagged 1671 trout (including cutthroat trout, rainbow trout, and hybrids) from 2 June 2011 to 13 June 2013; we actively recaptured 234 fish (at least one time) and detected (i.e., resighted) 260 unique fish at PIAs at least once.

We assembled three years of comprehensive mark-recapture data as input for a Barker comprehensive survival analysis. Data reconnaissance included: (1) Weber River sections 02, 03, and 04 and tributary PIT data 2011-2013; (2) 7 encounter periods - Apr-Jul 2011, Aug-Oct 2011, Nov 2011-Mar 2012, Apr-Jul 2012, Aug-Oct 2012, Nov 2012-Mar 2013, Apr-Jul 2013.

In our top models of survival, survival was constant with no differentiation among species groups or life-history groups *S*(.), active recapture probability varied with time *p*(t), resighting probability varied with group and time *R*(g*t), the probability that an animal stayed on site varied with time *F*(t), and the probability that an animal temporarily emigrated varied with time and group *F'*(g*t). The probability of resighting a known dead fish (*r*) and the probability that and animal dies without being found dead (*R'*) were both set as constants *a priori*.

Survival was high and 95 CI were very narrow indicating high confidence in this estimate (*S* = 84%, 95 CI = 81 - 86%; Figure 14). Recapture probability was unsurprisingly highest in summer (*p* = 0.30 [95% CI = 0.16 - 0.47]; August – October), when active sampling occurred, and was generally low in April – July and November – March. The probability of being resighted (detected on a PIA) was greatest in spring and early summer (*R* = 0.15 [95% CI = 0.09 - 0.26]) and was much lower in the other two later time periods. The probability of site fidelity was similar across the latter two time periods where the parameters could be estimated (*F* = 0.14 - 0.25). The probability of temporary emigration was high and variable overall, presumably due to fish migrating to and from spawning grounds. The probability of resighting a known dead (r) and the probability that and animal dies without being found dead (R') were both estimated to be extremely low (< 0.01), and R' could not be estimated with confidence.

Determining natal origin of cutthroat trout

Otolith microchemistry

Strontium ratios in water samples taken from the mainstem Weber River and eight tributaries varied between 0.709 and 0.728 (Table 7, Figure 15). Five of the nine stream-water-source strontium ratios were quite distinct allowing us to distinguish these tributaries from others. However, laser ablation of otoliths demonstrated that cutthroat trout were also utilizing and inhabiting streams or stream locations from which we do not have water samples; that is, water samples with strontium ratios around 0.733 – 0.741 and 0.720 – 0.730 (Figure 15).

Analysis of strontium elemental signature on cutthroat trout otoliths indicates that cutthroat trout captured in the Weber River originated from or make extensive use of tributary streams. Using laser ablation of otoliths, we recorded strontium levels across transects on the otoliths to determine the elemental "history" or signatures from streams used by cutthroat trout. Cutthroat trout used in this analysis ranged from 332 – 430 mm TL and were collected in 2011 (Table 8). Of the five ablated "mainstem cutthroat trout derived" otoliths, analyses indicate that all five cutthroat trout originated from or visited streams outside the mainstem (Figure 16).

Table 7. Select study streams (sorted by ^{87}Sr to ^{86}Sr ratios) sampled to determine ^{87}Sr to ^{86}Sr ratios, and the period and rock type relating to the given elemental signature. A "—" indicates information not available.

Stream	$^{87}Sr : ^{86}Sr$ ratio	Geologic period and rock type
Weber River	0.709932	—
Dry Creek	0.710864	Oligocene period: Volcanic rocks, undivided
Dalton Creek	0.716528	—
Gordon Creek	0.711766	Oligocene period: Sliver City Monzonite / Sunrise Peak Monzonite Por. / Swanson Quartz Monzonite
Cottonwood Creek	0.711947	Cambrian period: Tintic Quartzite
Peterson Creek	0.712186	Cambrian period: unsorted
Smith Creek	0.713074	—
Jacobs Creek	0.716528	Proterozoic period: Basalts; Big Cottonwood Formation
Strawberry Creek	0.728060	Quaternary period: Glacial deposits

Table 8. Sizes of Bonneville cutthroat trout from two mainstem sections of the Weber River, Utah, used for strontium analysis of otoliths.

Weber River section	Fish source code	Total length (mm)	Body mass (g)
Section 03	W1	361	429
Section 03	W2	332	358
Section 04	W4	396	556
Section 04	W5	390	523
Section 04	W6	430	660

Strontium ratios in otoliths from cutthroat trout harvested in the tributaries indicate that these tributary-derived fish also utilize (i.e., visit or use) other tributaries, some tributaries from which we have no elemental chemistry information. For example, a 181 mm (body mass = 66 g) cutthroat trout captured in Strawberry Creek originated from a yet-to-be determined source, moved to a yet-to-be-determined stream, and was finally captured in Strawberry Creek on 17 May 2012 (Figure 17). A 207 mm (94 g) cutthroat trout taken from Jacobs Creek on 15 May 2012 had originated from a yet-to-be-determined source (Figure 17). In contrast, a 156 mm (43 g) cutthroat trout captured in Cottonwood Creek on 22 May 2012, originated and stayed in Cottonwood Creek (Figure 17).

Five ablated "mainstem" otoliths showed great changes in strontium ratios across the otolith transect, indicating movement and use of tributary streams. As one prime example of multiple stream use, cutthroat trout W5 (390 mm) likely originated from Jacobs Creek, may have spent time in Smith Creek, moved through the mainstem Weber River to another yet-to-be-determined tributary, may have ventured into Smith and Jacobs creeks again, then ultimately was captured in the Weber River mainstem, Section 03, on 30 May 2012 (Figures 15 and 16). Cutthroat trout W2 (captured in the Weber River at 332 mm) likely originated in Smith Creek or Peterson Creek, spent time in the mainstem, and may have spent time in Cottonwood Creek or Gordon Creek (Figure 16).

Genetic analysis of cutthroat trout

DNA sequencing resulted in a total of 6,279 base pairs of mtDNA from 212 individuals, while microsatellite loci (nDNA) were also successfully amplified. The number of mtDNA haplotypes in the seven populations (i.e., stream reaches) ranged from 1 to 9 and only the Weber River and Peterson Creek contained haplotypes of Yellowstone cutthroat trout (*O. c. bouvieri*) and/or non-native rainbow trout (*O. mykiss*; Table 9). In the nDNA analyses, each population (stream reach) contained at least one locus that was not in Hardy-Weinberg equilibrium, and three had multiple loci that were not in equilibrium. The F_{ST} pairwise comparisons that were not statistically significant after Bonnferroni corrections were (1) Cottonwood Creek and the Weber River, (2) Peterson Creek and the Weber River, (3) Jacobs Creek and the Weber River, and (4) Jacobs Creek and Peterson Creek (Houston et al. 2013). Further, in their report, Houston et al. (2013) emphasized two points: (1) the introgression of Yellowstone cutthroat trout and rainbow trout influence in the Weber River and Peterson Creek is 6 – 17% but the other stream population samples are native cutthroat trout consisting of Bonneville cutthroat trout and Bear River cutthroat trout (lentic *O. c. utah*), and (2) the bottleneck tests found that the populations were moderately bottlenecked.

The cutthroat trout in the Weber River are unique compared with other Bonneville Basin drainages in that they exhibit native haplotypes from both Bonneville cutthroat trout and Bear River cutthroat trout (Houston et al. 2013). The populations in the study tributaries exhibited different haplotype frequencies between the two genetic lineages (Table 9), indicating that these populations have evolved on slightly different evolutionary paths. The presence of only native cutthroat trout haplotypes in Gordon and Strawberry creeks was not surprising as the genetic sample for both of these populations was collected upstream from a known barrier. In addition, only a single native haplotype of the Bear River strain, and consequently the dominant mtDNA haplotype in all seven populations (Table 9), was observed in the headwaters of Cottonwood Creek; this portion of the stream may be isolated by stream distance as this sample was collected 23 km upstream from the confluence with the Weber River.

We suspected that the remaining three genetic samples collected from Jacobs Creek, Peterson Creek, and the middle reaches of Cottonwood Creek would demonstrate consistencies with the genetic makeup of the Weber River population, since PIA data has demonstrated that barriers in these streams did not completely exclude fluvial Bonneville cutthroat trout. The difference in native haplotype frequencies between the two samples collected in Cottonwood Creek demonstrate that fluvial cutthroat trout from the Weber River have contributed genetically to the population in the middle reach, but apparently only contributing native haplotypes. Based on mtDNA, the presence of only one haplotype (the dominant Bear River haplotype) in Jacobs Creek suggests the Bonneville cutthroat trout in this tributary do not fully mix with the mainstem Weber River population. PIA data, however, demonstrated that Jacobs Creek is an important spawning tributary for Weber River fluvial Bonneville cutthroat trout. The genetic data suggest that cutthroat trout with the most dominant native haplotype still use Jacobs Creek extensively, while mixing with cutthroat trout that harbor genetic material representative of other subspecies is apparently limited. It is possible that the genetic sample from Jacobs Creek represented a resident population, rather than fluvial, as the total length of fin-clipped fish ranged from 53 – 191 mm (mean = 92 mm), and the samples were collected from just upstream of the upper culvert (the "barrier" between the 2013 antenna sites), upstream roughly 2 km (i.e., an area that is accessible to fluvial cutthroat trout). Further, a fluvial fish PIT tagged in the Weber River and identified by phenotype as a cutthroat-rainbow trout hybrid was resighted by both Jacobs Creek PIAs in 2013, suggesting that there are fish contributing (or attempting to contribute) non-native genetic material in upper Jacobs Creek. The genetic sample collected from Peterson Creek exhibited the greatest amount of mtDNA diversity, containing nine haplotypes, including Yellowstone cutthroat trout and rainbow trout. The genetic data are supported by the PIA data, which showed that Peterson Creek was utilized by more fluvial fish than any other tributary; incidentally, of all of the tributaries studied, fluvial fish are least impeded in Peterson Creek.

Table 9. Mitochondrial DNA characterization of the genetic composition of seven cutthroat trout populations in the Weber River, Utah. Hapoltypes are abbreviated as follows: Bear River cutthroat trout (BRCT), Bonneville cutthroat trout (BCT), Yellowstone cutthroat trout (YCT), and rainbow trout (RBT). Modified from Houston et al. (2013).

Stream location	Haplotype	n
Weber River	BRCT	25
	BRCT.1	1
	YCT	1
	YCT.2	1
	BCT	2
Cottonwood Creek, headwaters	BRCT	30
Cottonwood Creek, middle	BRCT	18
	BRCT.1	3
	BCT	9
Jacobs Creek	BRCT	30
Peterson Creek	BRCT	19
	BRCT.1	1
	BRCT.2	1
	BCT	1
	BCT.1	1
	BCT.2	1
	BCT.3	1
	YCT	3
	RBT	2
Gordon Creek	BRCT	28
	BCT	2
Strawberry Creek	BRCT	26
	BRCT.1	4

The stocking history of non-native *Oncorhynchus* spp. in the Weber River has been extensive with more than 12 million rainbow trout of various sizes being stocked in the Weber River directly in the study reach or in adjacent reaches since 1941, which were the earliest stocking records available. The last stocking of fertile rainbow trout was in 2001. The extensive stocking history of rainbow trout explains the presence of rainbow trout haplotypes in Peterson Creek, and while rainbow trout haplotypes were not detected in the genetic sample collected from the Weber River, some fish exhibiting phenotypic characteristics of both rainbow trout and Bonneville cutthroat trout were sampled in the Weber River during the study. Approximately 500,000 nonnative cutthroat trout from a Utah brood source were stocked in the Weber River since 1941. This brood was a combination of Yellowstone cutthroat trout, Colorado River cutthroat trout, and rainbow trout. However, these stockings likely did not contribute to introgression in the Weber River population, because no Colorado River cutthroat trout haplotypes were observed in any stream (Table 9). The Yellowstone cutthroat trout introgression observed in the Weber River and Peterson Creek populations most likely resulted from the stocking of 100,000 (range of 93 - 180 mm TL) Snake River cutthroat trout between 1988 and 1998 from the Jones Hole National Fish Hatchery. These fish originated from Wyoming and were originally produced in the Jackson National Fish hatchery and the State of Wyoming Auburn Hatchery. The genetics lab at BYU has demonstrated that Yellowstone cutthroat trout are more closely related to Bear River cutthroat trout than they are to Bonneville cutthroat trout (Houston et al. 2013). While the presence of Yellowstone cutthroat trout haplotypes in the Weber River are likely due to past stocking events, Houston et al. (2013) hypothesized that there is a chance they are native to the Weber River. Houston et al. (2013) did find that statistically significant F_{st} values for most of the population pairwise comparisons indicate a high degree of isolation among the populations. This finding was concordant with the bottleneck analysis which demonstrated that due to lack of gene flow, the populations had experienced bottlenecks.

REFERENCES

Ardren, W. R., P.W. DeHaan, C.T. Smith, E.B. Taylor, R. Leary, C.C. Kozfkay, L. Godfrey, M. Diggs, W. Fredenberg, J. Chan, C.W. Kilpatrick, M.P. Small, and D.K. Hawkins. 2011. Genetic structure, evolutionary history, and conservation units of bull trout in the coterminous United States. Transactions of the American Fisheries Society 140:506-525

Barker, R. 1992. Effect of heterogeneous survival on bird-banding model confidence interval coverage rates. Journal of Wildlife Management 56:111-116.

Barker, R. J. 1997. Joint modeling of live-recapture, tag-resight, and tag-recovery data. Biometrics 53:666-677.

Barker, R. J., K. P. Burnham, and G. C. White. 2004. Encounter history modeling of joint mark-recapture, tag-resighting and tag-recovery data under temporary emigration. Statistica Sinica 14:1037-1055.

Behnke, R. J. 1992. Native trout of western North America. American Fisheries Society, Monograph 6, Bethesda, Maryland.

Bernard, D. R., and E. K. Israelsen. 1982. Inter-and intra-stream migration of cutthroat trout (*Salmo clarkii*) in Spawn Creek, a tributary of the Logan River, Utah. Northwest Science 56:148-158

Bonar, S., W. Hubert, and D. Willis, editors. 2009. Standard methods for sampling North American freshwater fishes. American Fisheries Society, Bethesda, Maryland.

Bowerman, T. 2013. A multi-scale investigation of factors limiting bull trout viability. Doctoral dissertation. Utah State University, Logan, Utah.

Budy, P., G. P. Thiede, and P. McHugh. 2007. Quantification of the vital rates, abundance, and status of a critical, endemic population of Bonneville cutthroat trout. North American Journal of Fisheries Management 27:593-604.

Budy, P., S. Wood, and B. Roper. 2012. A study of the spawning ecology and early life history of Bonneville cutthroat trout. North American Journal of Fisheries Management 32:436-449.

Burnham, K.P., and D.R. Anderson. 2002. Model selection and multimodel inference. Second edition. Springer-Verlag, New York, New York, USA.

Carlson, A. J., and F. J. Rahel. 2010. Annual intrabasin movement and mortality of adult Bonneville cutthroat trout among complementary riverine habitats. Transactions of the American Fisheries Society 139:1360-1371.

Cegelski, C.C., M.R. Campbell, K.A. Meyer, and M.S. Powell. 2006. Multiscale genetic structure of Yellowstone cutthroat trout in the upper Snake River basin. Transactions of the American Fisheries Society 135:711-726.

Chart, T.E., and E.P. Bergersen. 1992. Impact of mainstream impoundment on the distribution and movements of the resident flannelmouth sucker (Catostomidae: *Catostomus latipinnis*) population in the White River, Colorado. The Southwestern Naturalist 37:9-15.

Colyer, W.T., J.L. Kershner, and R.H. Hilderbrand. 2005. Movements of fluvial Bonneville cutthroat trout in the Thomas Fork of the Bear River, Idaho-Wyoming. North American Journal of Fisheries Management 25:954-963.

Cooch, E., and G. White. 2011. Program MARK: A gentle introduction. (10th edition, but constantly updated). Available online in PDF format at: *http://www.phidot.org/software/mark/docs/book/*

Cooper, A.B., and M. Mangel. 1999. The dangers of ignoring metapopulation structure for the conservation of salmonids. Fishery Bulletin 97:213-226.

Cope, E.D., and H.C. Yarrow. 1875. Report upon the collections of fishes made in portions of Nevada, Utah, California, Colorado, New Mexico, and Arizona, during the years 1871, 1872, 1873, and 1874. Report on the Geographic and Geologic Exploration and Survey West of the 100th Meridian (Wheeler Survey) 5(Zoology): 635-703.

Dudgeon, D., A. H. Arthington, M. O. Gessner, Z.-I. Kawabata, D. J. Knowler, C. Lévêque, R. J. Naiman, A.-H. Prieur-Richard, D. Soto, M. L. J. Stiassny, and C. A. Sullivan. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81:163-182.

Dunham, J.B., and B.E. Rieman. 1999. Metapopulation structure of bull trout: influences of physical, biotic, and geometrical landscape characteristics. Ecological Applications 9:642-655.

Dunham, J.B., G.L. Vinyard, and B.E. Rieman. 1997. Habitat fragmentation and extinction risk of Lahontan cutthroat trout. North American Journal of Fisheries Management 17:1126-1133.

Fagan, W.F. 2002. Connectivity, fragmentation, and extinction risk in dendritic metapopulations. Ecology 83:3243-3249.

Fausch, K. D., B. E. Rieman, M. K. Young, and J. B. Dunham. 2006. Strategies for conserving native salmonid populations at risk from nonnative fish invasions: tradeoffs in using barriers to upstream movement. General technical report RMS-GTR-174. U.S. Department of Agriculture Forest Service, Fort Collins, Colorado.

Fausch, K. D., C. E. Torgersen, C. V. Baxter, and H. W. Li. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. Bioscience 52:483-498.

Fullerton, A. H., S. T. Lindley, G. R. Pess, B. E. Feist, E. A. Steel, and P. McElhany. 2011. Human influence on the spatial structure of threatened Pacific salmon metapopulations. Conservation Biology 25:932-944.

Godiksen, J. A., M. Power, R. Borgstrom, J. B. Dempson, and M. A. Svenning. 2012. Thermal habitat use and juvenile growth of Svalbard Arctic charr: evidence from otolith stable oxygen isotope analyses. Ecology of Freshwater Fish 21:134-144.

Hanski, I., and D. Simberloff. 1997. The metapopulation approach, its history, conceptual domain, and application to conservation. Pages 1-26 *in* I. Hanski and M. E. Gilpin, editors. Metapopulation biology: ecology, genetics, and evolution. Academic Press, San Diego, California.

Haro, A., T. Castro-Santos, J. Noreika, and M. Odeh. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through velocity barriers. Canadian Journal of Fisheries and Aquatic Sciences 61:1590-1601.

Hess, J. E., A. P. Matala, and S. R. Narum. 2011. Comparison of SNPs and microsatellites for fine-scale application of genetic stock identification of Chinook salmon in the Columbia River Basin. Molecular Ecology Resources 11(suppl. 1):137-149.

Hilderbrand, R. H. 2003. The roles of carrying capacity, immigration, and population synchrony on persistence of stream-resident cutthroat trout. Biological Conservation 110:257-266.

Houston, D. D., R. P. Evans, and D. K. Shiozawa. 2013. Genetic characterization of seven cutthroat trout populations in the Weber River drainage using mtDNA and microsatellites. Brigham Young University report to the Utah Division of Wildlife Resources, Salt Lake City, Utah.

Jelks, H.L., S.J. Walsh, N.M. Burkhead, S. Contreras-Balderas, E. Diaz-Pardo, D.A. Hendrickson, J. Lyons, N.E. Mandrak, F. McCormick, J.S. Nelson, S.P. Platania, B.A. Porter, C.B. Renaud, J.J. Schmitter-Soto, E.B. Taylor, and M.L. Warren Jr. 2008. Conservation status of imperiled North American freshwater and diadromous fishes. Fisheries 33:372–386.

Kalish, J. M. 1989. Otolith microchemistry: validation of the effects of physiology, age and environment on otolith composition. Journal of Experimental Marine Biology and Ecology 132:151-178.

Krebs, C.J. 1999. Ecological methodology. Harper & Row, New York, New York.

Lamphere, B. A., and J. J. Blum. 2012. Genetic estimates of population structure and dispersal in a benthic stream fish. Ecology of Freshwater Fish 21:75-86.

Lebreton, J. D., K. P. Burnham, J. Clobert, and D. R. Anderson. 1992. Modeling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecological Monographs 62:67-118.

Leidy, R.A., and P.B. Moyle. 1998. Conservation status of the world's fish fauna: an overview. Pages 187–227 *in* Fiedler P.L., and P.M. Kareiva, eds. Conservation Biology. 2nd edition. New York: Chapman and Hall.

Lenhardt, M., Jaric, I., Kalauzi, A., & Cvijanovic, G. 2006. Assessment of extinction risk and reasons for decline in sturgeon. Biodiversity and Conservation 15(6): 1967-1976.

Lentsch, L., Y. Converse, and J. Perkins. 1997. Conservation agreement and strategy for Bonneville cutthroat trout (*Oncorhynchus clarkii utah*) in the state of Utah. Utah Division of Wildlife Resources, Publication 97-19, Salt Lake City, Utah.

Levins, R. 1969. Some demographic and genetic consequences of environmental heterogeneity for biological control. Bulletin of the Entomological Society of America, 15:237-240.

McHugh, P., and P. Budy. 2005. An experimental evaluation of competitive and thermal effects on brown trout (*Salmo trutta*) and Bonneville cutthroat trout (*Oncorhynchus clarkii utah*) performance along an altitudinal gradient. Canadian Journal of Fisheries and Aquatic Science 62:2784-2795.

McHugh, P., and P. Budy. 2006. Experimental effects of nonnative brown trout on the individual- and population level performance of native Bonneville cutthroat trout. Transactions of the American Fisheries Society 135:1441-1455.

Morita, K., and S. Yamamoto. 2002. Effects of habitat fragmentation by damming on the persistence of stream-dwelling charr populations. Conservation Biology 16:1318-1323.

Muhlfeld, C. C., and B. Marotz. 2005. Seasonal movement and habitat use by sub-adult bull trout in the upper Flathead River system, Montana. North American Journal of Fisheries Management 25:797-810.

Neville, H. M., J. B. Dunham, and M. M. Peacock. 2006. Landscape attributes and life history variability shape genetic structure of trout populations in a stream network. Landscape Ecology 21:901-916.

Nyce, L. G., L. Eby, C. G. Clancy, S. Painter, and R. F. Leary. 2013. Genetic population structure of bull trout in the East Fork Bitterroot River drainage, Montana. North American Journal of Fisheries Management 33:432-445.

Osmundson, D. B. 2002. Population dynamics of Colorado pikeminnow in the upper Colorado River. Final Report. U.S. Fish and Wildlife Service, Grand Junction, Colorado.

Peterson, D. P., and K. D. Fausch. 2003. Dispersal of brook trout promotes invasion success and replacement of native cutthroat trout. Canadian Journal of Fisheries and Aquatic Sciences 60:1502-1516.

Power, G. 2002. Charrs, glaciations, and seasonal ice. Environmental Biology of Fishes 64:17-35.

Powers, P. D., and J. F. Osborn. 1985. Analysis of barriers to upstream fish migration. BPA Fisheries Project. Project 82-14. Final Report, Part 4. Bonneville Power Administration, Portland, Oregon.

Pracheil, B. M., P. B. McIntyre, and J. D. Lyons. 2013. Enhancing conservation of large-river biodiversity by accounting for tributaries. Frontiers in Ecology and the Environment 11:124-128.

Pringle, C. P., M. C. Freeman, and B. J. Freeman. 2000. Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. BioScience 50:807-823.

Ricciardi, A., and J. B. Rasmussen. 1999. Extinction rates of North American freshwater fauna. Conservation Biology 13:1220-1222.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Fisheries Research Board of Canada, Bulletin 191.

Rieman, B. E., and J. B. Dunham. 2000. Metapopulations and salmonids: a synthesis of life history patterns and empirical observations. Ecology of Freshwater Fish 9:515-564.

Rieman, B. E. and J. D. McIntyre. ∟1993. Demographic and habitat requirements for conservation of bull trout. U. S. Forest Service, General Technical Report INT-302, Ogden, Utah.

Schrank, A. J., and F. J. Rahel. 2006. Factors influencing summer movement patterns of Bonneville cutthroat trout (*Oncorhynchus clarkii utah*). Canadian Journal of Fisheries and Aquatic Sciences 63:660-669.

Schlosser, I.J., and P.L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Pages 392-401 *in* J. L. Nielsen, editor. Evolution and the aquatic ecosystem: defining unique units in population conservation. American Fisheries Society Symposium 17. Bethesda, Maryland.

Sigler, W.F., and R.R. Miller. 1963. Fishes of Utah. Utah Department of Fish and Game, Salt Lake City, Utah.

Stacey, P.B., V.A. Johnson, and M.L. Taper. 1997. Migration within metapopulations: the impact upon local population dynamics. Pages 267-291 *in* Metapopulation Biology: Ecology, Genetics and Evolution. I. Hanski and M.E. Gilpin, editors. Academic Press, New York.

Tanner, V.M. 1936. A study of the fishes of Utah. Utah Academy of Science, Arts, Letters. 13: 155-183.

Thurow, R. F., D. C. Lee, and B. E. Rieman. 1997. Distribution and status of seven native salmonids in the interior Columbia River basin and portions of the Klamath River and Great basins. North American Journal of Fisheries Management 17:1094–1110.

Tsuboi, J., E. Shinsuke, and K. Morita. 2010. Habitat fragmentation by damming threatens coexistence of stream-dwelling charr and salmon in the Fuji River, Japan. Hydrobiologia 650:223-232

Utah Division of Wildlife Resources. 2005. Utah Comprehensive Wildlife Conservation Strategy. Utah Department of Natural Resources, Division of Wildlife Resources, Publication No. 05-19, Salt Lake City, Utah.

Van Den Avyle, M.J., and R.S. Hayward. 1993. Dynamics of exploited fish populations. Pages 127-166 *in* C.C. Kohler and W.A. Hubert, editors. Inland fisheries management in North America, 2nd edition. American Fisheries Society, Bethesda, Maryland.

Vanicek, C.D., R.H. Kramer, and D.R. Franklin. 1970. Distribution of Green River fishes in Utah and Colorado following closure of Flaming Gorge Dam. The Southwestern Naturalist 14(3):297-315.

Vitousek, P.M., H.A. Mooney, J. Lubchenco, and J.M. Melillo. 1997. Human domination of Earth's ecosystems. Science 277:494-499.

Ward, J.V., and J.A. Stanford. 1983. The serial discontinuity concept of lotic systems. Pages 29-42 *in* T.D.Fontaine, S. M. Bartell, editors. Dynamics of lotic ecosystems. Ann Arbor Science. Ann Arbor, Michigan.

Wells, B.K., B.E. Rieman, J.L. Clayton, D.L. Horan, and C.M. Jones. 2003. Relationships between water, otolith, and scale chemistries of westslope cutthroat trout from the Coeur d'Alene River, Idaho: the potential application of hard-part chemistry to describe movements in freshwater. Transactions of the American Fisheries Society 132:409-424.

White, G.C., and K.P. Burnham. 1999. Program MARK: Survival estimation from populations of marked animals. Bird Study 46 Supplement, 120-138.

Wiens, J. A. 2002. Riverine landscapes: taking landscape ecology into the water. Freshwater Biology 47:501-515.

Williams J. E., A. L. Haak, H. M. Neville, and W. T. Colyer. 2009. Potential consequences of climate change to persistence of cutthroat trout populations. North American Journal of Fisheries Management 29:533-548.

Winans, G.A., M.M. Paquin, D.M. Van Doornik, B.M. Baker, P. Thornton, D. Rawling, A. Marshall, P. Moran, and S. Kalinowski. 2004. Genetic stock identification of steelhead in the Columbia River Basin: an evaluation of different molecular markers. North American Journal of Fisheries Management 24:672-685.

Young, M.K. 1995. Conservation assessment for inland cutthroat trout. U.S. Forest Service, General Technical Report RM-GTR-256, Fort Collins, Colorado.

Zippin, C. 1958. The removal method of population estimation. Journal of Wildlife Management 22:82-90.

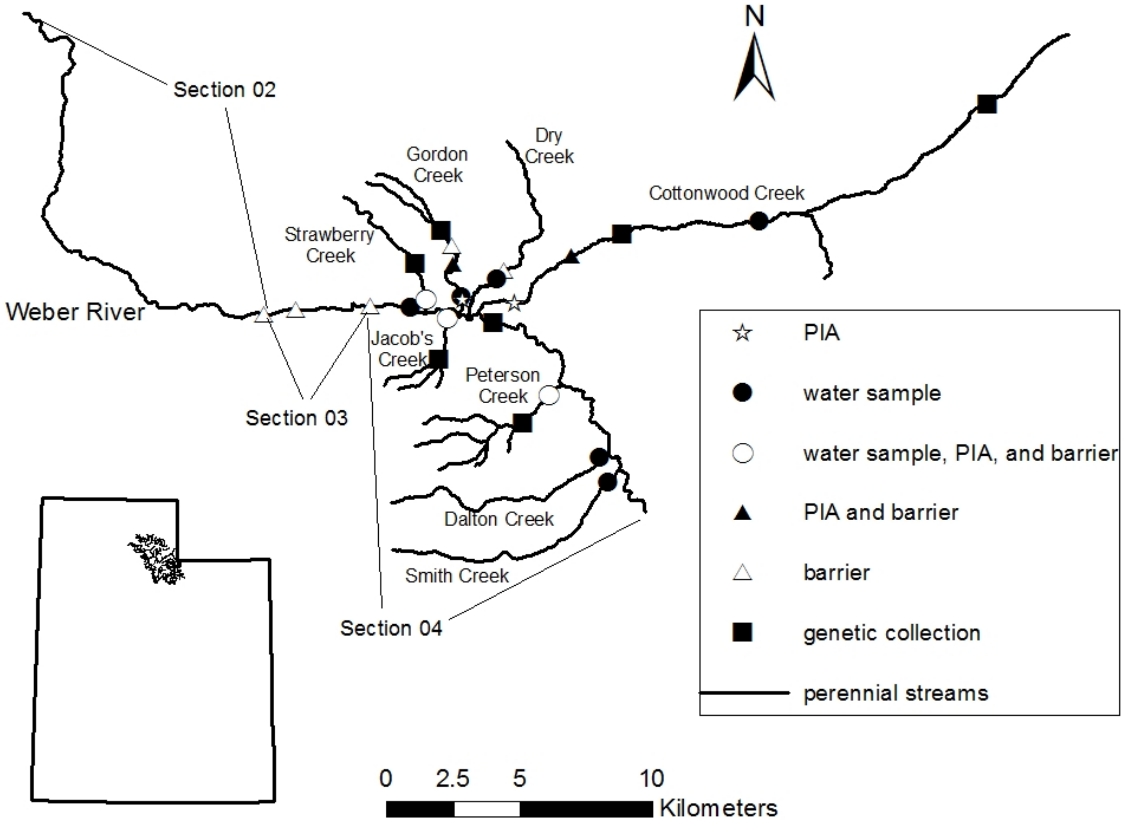


Figure 1. Map of the study area showing barriers to upstream movement in the mainstem Weber River and tributaries, water sample locations, genetic tissue sampling locations, and PIA locations.

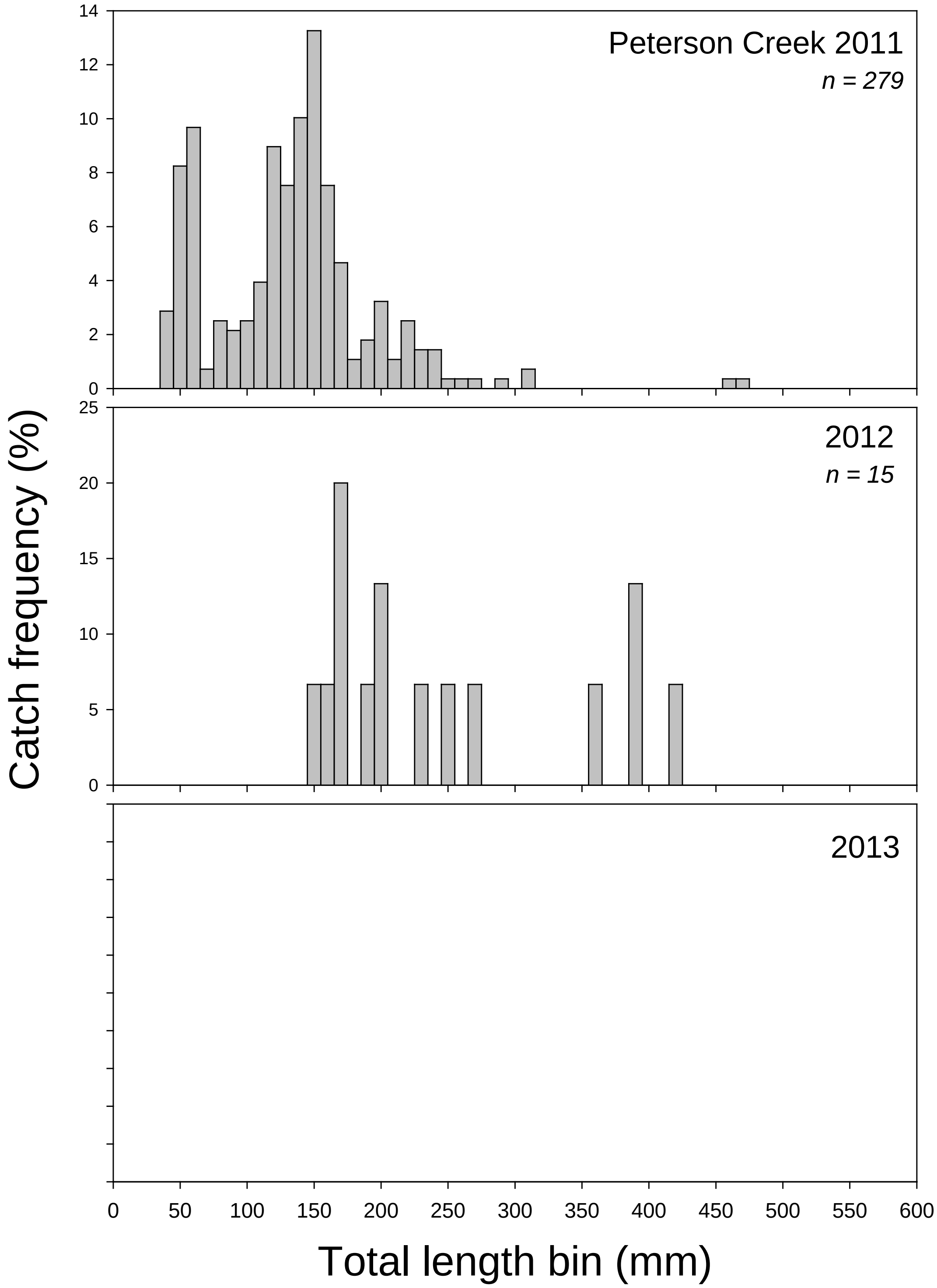


Figure 2. Length-frequency (%) histograms of cutthroat trout catch by year in Peterson Creek, a tributary to the Weber River, Utah. Sample size (n) is given.

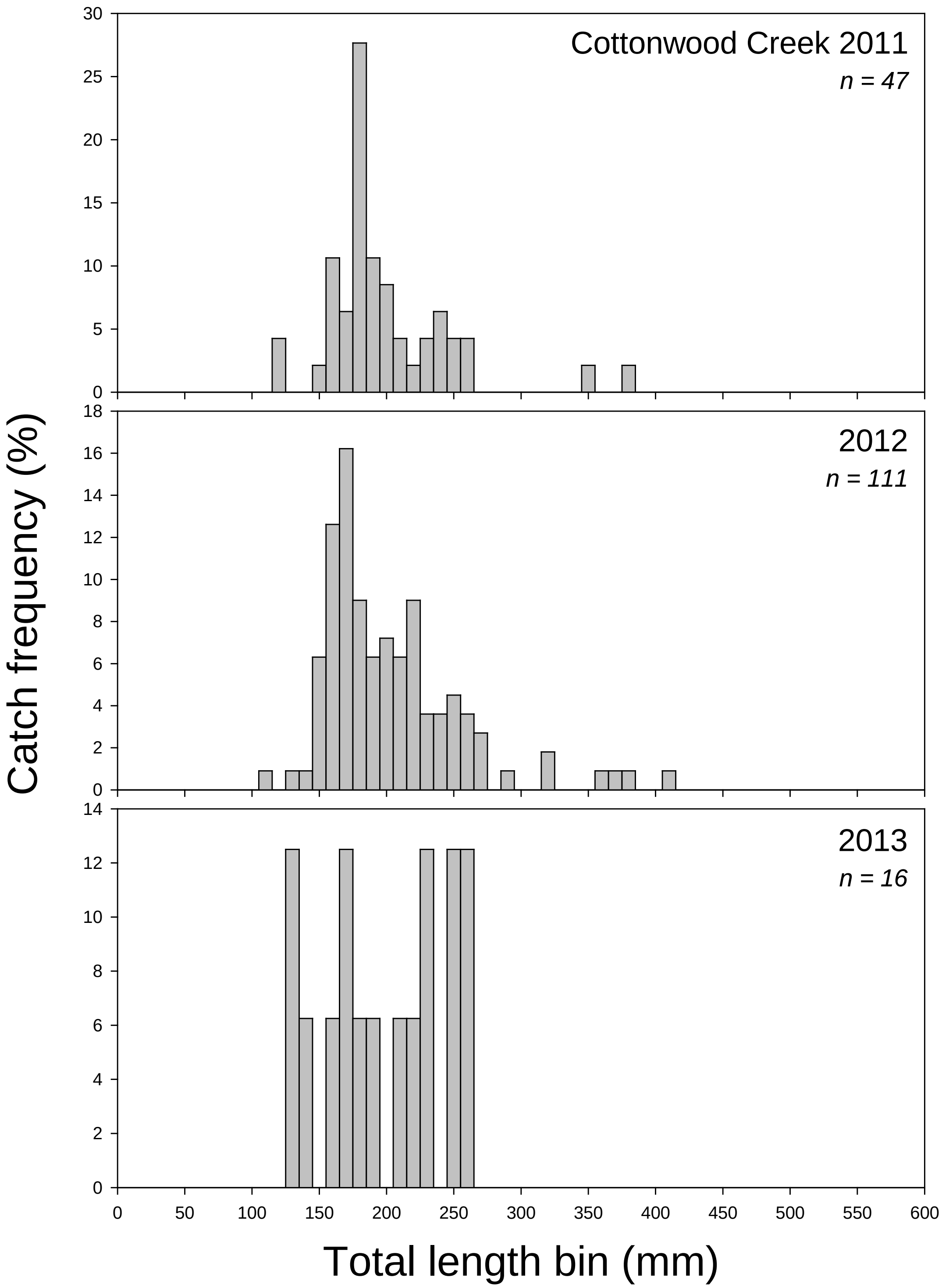


Figure 3. Length-frequency (%) histograms of cutthroat trout catch by year in Cottonwood Creek, a tributary to the Weber River, Utah. Sample size (n) is given.

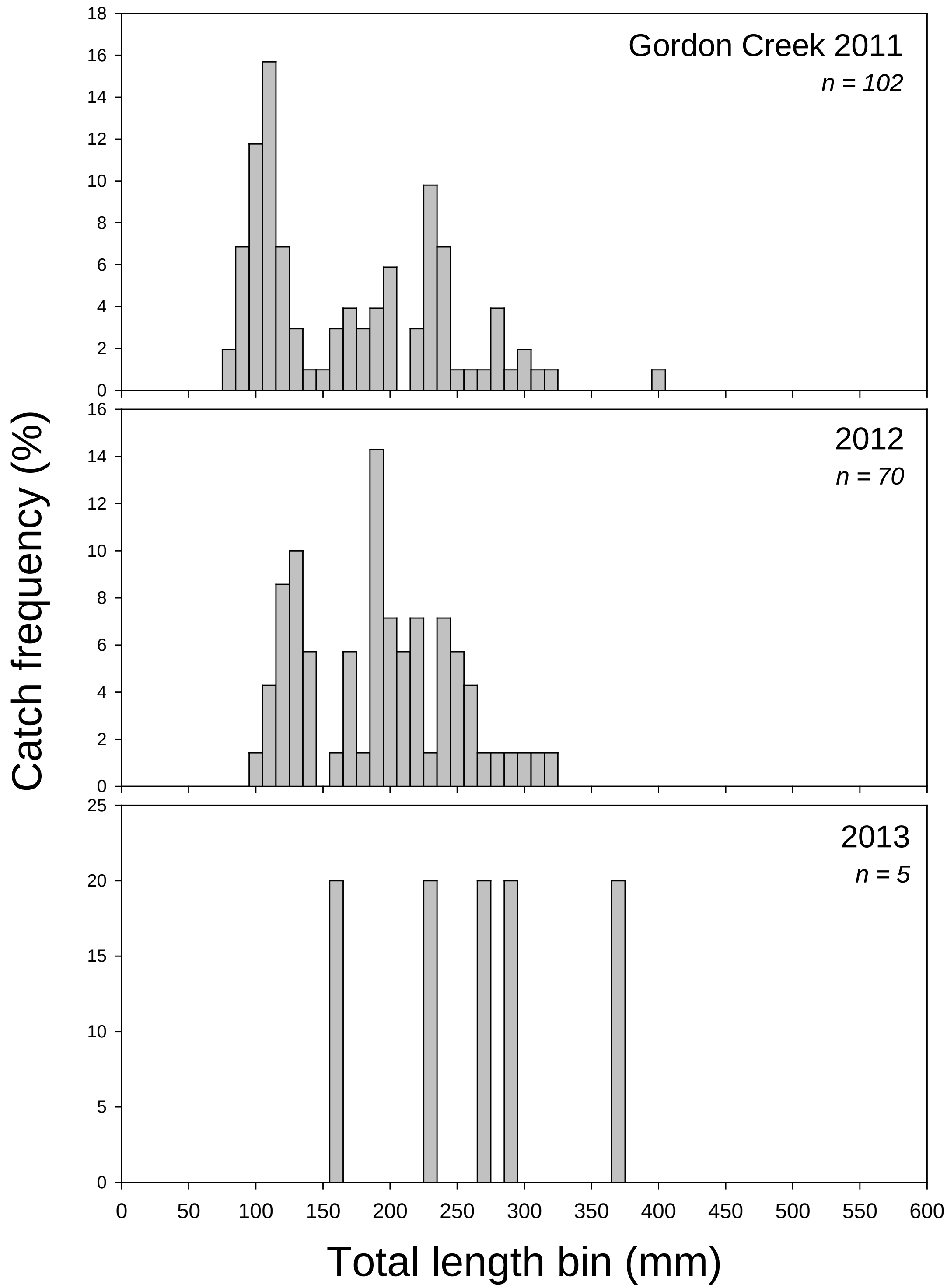


Figure 4. Length-frequency histograms of cutthroat trout catch by year in Gordon Creek, a tributary to the Weber River, Utah. Sample size (n) is given.

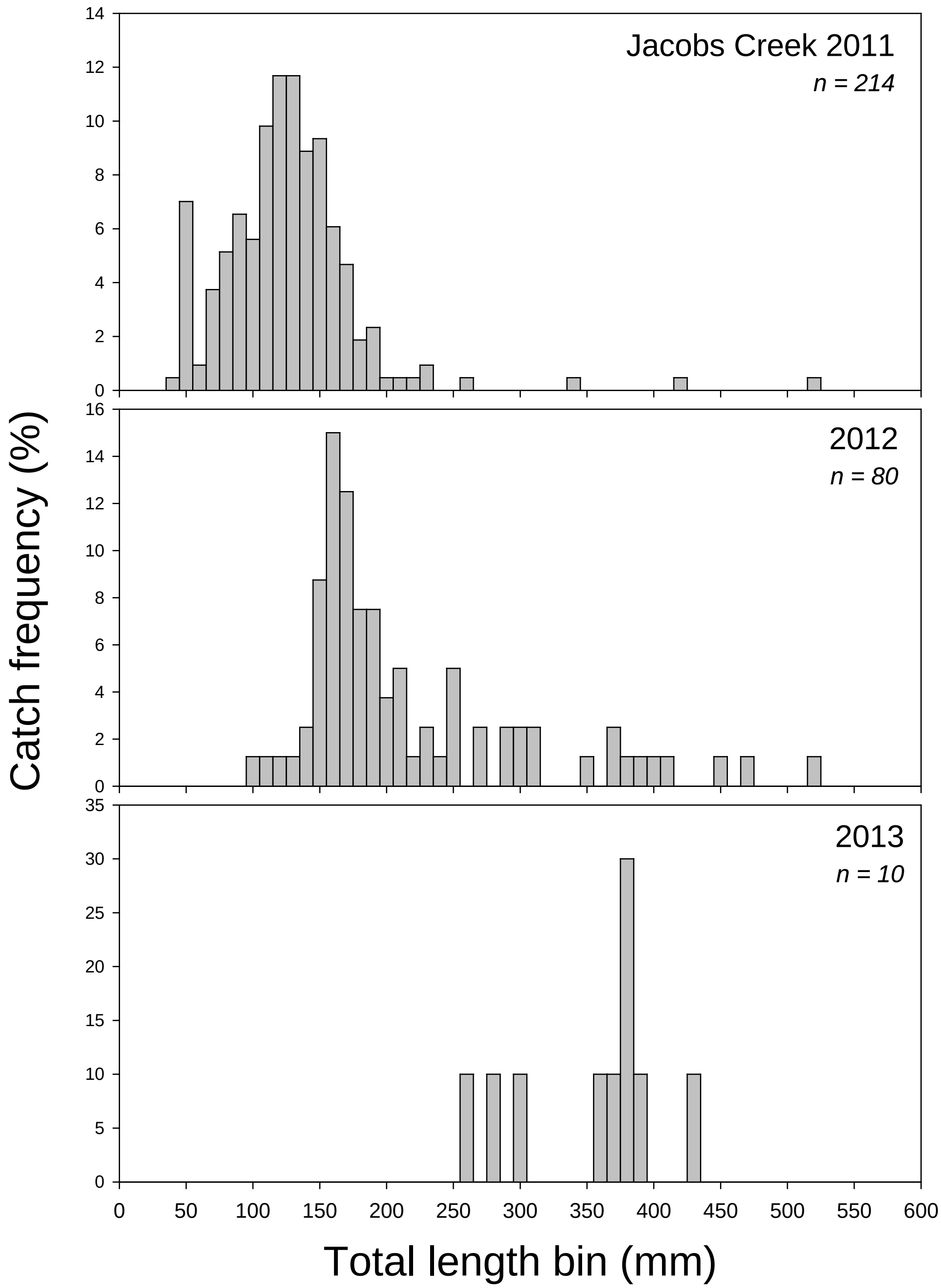


Figure 5. Length-frequency histograms of cutthroat trout catch by year in Jacobs Creek, a tributary to the Weber River, Utah. Sample size (n) is given.

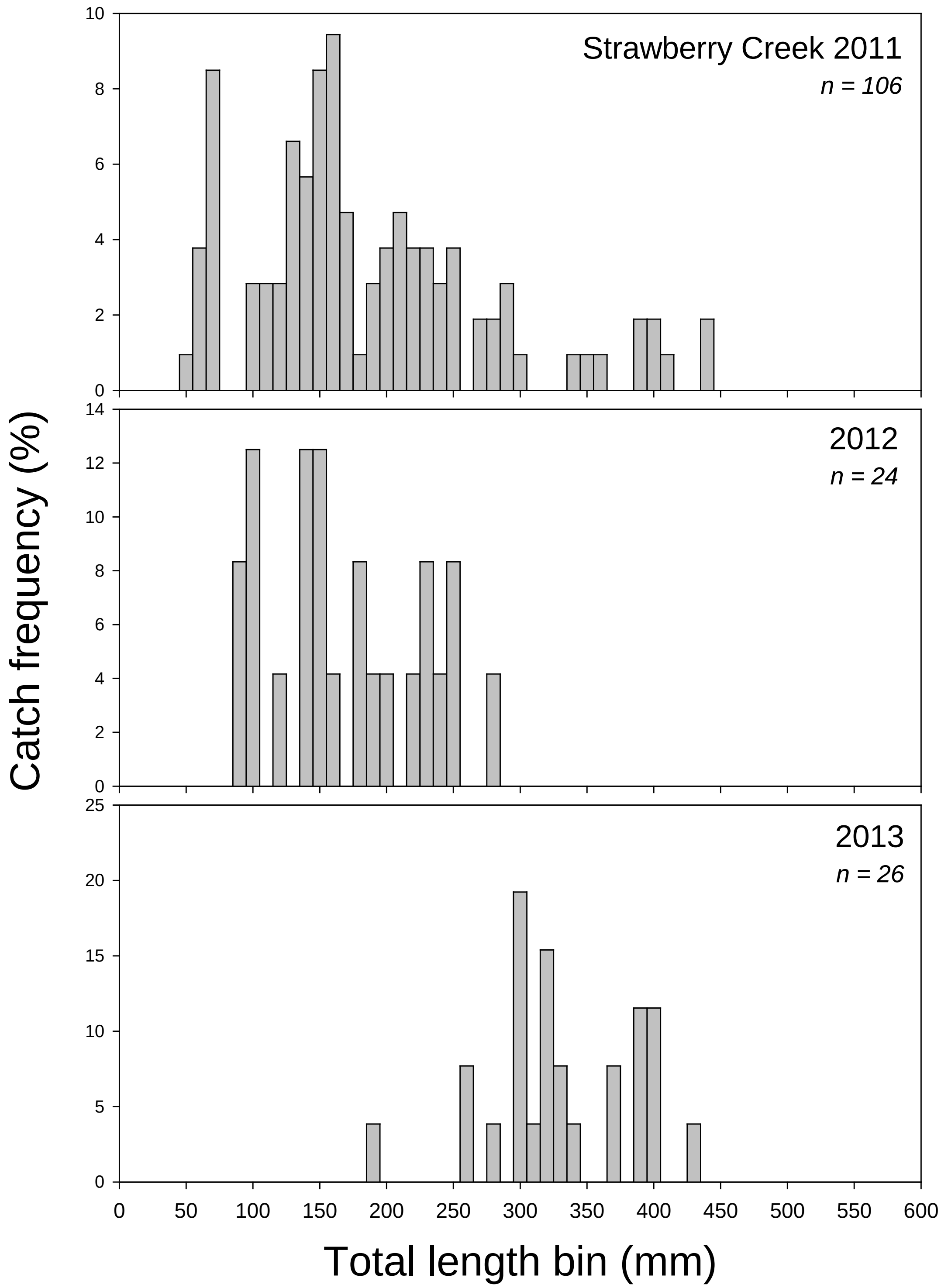


Figure 6. Length-frequency histograms of cutthroat trout catch by year in Strawberry Creek, a tributary to the Weber River, Utah. Sample size (n) is given.

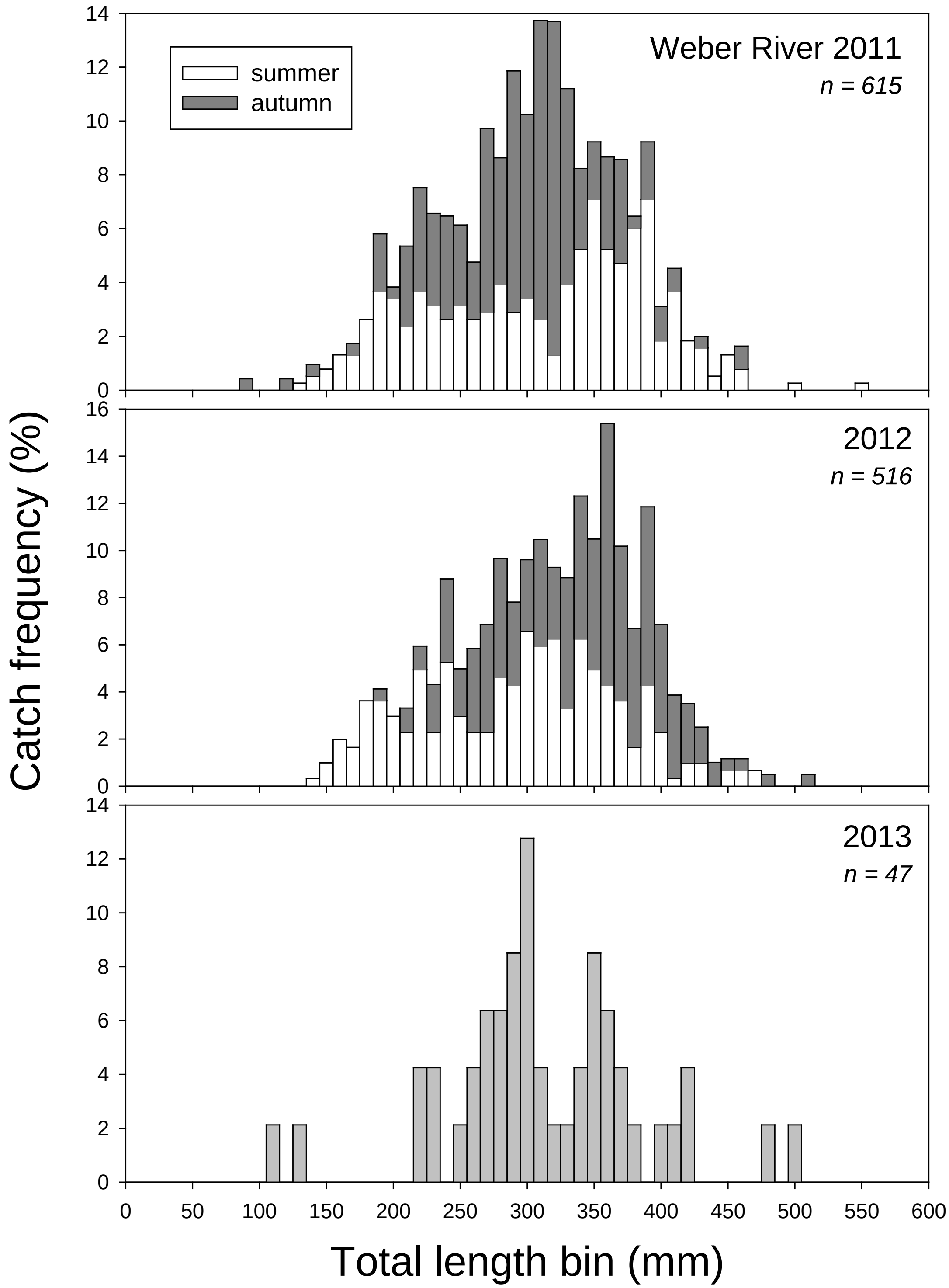


Figure 7. Length-frequency histograms of cutthroat trout catch by year in the Weber River mainstem, Utah. Only in 2011 and 2012, sampling occurred in summer (May – August) and autumn (October – December). Sample size (n) is given.

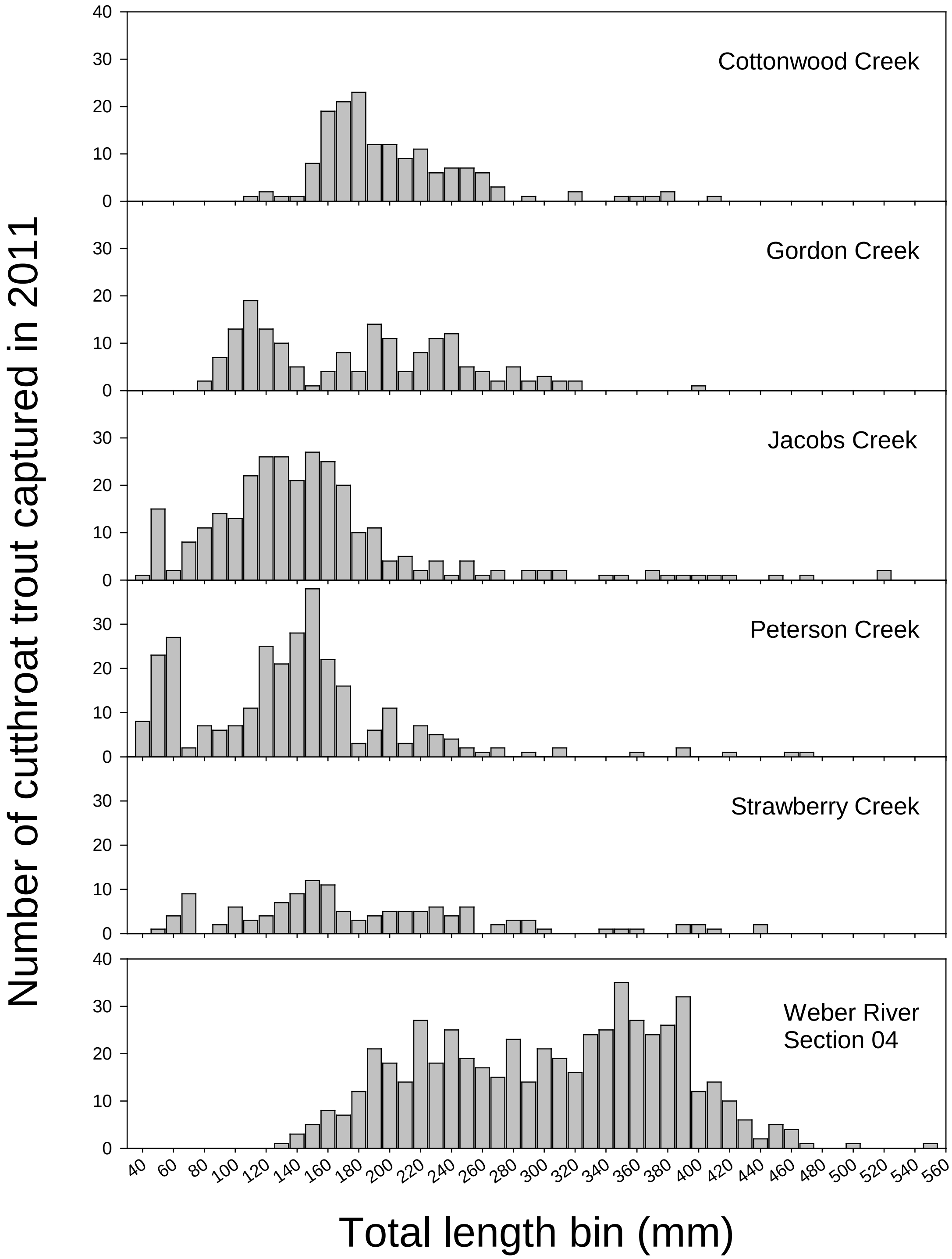


Figure 8. Length frequency (by number) of Bonneville cutthroat trout captured in Weber River Section 04 (June – September 2011) and tributaries (June – October 2011).

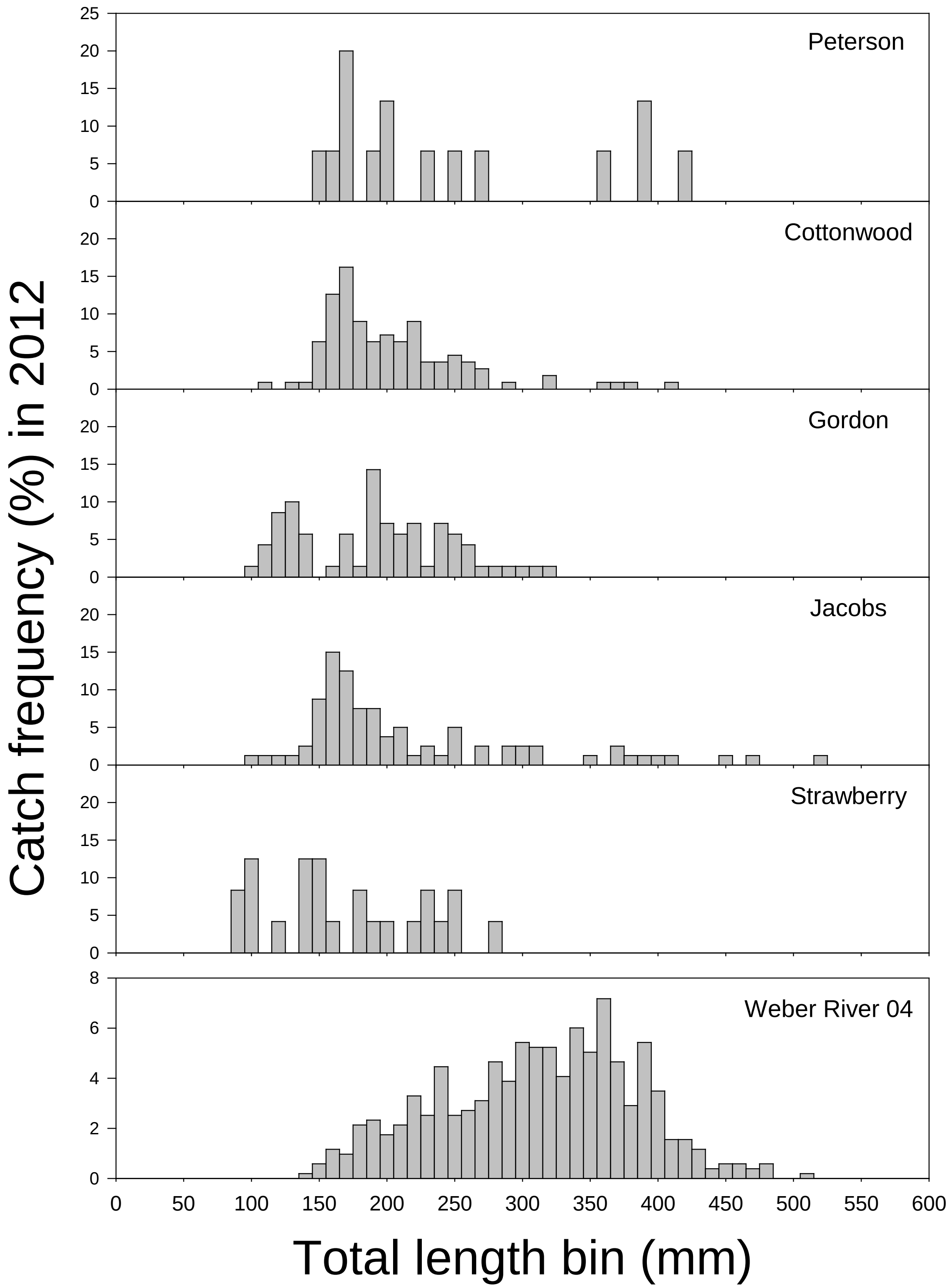


Figure 9. Length frequency (%) of Bonneville cutthroat trout captured in Weber River Section 04 and tributaries, 2012.

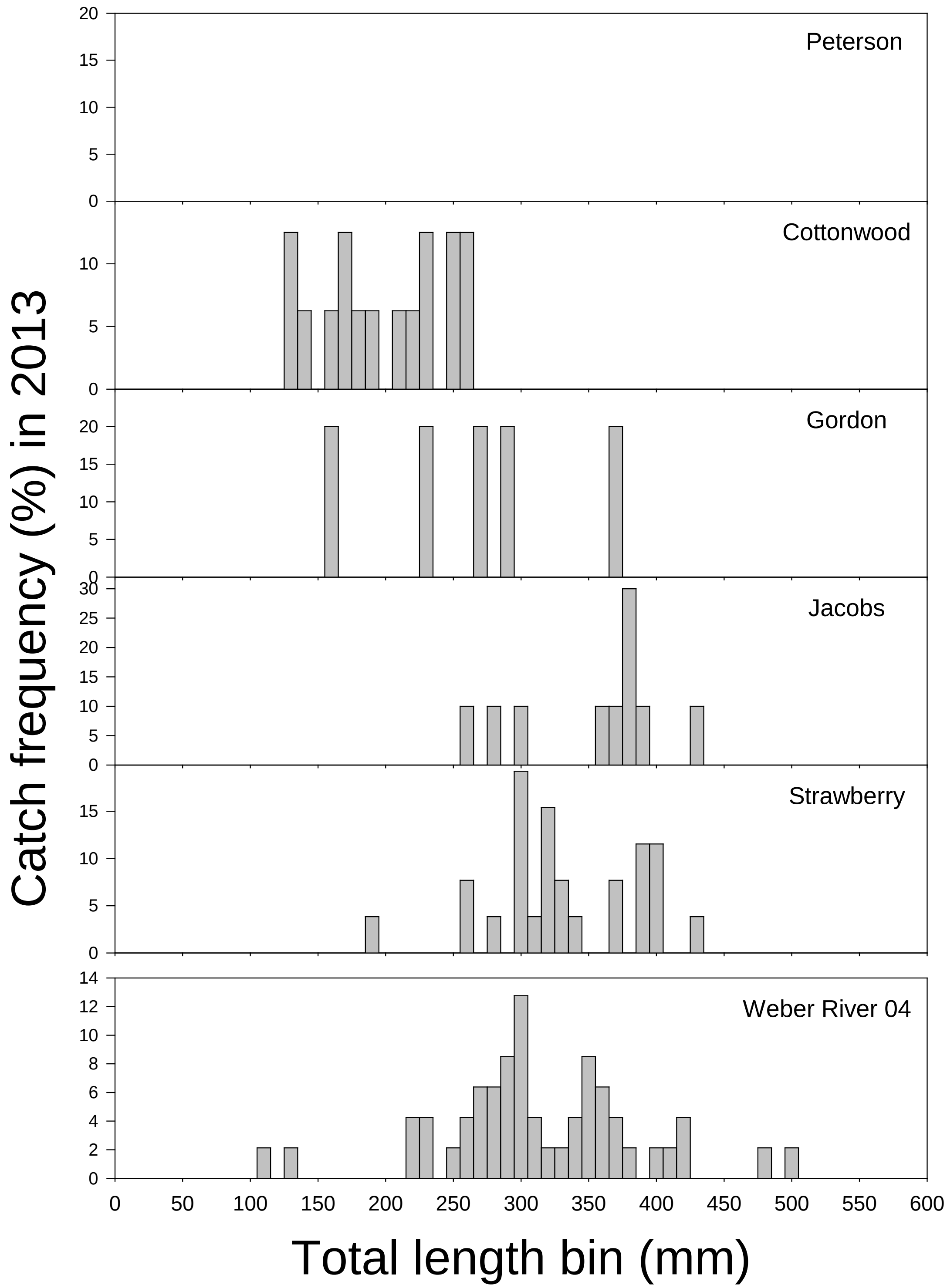


Figure 10. Length frequency (%) of Bonneville cutthroat trout captured in Weber River Section 04 and tributaries, 2013.

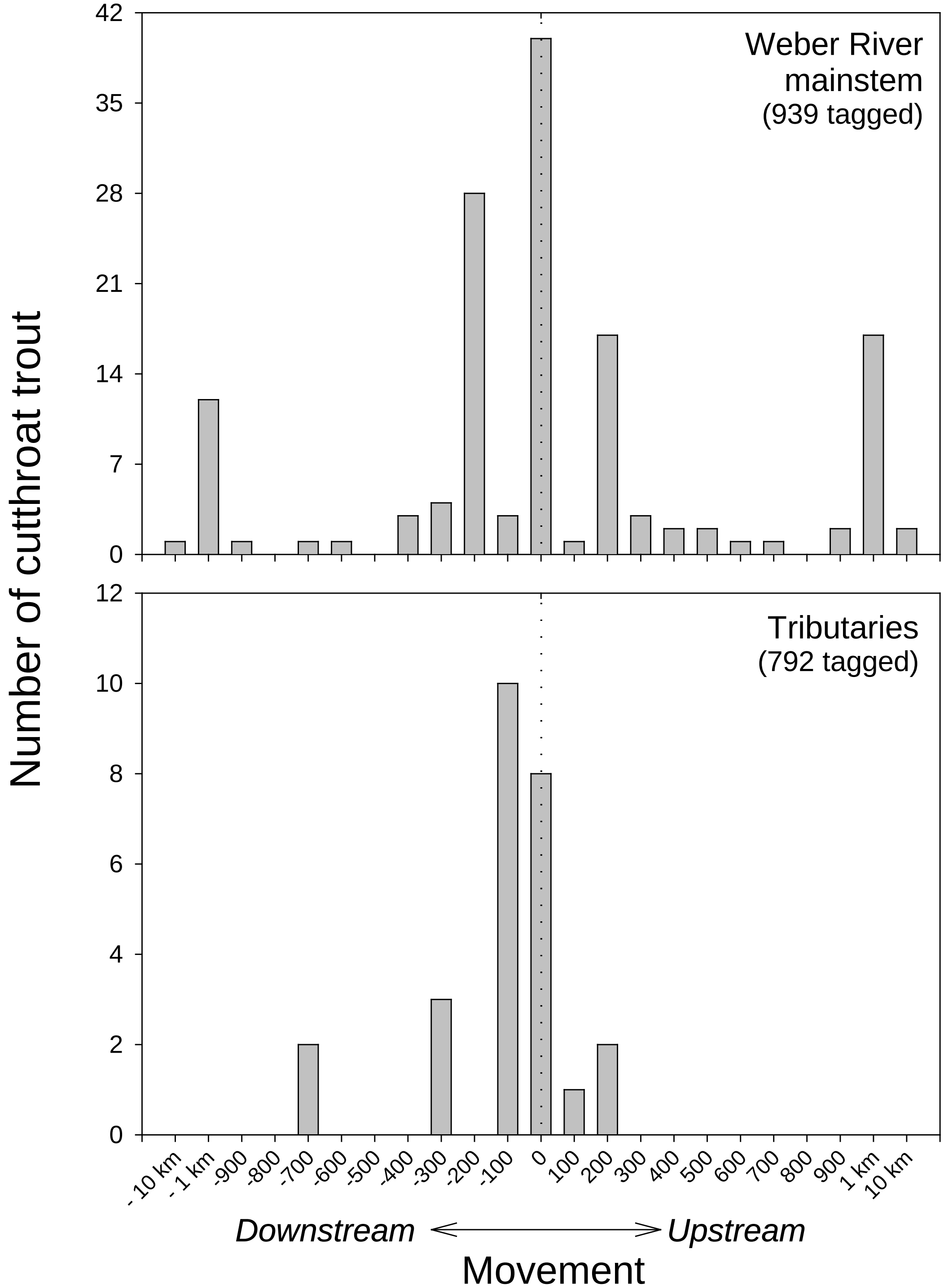


Figure 11. Upstream (positive distance to right of dashed line) and downstream (negative distance) movement of PIT-tagged cutthrout trout from the mainstem Weber River (top panel) and combined tributaries (bottom panel) in 2011. Total number of PIT-tagged fish is noted.

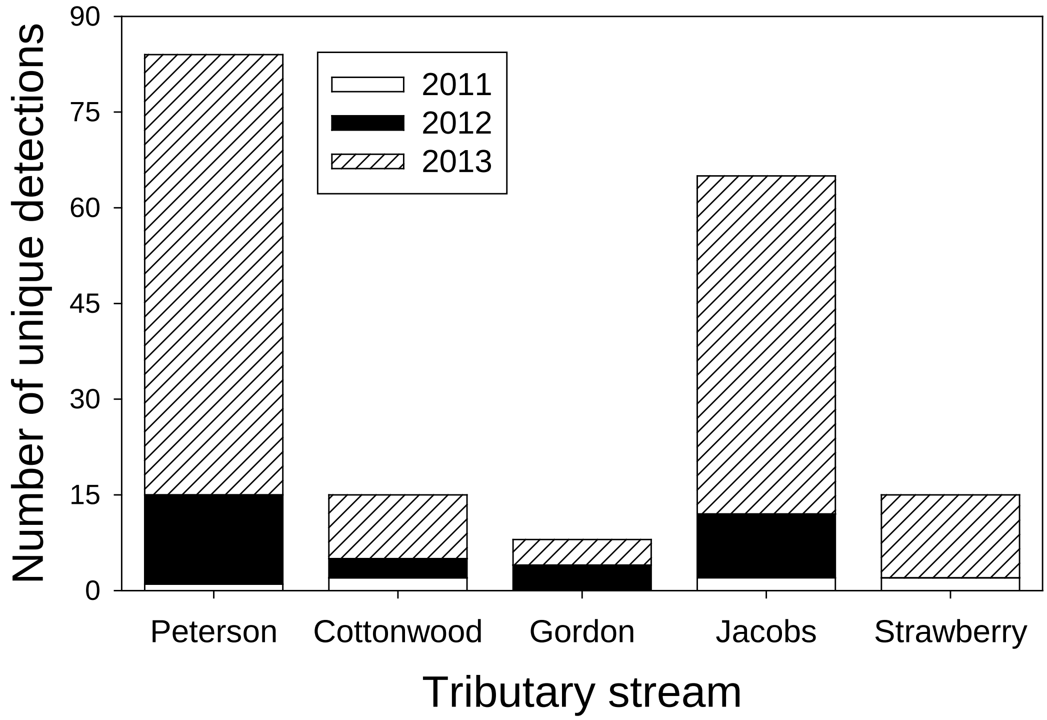


Figure 12. Number of unique detections at PIAs in each tributary of the Weber River of PIT-tagged cutthroat trout by year.

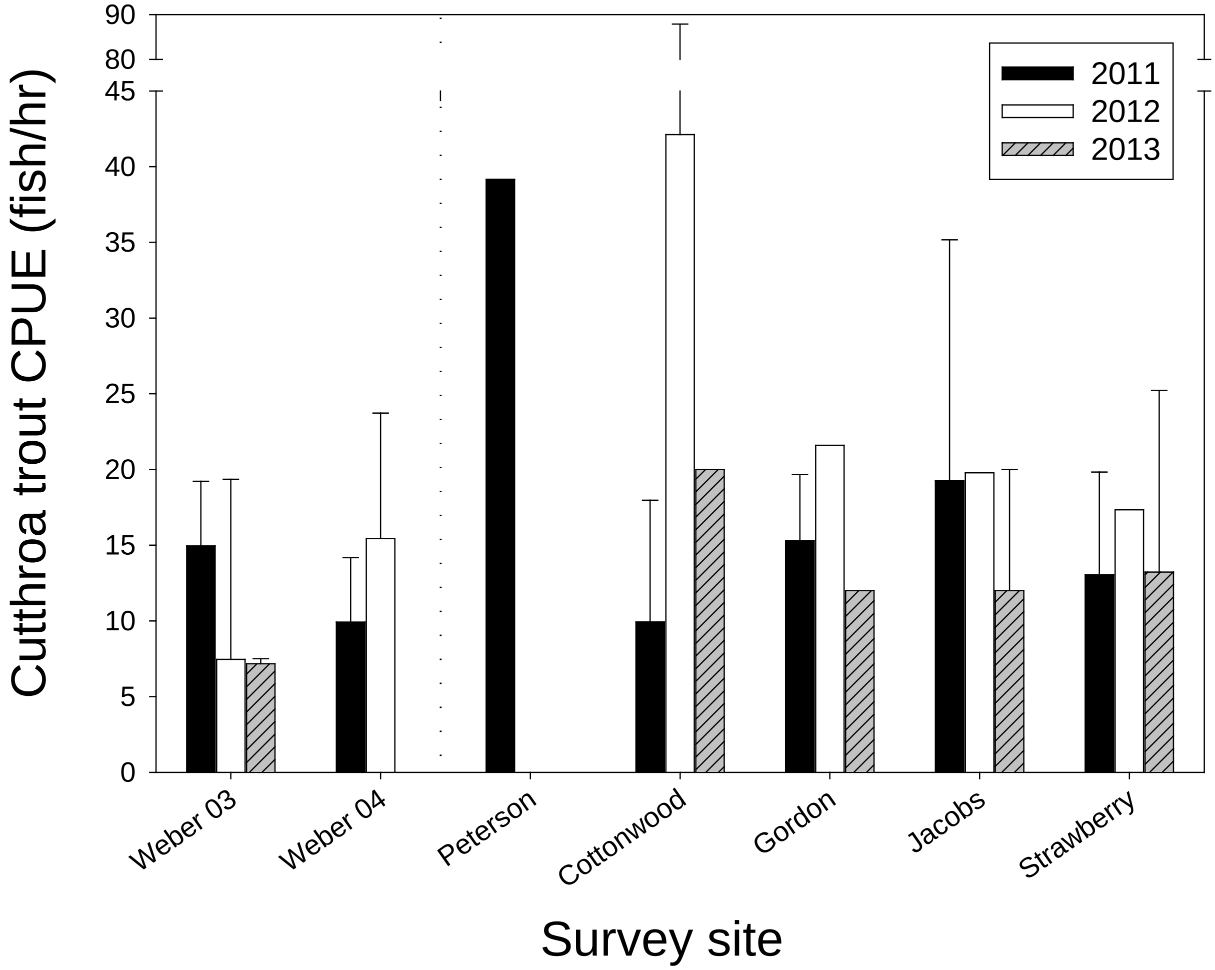


Figure 13. Catch-per-unit effort (CPUE ± 1 SE) of Bonneville cutthroat trout across 7 sampling sites in the Weber River (left of dashed line) and tributaries during 2011, 2012, and 2013. We did not sample all sites in all years, e.g., Weber 04 in 2013 and Peterson Creek in 2012 and 2013. Note break in y-axis.

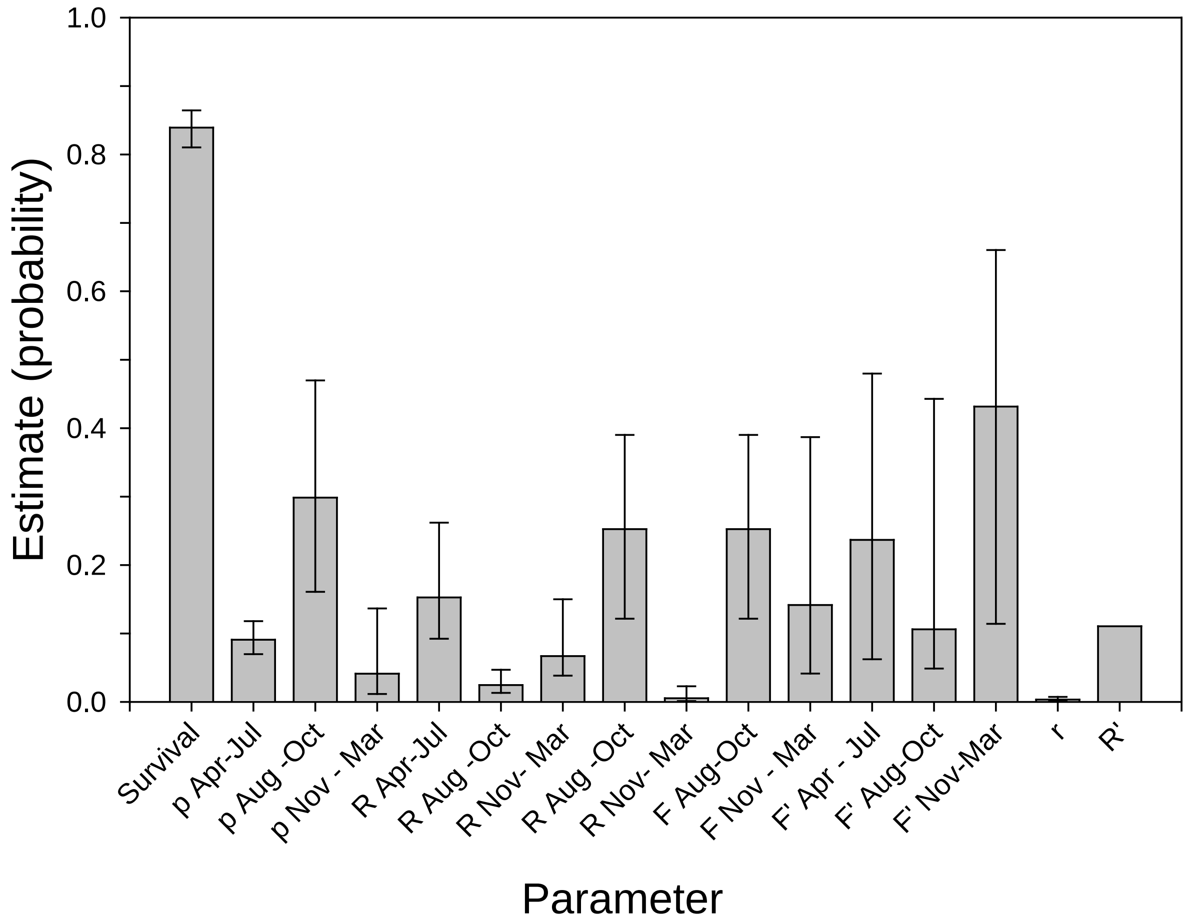


Figure 14. Parameter estimates from the top Barker model in program MARK. Survival (*S*) is true survival overall (for the entire time period), *p* is active recapture probability, *R* is resighting probability, *F* is the probability that an animal stayed on site, *F'* is the probability of temporary emigration, *r* is the probability of resighting a known dead fish, and R' is the probability that an animal dies without being found dead. See text for additional details.

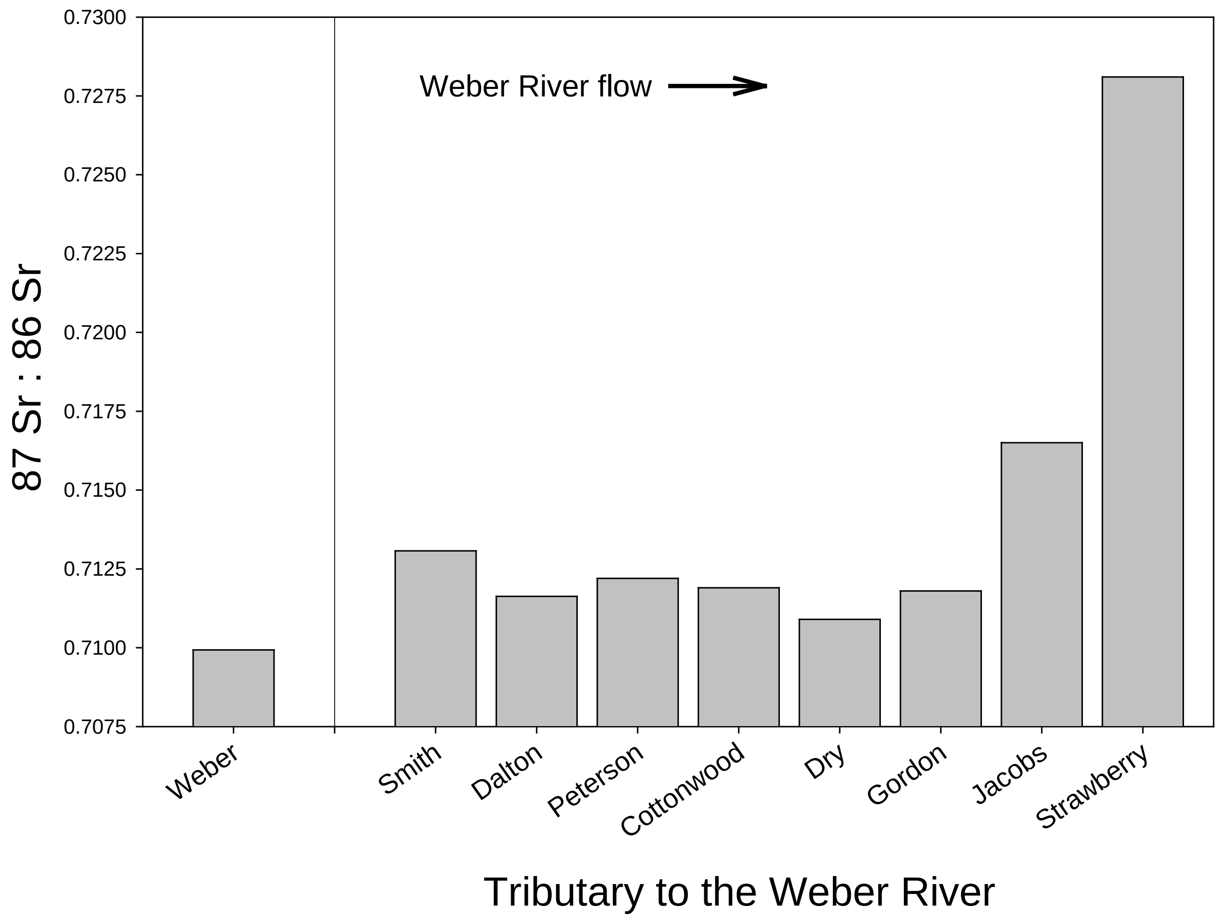


Figure 15. Strontium ratios (^{87}Sr:^{86}Sr) from 8 tributaries to the Weber River and the mainstem Weber River, Utah. Stream flow is denoted, flowing east to west. The eastern-most tributary from which we collected water is Smith Creek.

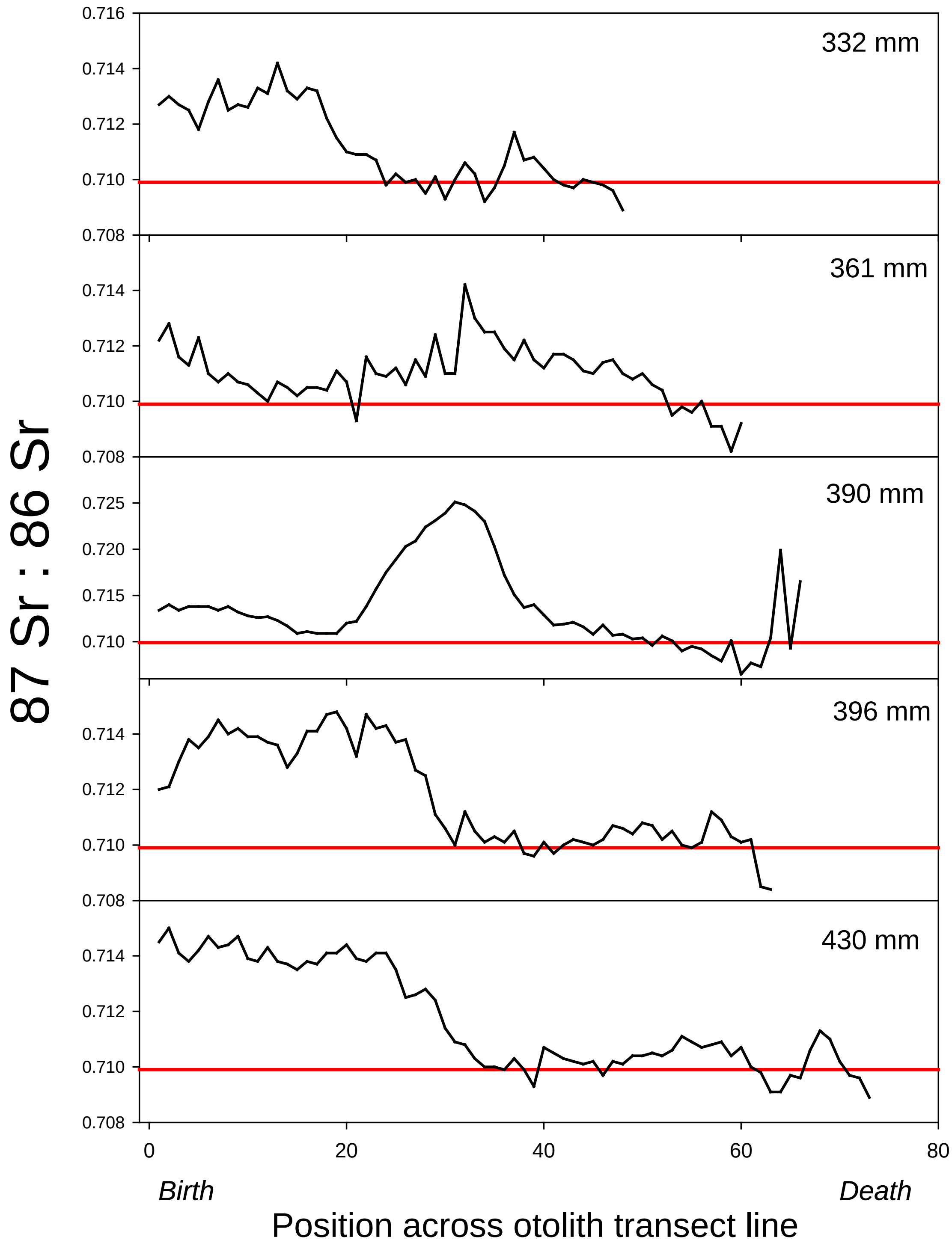


Figure 16. Strontium ratios (^{87}Sr:^{86}Sr) measured by laser ablation across a single transect (center, birth to edge, death) on five otoliths from cutthroat trout (lengths given) from the Weber River mainstem. Strontium ratio from mainstem stream water is also depicted with solid red reference lines.

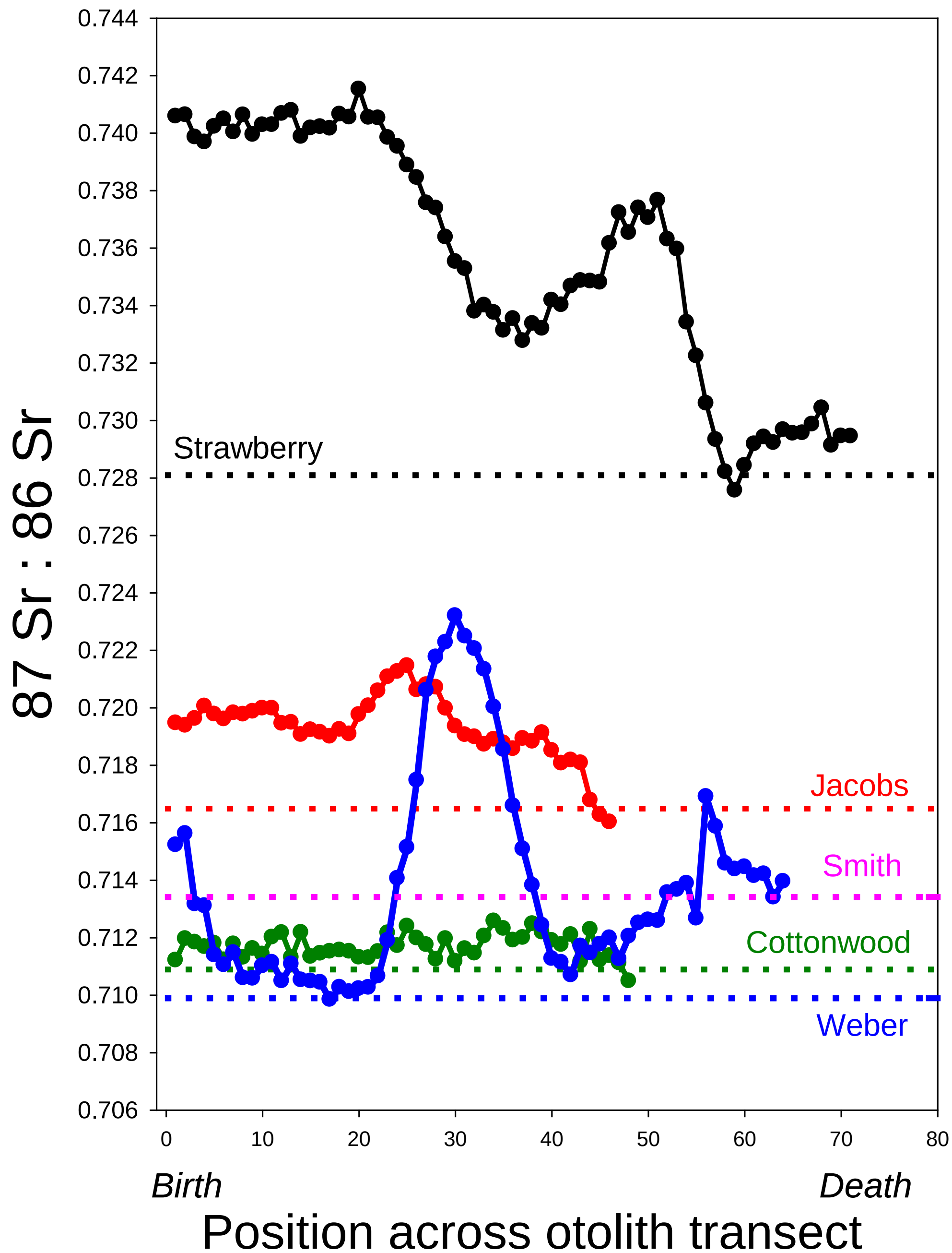


Figure 17. Strontium ratios across ablation transects (center, birth to edge, death) on four otoliths for cutthroat trout from Strawberry Creek (tributary, top, black), Jacobs Creek (tributary, middle, red), Weber River (mainstem, blue), and Cottonwood Creek (tributary, bottom, green). Strontium ratio from stream water is also depicted and labeled with reference lines: dashed black line for Strawberry Creek, dashed red line for Jacobs Creek, dashed green line for Cottonwood Creek, and dashed blue line at bottom for the Weber River mainstem. Strontium ratios in water from the other six tributaries are approximately between the two lower dashed lines.

APPENDIX 1

Appendix Table A1. Fish captured via electrofishing and handled in the Weber River and tributaries, 2011 – 2013. Effort was not equal between years.

Species	2011	2012	2013
Cutthroat trout	1364	816	104
Cutthroat × Rainbow	4	7	2
Brown trout	93	–	–
Rainbow trout	29	2	–
Mountain whitefish	13	–	–
Bluehead sucker	7	15	8
Mountain sucker	73	–	–
Utah sucker	27	–	–
Sculpin	2	–	–
Longnose dace	27	–	–
Speckled dace	119	–	–
Redside shiner	172	–	–
TOTAL	1930	840	114

Appendix Table A2. Cutthroat trout sampling via spot electrofishing in the Weber River and tributaries, 2013.

Stream, location	Dates	BCT captured	BCT re-captured	BCT newly PIT tagged
Jacobs Creek	2 May 2013	6	2	4
Strawberry Creek, below culvert	2 May 2013	4	2	2
Gordon Creek	2 May 2013	5	0	5
Cottonwood Creek	2 May 2013	1	1	0
Weber River, section 03	3 May 2013	7	3	4
Strawberry Creek, below culvert	14 May 2013	14	1	13
Jacobs Creek, below culvert	20 May 2013	4	1	3
Strawberry Creek, below culvert	20 May 2013	7	0	7
Cottonwood Crk, below diversion dam	13 June 2013	15		

<u>Brown trout abundance</u>

Appendix Table A3. Population estimates (with 95% confidence intervals) of brown trout (> 200 mm) in two mainstem sections of the Weber River, Utah, in 2011 and 2012.

Year and Weber River section	Distance	Number of passes	Dates of sampling	Population estimate (N hat)	95% confidence intervals
2011 Section 04	2.4 km. Red Barn to Diversion below Peterson Bridge	3	20 Jul, 21 Jul, 26 Jul	1887	1498 – 2548
2011 Section 04	2.1 km. Mountain Green Bridge to Rest Stop	3	20 Jul, 21 Jul, 26 Jul	449	251 – 915
2012 Section 02	Lower 19 km of 20 km reach	2	20 Jul, 21 Jul	2242	1965 – 2520

<u>Brown trout diets</u>

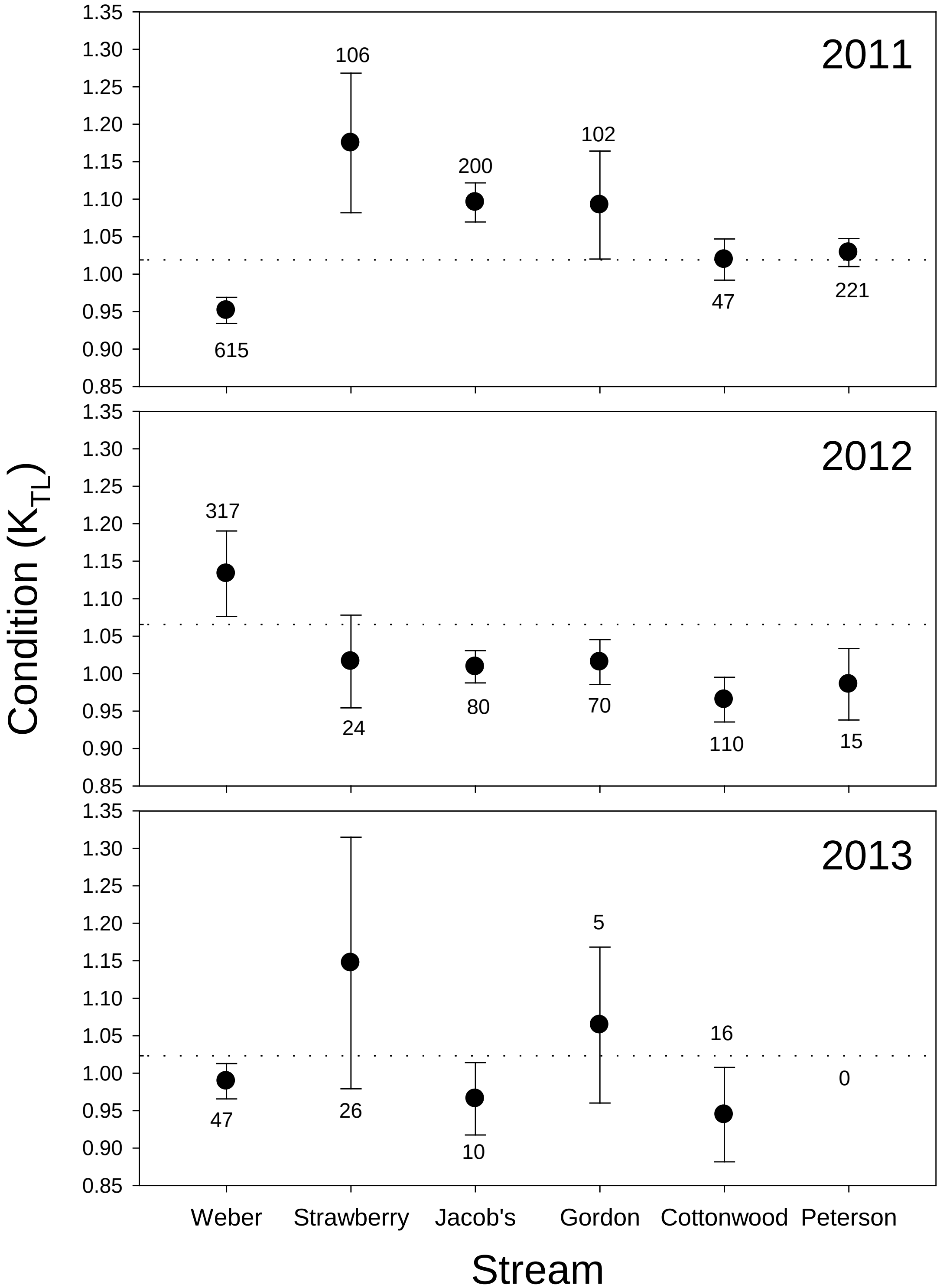
On 24 July 2013, Utah Division of Wildlife Resources biologists captured 21 brown trout (*Salmo trutta*) from Section 04 of the Weber River, Utah. Coordinates (GPS-derived UTM) were noted

near location of capture for all fish. Brown trout ranged in size from 399 – 630 mm TL (mean = 473 mm, ± 1 SE = 10), 630 – 1574 g (mean 1006 g, ± 1 SE = 61). Six fish (29%) were mature females, ranging in size from 487 – 572 mm (mean = 518 mm). Males ranged from 399 – 536 mm (mean = 455 mm). Fish were numbered and stored individually in bags on ice and transferred to the laboratory at USU for processing. We removed stomachs, otoliths and dorsal fin rays (first 5 complete dorsal rays), and noted sex and maturity level from all fish. We took anal-fin clips for isotopic analysis from 6 fish. Four fish (19%), all males, had empty stomachs.

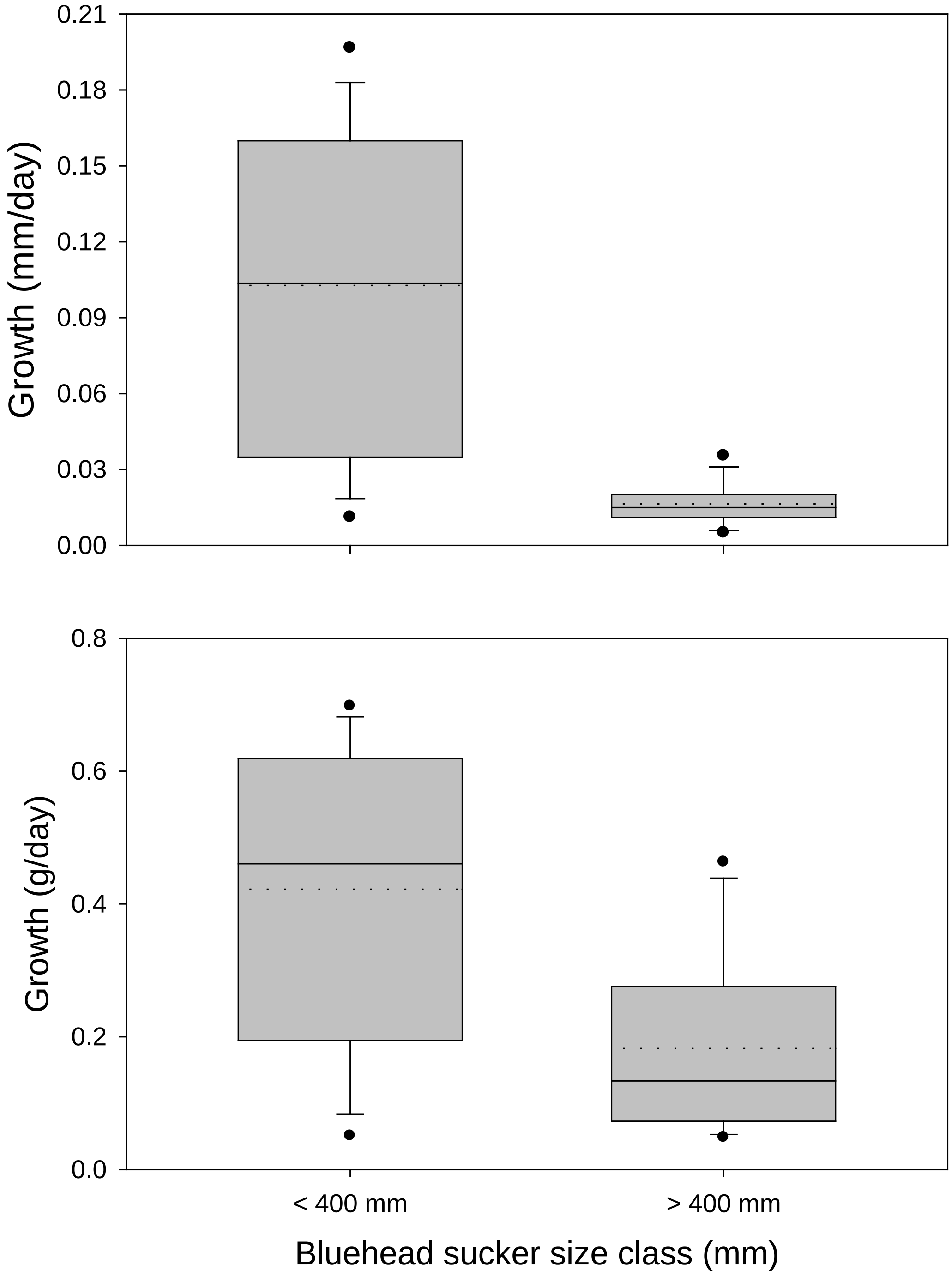
Diet items included isopods, gastropods, amphipods, ephemeropterans, dipterans, hirudineans, and fish (redside shiner). Dominant diet items (as percent composition by wet weight) included isopods (41%), gastropods (18%), and fish (14%). Interestingly, full female brown trout (n = 6) in our sample consumed primarily fish (30%, two females had fish in stomachs) and gastropods (27%), while full males (n = 11) consumed primarily isopods (55%) and gastropods (13%).

Growth of bluehead sucker

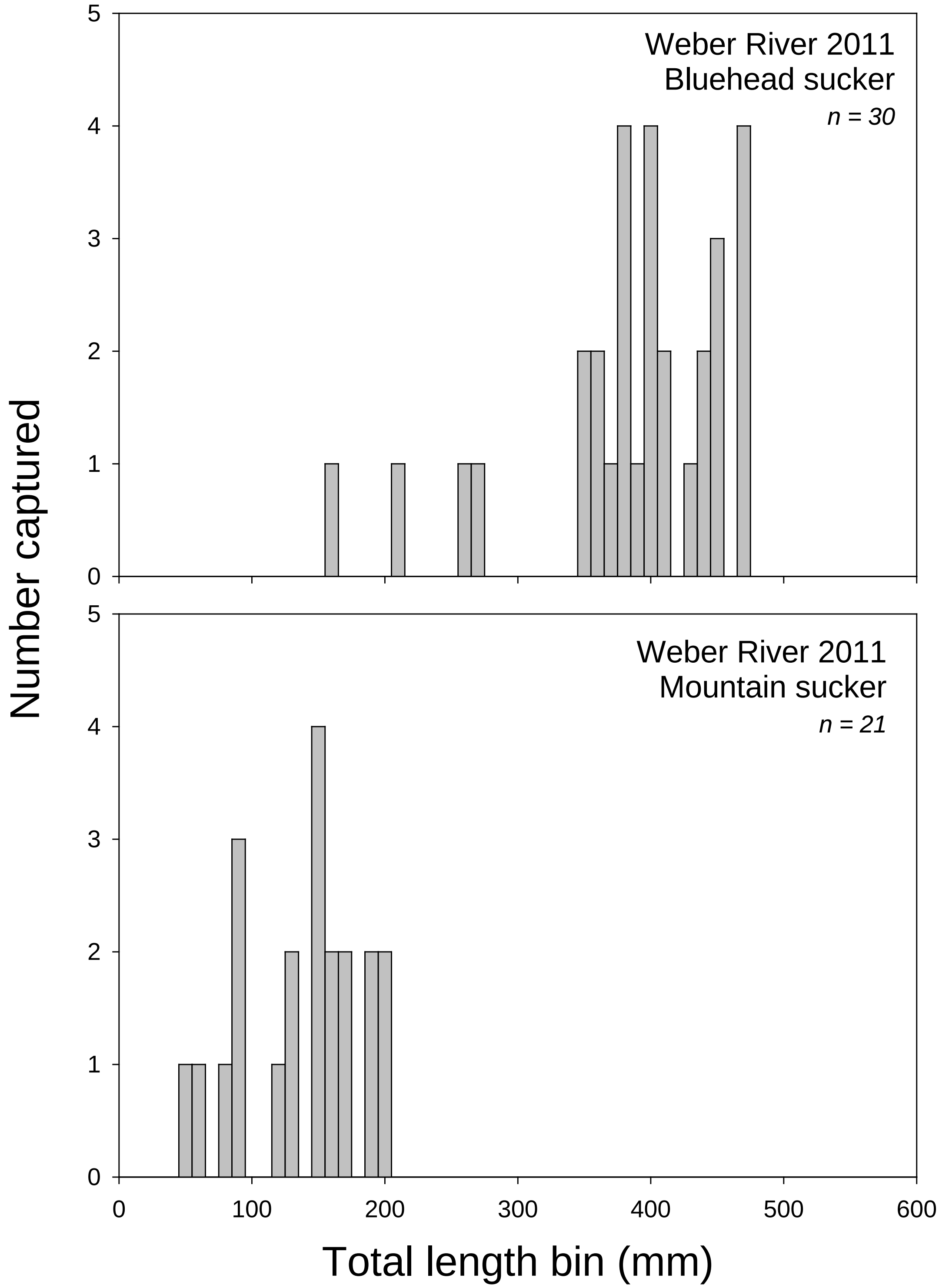
We determined growth (total length and body mass) for two size classes (small ≤ 400 mm and large > 400 mm) of PIT-tagged bluehead sucker between tagging (mostly in 2009) and subsequent recapture dates (mostly in 2012). At tagging, small bluehead sucker ranged in size from 161 – 396 mm TL (54 – 777 g) and grew, on average, 0.1 mm/day (0.4 g/day) across the roughly 3 year interval between mark and recapture (Appendix Figure 3). At tagging, large bluehead sucker ranged in size from 420 – 505 mm TL (789 g – 1.4 kg) and grew, on average, 0.02 mm/day (0.2 g/day) across the roughly 3 year period (Appendix Figure 3).



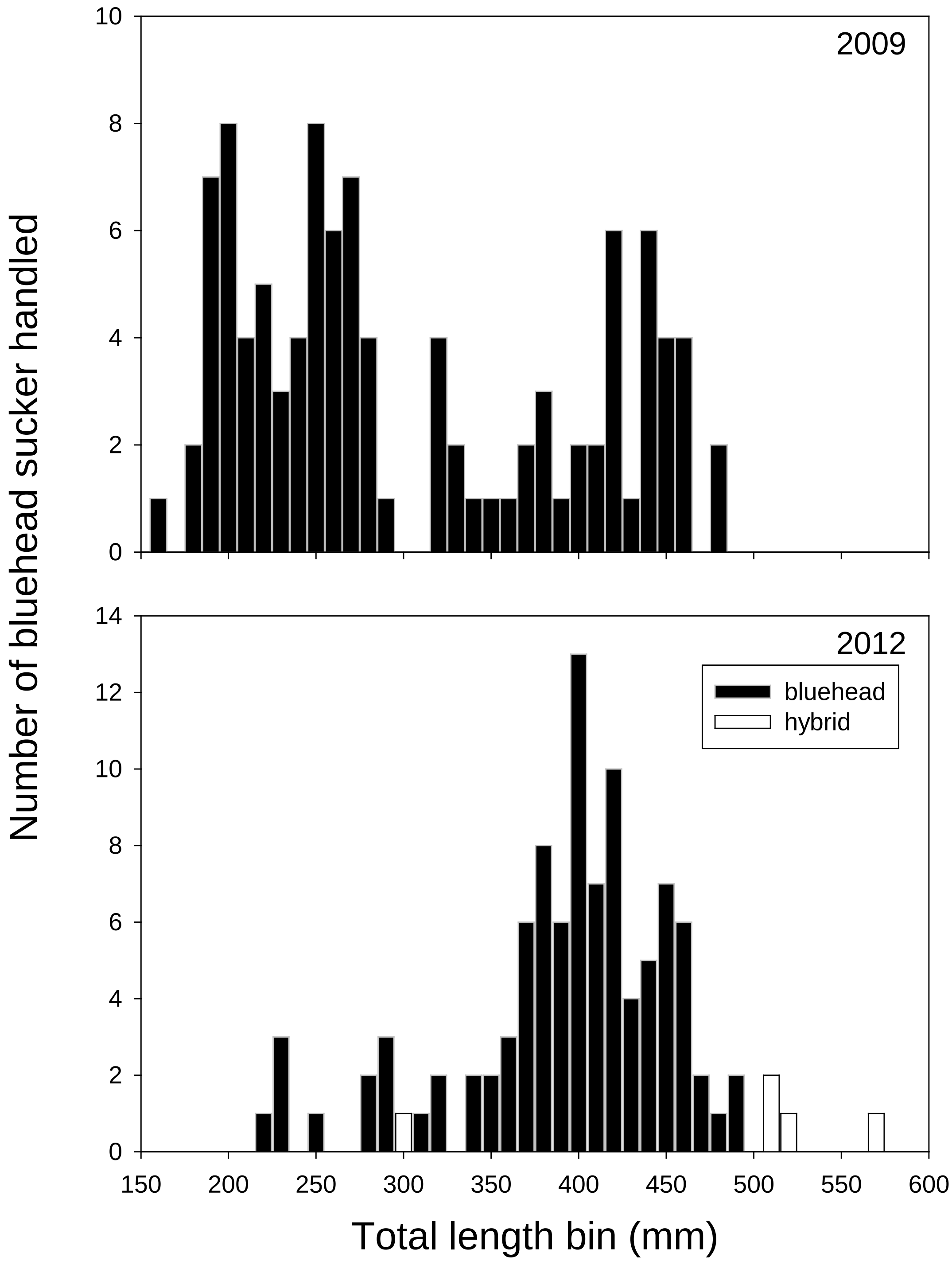
Appendix Figure A1. Condition (Fulton's K ± 1 SE) of cutthroat trout captured in tributaries and mainstem Weber River, Utah, 2011, 2012, and 2013. Sample size is given by error bar. Dashed line indicates year-specific mean condition.



Appendix Figure A2. Growth in length (top panel) and body mass (bottom panel) of two size classes of bluehead sucker in the Weber River, Utah over the interval 2009 – 2012 (with some exceptions). The boundaries of the box indicates the 25th and 75th percentile, the solid line within the box marks the median, the dashed line represents the mean. Whiskers (error bars) above and below the box indicate the 90th and 10th percentiles, and outliers are shown with dots.



Appendix Figure A3. Length-frequency histograms of bluehead sucker (top panel) and mountain sucker (bottom panel) catch in 2011 in the Weber River mainstem, Utah. Sample size (n) is given.



Appendix Figure A4. Length-frequency histograms of bluehead sucker in 2009 (top panel, would include hybrids) and 2012 (bottom panel, hybrids [n = 5] in white bars) in the Weber River mainstem, Section 02, Utah.