Analysis of Relationships between Streamflow and Trout Populations on the South Fork Snake River

Project completion report for

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Abstract. The South Fork Snake River (SFSR) supports one of the largest populations of native fluvial-adfluvial Yellowstone Cutthroat Trout (YCT) in their native range. Competition and hybridization with nonnative Rainbow and Hybrid trout (RHT) pose a serious threat to YCT in the SFSR. To preserve genetically pure YCT and reduce RHT numbers, Idaho Department of Fish and Game implemented a three-pronged management approach in 2004, consisting of 1) preventing upstream migration of RHT into the four major spawning tributaries via trapping at weirs, 2) managing springtime flows at Palisades Dam to mimic the river's natural freshet, and 3) increasing angler harvest of RHT. The success of the three-prong approach was assessed with a stochastic simulation model of YCT-RHT dynamics calibrated to 1989-2012 conditions (DeVita 2014). Results showed that if YCT and RHT remain genetically isolated via the tributary weir program, angler harvest was likely the most effective tool for preserving YCT. Due to irrigation and flood-control constraints on operation of Palisades Reservoir, it was unlikely that freshet magnitude and frequency would be great enough to hinder RHT recruitment, but absent these constraints, freshet flow could still be an effective tool for RHT suppression. In this report, we assessed assumptions on which DeVita's model was based by applying it to actual environmental conditions and management actions over 2013-2017. Based on model output, we conducted a series of new statistical analyses to investigate the effects of SFSR flows and tributary conditions on YCT and RHT recruitment. DeVita's model predicted YCT numbers to within 20%, suggesting that YCT dynamics are well understood and stable. However, the model performed very poorly at predicting RHT numbers, suggesting that factors affecting RHT numbers are different than they were during the initial RHT invasion and are poorly understood. Statistical analysis confirmed earlier results that winter flow downstream of Palisades Dam has a positive effect on recruitment of both species and that late-summer tributary conditions during a cohort's first year affect YCT recruitment. However, the updated analysis showed that late-summer temperature, rather than tributary flow, was a stronger predictor of YCT recruitment. Because recommended freshet magnitude of 25,000 cfs has never been achieved since the three-pronged approach was implemented, data are insufficient to statistically test the freshet effect. However, we found that recruitment of both YCT and RHT was positively related with the spring-time flows that were delivered (14,000-20,000 cfs in most years). We recommend the following management and research actions.

1. Maximize winter flow, and maintain a minimum mean flow of 1,800 cfs from December 1-February 28.
2. Maximize spring freshet flow to maintain ecological processes in the stream channel and floodplain.
3. Because operational constraints are unlikely to allow freshet flows exceeding 25,000 cfs, continue to promote angler harvest and conduct additional research into YCT-RHT interactions to find alternatives to the freshet that favor YCT recruitment over that of RHT.
4. Update and recalibrate DeVita's model, and use it to assess future management strategies.
5. Investigate sources of YCT recruitment between river and tributaries, and among tributaries.
6. Investigate YCT and RHT population trends in the lowest reach of the SFSR (Twin Bridges to confluence of Henry's Fork River), where RHT invasion success has been limited.

Contents

List of Tables

List of Figures

Introduction

The South Fork Snake River (SFSR), comprising about 60 river miles from Palisades Dam downstream to the Henry's Fork confluence, supports an economically important recreational fishery for Yellowstone Cutthroat Trout (YCT, *Oncorhynchus clarkii bouvieri*), Rainbow Trout (*O. mykiss*), Rainbow Trout × Cutthroat Trout hybrids, and Brown Trout (*Salmo trutta*) (Loomis 2006; Van Kirk et al. 2010). Furthermore, the SFSR supports one of the largest, most robust populations of native fluvial-adfluvial YCT in their native Idaho range (Fredericks et al. 2004; Meyer et al. 2006; Gresswell 2011). Competition and hybridization with Rainbow and Hybrid trout (RHT) pose a serious threat to native YCT in the SFSR, so the Idaho Department of Fish and Game's (IDFG) management objectives aim to preserve protect genetically pure YCT and reduce the numbers of rainbow and hybrid trout (RHT) to no more than 10% of the total trout population (IDFG 2007). These objectives are being pursued through a three-pronged approach of 1) preventing upstream migration of RHT into the four major SFSR spawning tributaries via trapping at weirs, 2) managing springtime flows at Palisades Dam to mimic the river's natural spring freshet, and 3) reducing RHT numbers through increased angler harvest (Fredericks et al. 2004; High 2010). Estimable numbers of RHT were first sampled in 1989, and the three-pronged approach was first implemented in 2004, following initial research that identified spatiotemporal overlap in spawning between RHT and YCT (Henderson et al. 2000) and quantified hydrologic alteration due to Palisades and Jackson Lake dams and its potential negative effects on YCT and positive effects on RHT (Moller and Van Kirk 2003).

A simple analytical model of YCT-RHT interactions in the SFSR fit to population data through 2008 provided strong evidence that hybridization was the primary mechanism for displacement of YCT by RHT but also indicated that competition among young-of-year fish in the main river may also be contributing to displacement of YCT (Van Kirk et al. 2010). Competition is expected to be highest during dry years, when tributary-spawned YCT are more likely to out-migrate to the river during their first autumn rather than remain in the natal tributary until age 1 or 2. Van Kirk et al. (2010) also provided some evidence that the displacement of YCT by RHT had slowed since implementation of the three-pronged approach. Subsequent assessment of the three-pronged management strategy revealed that because of physical and legal constraints associated with managing the upper Snake Reservoir system, freshet flows needed to mobilize substrate and theoretically dislodge RHT eggs (25,000 cfs or greater, for 8-15 consecutive days), had never been achieved since the implementation of the three-pronged management strategy. These flow constraints greatly limited the effectiveness of freshet flow management in achieving fisheries management objectives (High 2010). Furthermore, despite a high potential for angler harvest to help achieve these objectives, exploitation of RHT from angler harvest remains at or below 25% and has had little apparent effect on species composition (High 2010). A preliminary version of a demographically explicit simulation model supported these observations and predicted that angler exploitation around 30% would be required to reduce RHT numbers in the long run (Battle et al. 2010).

A decade after initiation of the three-prong approach, sufficient data were available to conduct statistically meaningful assessment of the effects of management actions on YCT-RHT dynamics in the SFSR. Building from the population model first proposed by Battle et al. (2010), DeVita (2014) created a stochastic population model specific to SFSR YCT and RHT that utilized demographic parameters, flow parameters, flow-dependent population attributes, species interactions, and management actions to simulate how various harvest and flow scenarios could affect populations and species compositions into the future (Figure 1). Results showed that assuming the weir program that maintains YCT and RHT genetic isolation is continued into the future, angler harvest was likely the most effective tool for preserving YCT. Due to irrigation and flood-control constraints on operation of Palisades Reservoir, it was unlikely that freshet magnitude and frequency would be great enough to hinder RHT recruitment. However, in absence of these operational constraints on Palisades Reservoir, freshet flow could still be an effective tool for RHT suppression.

In this report, we assessed assumptions on which DeVita's (2014) model was based by applying it to actual environmental conditions and management actions over the 2013-2017 period. After initial assessment based on model output, a series of new statistical analyses were performed to investigate the effects of SFSR flows specific to critical trout life history periods had on YCT and RHT recruitment; how freshet timing and magnitude characteristics effected RHT recruitment; and how SFSR tributary conditions effected YCT recruitment.

Methods

Data

Trout population data were collected in the fall by the IDFG in the Conant reach of the South Fork Snake River. Fish were captured using direct-current elecrofishing equipment mounted to a jet boat. Captured trout age-1 and older were anesthetized, identified to species, measured for total length, and marked with a caudal punch and released. Typically, four sampling events occurred over a two-week period each year. Population estimates were calculated using a modified Petersen estimator and the computer program Mark Recapture 5.0. For a complete explanation of sampling and population estimate procedures, see Schrader and Fredericks (2008). Climatic data (air temperature) were collected from the Bureau of Reclamation (BoR) Agrimet station in Rexburg, ID. Tributary temperature data were collected by IDFG at Rainey Creek, Pine Creek, Palisades Creek, and Burns Creek from 2010-2017 and were used to verify the relationship between tributary temperature and air temperature as measured at the Rexburg AgriMet station. Flow data for the analysis were collected at United States Geological Survey (USGS) gage station 13032500 Snake River near Irwin, ID. Cumulative tributary flow for the SFSR was calculated as the net river-reach gain between the Irwin gage station and USGS gage station 13037500 Snake River at Heise, ID.

Assessment of DeVita (2014) model performance

This stochastic, discrete-time, age-structured population model tracks same-age cohorts of tributary-spawning YCT, river-spawning YCT, and RHT separately through life stages, mortality, spawning and interspecies hybridization, potential springtime freshet-flow-induced mortality of RHT eggs and fry, age-0 competition for flow-dependent habitat during the first winter, and size-dependent angler harvest of RHT (Figure 1). The model assumes that offspring of tributary-spawned YCT return to tributaries to spawn and offspring of river-spawned YCT spawn in the main river, i.e., there is no straying in reproductive strategy. However, tributary-spawned YCT that out-migrate at age 0 compete with river-spawned YCT and with RHT during their first winter in the main river. This is the only assumed interaction between tributary-spawning YCT population and the other two populations.

All but five demographic, RHT harvest, flow, and flow-dependent population parameters in the model were estimated from site-specific data provided by Idaho Department of Fish and Game or drawn from literature applicable to YCT and RHT in the Yellowstone region. The model contained two flow-dependent population attributes that were statistically fit to 1989-2012 data: 1) positive effect of winter flow release from Palisades Dam on total RHT+YCT recruitment, and 2) increased tendency of young-of-year YCT to migrate out of tributaries with decreased summer tributary flow. The five parameters that could not be directly estimated were 1) fractional reduction in growth of age-0 YCT in tributaries compared with their counterparts in the main river, 2-3) two mathematical parameters in the sigmoidal function that described RHT egg/fry mortality as a function of freshet flow, 4) fraction of total winter carrying capacity for age-0 *Oncorhynchus* that is provided by winter habitat in the tributaries, 5) fraction of the total YCT population in the tributary-spawning population at the beginning of RHT invasion. These five parameters were estimated by maximizing the likelihood that the observed 1989-2012 population data were produced by the parameterized model. In this sense, the model was "calibrated" to 1989-2012 conditions, although only these five out of dozens of model parameters were estimated by fitting model output to the observed data. The model was insensitive to parameters 1-3, so the actual calibration itself really consisted of estimating two parameters related to tributary contribution to total YCT numbers. Based on the best fit of model output to the 1989-2012 population data (maximum likelihood), we estimated that 6% of total over-winter habitat for age-0 *Oncorhynchus* is found in the tributaries versus 94% in the main river, and that prior to RHT invasion, 37% of total YCT in the SFSR belonged to the tributary-spawning population and the remainder to the river-spawning population. All details of model parameterization and calibration are given in DeVita (2014).

For this report, we initialized the model as it was originally parameterized with observed 2012 population data, replaced stochastic flow inputs with actual flows observed over the 2013-2017 period, replaced stochastic survival rates with actual annual survival observed over the 2013-2017 period, and fixed angler harvest of RHT at 22% annual exploitation. Harvest was restricted to fish of age 2 and older, in proportion to relative abundance of cohorts, and was distributed temporally at 32% during October-March and 68% during April-September. Fecundity, baseline egg-to-fry survival, and growth remained stochastically drawn from the original distributions fit by DeVita (2014) to pre-2012 data. The model was run 2000 times over the 2013-2017 period. We report mean population values and the 90% prediction interval around the mean. We compared observed and model-predicted population over the five-year model period with two measures: root-mean-square-error (RMSE) and mean absolute relative error (MARE), defined below.

$$RMSE = \sqrt{\frac{1}{5}\sum_{i=1}^{5}(observed_i - predicted_i)^2}$$

$$MARE = \sqrt{\frac{1}{5}\sum_{i=1}^{5}\frac{|observed_i - predicted_i|}{observed_i}}$$

RHT and YCT flow-recruitment relationships

RHT and YCT population data collected by the IDFG from 1988 through 2017 were used to investigate the effect of mainstem SFSR flow and environmental variables corresponding to critical life history periods on total RHT+YCT recruitment, species-specific recruitment, and relative recruitment for both populations. Critical life history variables included:

Mean flow during RHT spawning (April 1-May 15)
Mean flow during YCT spawning (May 24-July 7)
Mean flow during RHT emergence (June 15 – July 31)
Mean flow during coldest 90-day period
Mean flow during December 1 – February 28
Max flow during the year
Mean temperature during coldest 90-day period

Flow data for the analysis were collected at the USGS gage at Irwin. Air temperature data were collected at the BoR Agrimet station in Rexburg, ID. A set of candidate models was created and evidence for/against models were based on Akaike's Information Criterion (AICc), following the parsimonious, *a priori* model-selection methods detailed in Burnham and Anderson (2002).

Spring freshet and winter flow management effectiveness

Concurrent geomorphic research found that freshet flows (flows immediately after RHT spawning, May 1- June 30) necessary to effectively mobilize substrate and dislodge RHT eggs from the mainstem SFSR were on the order of 25,000 cfs or greater, for 8-15 consecutive days (Moller and Van Kirk 2003; Hauer et al. 2004). Based both on the statistical analysis of Moller and Van Kirk (2003) and on the geomorphic analysis of Hauer et al. (2004), we reviewed whether spring freshet flows from 2004-2017 met the management objective set for the freshet flow of 25,000 cfs for at least one week in as many years as possible. Additionally, we reviewed whether flows achieved objectives outlined by Hauer et. al (2004) for spring flows of 19,000 cfs for as many days as possible during moderate water years. Additionally, winter flows (December

1 – February 28) were reviewed from 2004-2017 to assess whether flows were above the identified >2000 cfs necessary to optimize RHT and YCT recruitment (DeVita 2014).

Last, RHT population data collected by the Idaho Department of Fish and Game from 1989 through 2017 were used to analyze the effect freshet longevity, magnitude, and minimum/maximum freshet characteristics had on RHT recruitment. Flow data used for the analysis were from the USGS gage station at Heise. Similar to Objective 2, a set of candidate models were created and AICc was used to assess model performance.

Tributary flow effect on YCT recruitment

Environmental variables corresponding to critical periods when juvenile YCT resided in SFSR tributaries were used to predict YCT recruitment. A set of candidate models was created using mean air air temperature and mean tributary flow during July, August, and September during age-0 and age-1 life stages. These periods were identified as critical under the hypothesis that stressful summer tributary conditions force juvenile YCT to out-migrate to the mainstem SFSR where they are subject to increased interspecies competition with larger juvenile RHT. The YCT population data were collected by IDFG from 1989-2017. Air temperature data from the AgriMet station at Rexburg, ID were used as an index for tributary water temperatures. Cumulative tributary flow for the SFSR was calculated as the net river gain from Palisades Dam to the USGS gage station at Heise, ID. Evidence for/against candidate models were based on Akaike's Information Criterion (AICc), following the parsimonious, *a priori* model-selection methods detailed in Burnham and Anderson (2002).

Results

Assessment of DeVita (2014) model performance

Predicted YCT abundance was reasonably close to observed abundance and successfully captured the slight decreasing trend in the YCT population between 2012 and 2017 (Figure 2). The RMSE was 1,148, roughly 20% of the mean population over the model period, consistent with the MARE of 19%. However, the 90% prediction interval contained observed values in only two of the five model years. Model performance in predicting RHT abundance was much worse (Figure 3). Although the 2017 prediction was essentially equal to the observed value, RMSE was 3,070, and MARE was 55%. The 90% prediction interval contained the actual population value in only one of the five model years.

RHT and YCT flow-recruitment relationships

Recruitment of both RHT and YCT depended positively on flow during the cohort's first winter (mean flow from December 1- February 28). Fit with a logistic function, mean winter flow up to roughly 1,800 cfs had significant benefits for winter survival and recruitment for both species, but flows exceeding 1,800 cfs provided only marginal benefits (Figure 4). The model-selection results showed that winter and spawning-season flows were positively associated with RHT recruitment and were the most important predictors of RHT recruitment. One or both of these variables were included in the top four models, which accounted for a cumulative model weight of 75% (Table 1).

Similarly, winter flows and spring flows had a positive relationship to YCT recruitment as well. The top four models had comparable AICc scores, with winter flow being the best model out of the YCT recruit multi-model selection (Table 2).

Spring freshet and winter flow management effectiveness

Freshet flows never reached the recommended >25,000 cfs in any year since the three-pronged approach was initiated in 2004 (Table 3). Freshet flows exceeded 19,000 cfs in only five years (2006, 2009, 2010, 2011, and 2017), and in these five years, mean duration of flows exceeding 19,000 cfs was 12.4 days. Even though several years between 2004 and 2017 were above-average water years, flood control management below Palisades Dam restricted flows from reaching >25,000 cfs necessary to mobilize substrate and dislodge RHT eggs.

Freshet duration (number of days with flows >19,000 cfs and >25,000 cfs), freshet magnitude, and the ratio of mean flow during RHT spawning to freshet maximum from 1989-2017 showed no statistically significant relationship to RHT recruitment. This reinforces prior literature and recommendations that effective freshet flows need be at least 25,000 cfs in magnitude and sustained for sufficient duration to be effective at depressing RHT recruitment.

Last, mean winter flows (December 1 – February 28) for the SFSR exceeded 1,800 cfs only in 2012, following a year in which very little storage water was delivered from the entire upper Snake River reservoir system. Winter flows from 2004-2017 averaged 1,311 cfs.

Tributary flow effect on YCT recruitment

Results from the multi-model selection process showed the model with mean August temperature during a cohort's first summer (at age 0) was the best predictor for YCT recruitment (Table 4). The two next best models were within 2 AICc values of the top model; one model included both July and August mean temperatures at age 0, and the other included August mean temperatures at age 0 and age 1. Monthly mean flow did not appear to have a significant effect on YCT recruitment nor did conditions in September.

In all models containing temperature, recruitment was a decreasing function of temperature. The top model, with age-0 mean August temperature as the only predictor, accounted for 30% of the total sum-of-squares (Figure 5). The second-best model, which included mean July and August temperatures at age-0, accounted for more variability in recruitment but only slightly more so than the top model, at a cost of one extra fitted coefficient. The third model, which included August mean temperatures at age 0 and age 1 performed similarly to the second model, but August mean temperature at age 1 had a positive relationship to YCT recruitment, in contrast to the negative relationship with August mean temperature at age 0. It is evident that increased temperatures during late summer of a cohort's first year negatively affect YCT recruitment.

Additionally, July had the hottest mean monthly air temperature (65.8 F), slightly warmer than mean temperature in August (64.6 F). Mean tributary flow in August was 12.2% lower than mean tributary flows in July, which may explain why August temperatures had a greater effect on YCT recruitment than July temperatures. Comparing July and August air temperatures to tributary temperatures from 2010-2017, the correlation between air temperature and tributary temperature was much stronger in August than in July (Figure 5 & 6).

Discussion

Some of the results of this report echo those from prior research done over the last decade, particularly with respect to conditions in the tributaries during a YCT cohort's first year and the effects of winter flow in the main river on both species. These two flow-dependent effects are included in DeVita's model, although the tributary conditions appear in the model as late-summer flow, whereas the analysis here shows that temperature is more important than flow. In general, DeVita's model captured general interannual variability and trends in the YCT population fairly well. A prediction error of around 20% is sufficiently low for management purposes, indicating that the basic demographic and environmental dynamics acting on YCT prior to 2012 are still present. This relatively low error rate also suggests that the two calibrated parameters describing tributary contributions to the YCT population are roughly correct.

However, the model did not predict the RHT population any better than random selection from an empirical distribution fit to the existing data—with no external predictors or internal dynamics included. This suggests that 1) the model was based on incorrect assumptions about environmental factors affecting RHT dynamics, 2) the 2013-2017 model inputs were incorrect, and/or 3) factors affecting the RHT population have changed since 2012.

Our updated statistical modeling confirmed the earlier observations that recruitment of both species is a positive function of winter flow at Palisades Dam, so this aspect of DeVita's model remains correct. Freshet-induced mortality of RHT in the model occurs above a threshold at 25,000 cfs, below which spring-time peak flows have little effect on RHT reproductive success. Although the model predicts a theoretical freshet effect, the actual flow values used in the 2013-2017 did not reach this threshold, so the freshet effect, or lack thereof, does not provide an explanation for poor model performance in predicting RHT abundance. However, the updated statistical analysis provided evidence that higher spring-time flows actually led to increased RHT recruitment (Table 1). This effect is not included in DeVita's model, which may contribute to its poor predictive ability for RHT.

Model inputs for the 2013-2017 period included flow values, which are known with certainty, and RHT exploitation rates, which were estimated from a creel survey in 2012 but not subsequently. We assumed that the same exploitation and harvest characteristics estimated in 2012 applied to the entire 2013-2017 period. Deviations from these assumed harvest characteristics could also explain poor model predictions for RHT.

Finally, the model could perform poorly for RHT because the dynamics of the RHT population have changed since 2012. The model-calibration period contained 16 years over which the primary population trend was displacement of YCT by RHT and only 8 years since the implementation of the three-prong approach, when YCT and RHT numbers have been roughly equal and relatively stable. It is possible that reproductive isolation via the tributary weir program has allowed persistence of a relatively stable YCT population that may now interact very little with the RHT population. The model correctly captures this situation from the YCT perspective because it tracks tributary-spawned and river-spawned YCT separately. However, during the early part of the RHT invasion, the RHT population was most likely driven by hybridization and not by environmental factors, whereas now it is probably driven primarily by environmental factors. Thus, the model could have performed well during the early part of the invasion despite incorrect assumptions about environmental factors but now performs poorly because these factors are not correctly quantified. Further research will be necessary to understand and correctly account for these factors.

Updated statistical modeling confirmed the earlier observations that recruitment of both species is a positive function of winter flow at Palisades Dam. Maintaining winter flows roughly >=1,800 cfs was optimal for maximizing RHT and YCT recruitment without releasing excess storage water out of Palisades Reservoir. At flows below 1,800 cfs, increases in flow lead to increases in winter habitat. However, given the geomporphology of the South Fork, as flows exceed 1,800 cfs, it is likely that new bank habitat becomes available for juvenile trout, while at the same time, velocities of some mid-river habitat becomes too fast and unsuitable for juvenile trout.

Freshet flows never reached the recommended >25,000 cfs, so essentially no data were available to statistically test the theory that mobilizing substrate would decrease RHT recruitment. Under the current flood control management restrictions, it is unlikely that flows may ever exceed 25,000 cfs to test the freshet hypothesis. Furthermore, given the positive dependence of RHT recruitment on flows during the spring and early summer, the current freshet operation—with magnitudes well below the 25,000-cfs threshold—may actually be increasing RHT reproductive success rather than decreasing it. Nonetheless, a freshet delivered during the time period of the river's natural peak flow still has benefit to the river ecosystem by maintaining ecological processes in the stream channel and floodplain. In the long run, these processes maintain trout habitat necessary for YCT persistence, but management actions other than the freshet will be needed to favor YCT recruitment over that of RHT.

The statistical analysis presented here shows that increased temperatures during July and August of a YCT cohort's first year have a negative effect on YCT recruitment. Use of August air temperature as a proxy for August water temperature was supported by the statistically significant relationship we found between the air and water temperatures. The stronger dependence on temperature rather than on flow, as was suggested by previous analyses, may reflect the increasing effect of a warming climate, in which temperature may play a more important role than flow per se. In a meta-analysis, Kovach et al. (2016) found that although summer streamflow was most often reported as affecting salmonids, summer and autumn temperature was frequently reported as having negative effects on trout survival. The exact mechanism between summer temperature and YCT recruitment is unknown. It is likely that warm temperatures reduce suitable habitat within tributaries and increase competition for the remaining habitat, leading either to lower survival of juvenile YCT or to increased out-migration from tributaries to the main river, where they face increased interspecies competition with RHT.

Implications for Management

Maximize winter flow, and maintain a minimum mean flow of 1,800 cfs from December 1-February 28. Maximizing winter flows under irrigation storage requirements should be a primary goal to increase juvenile YCT and RHT survival and recruitment. Winter flows are largely dictated by the amount of water needed to fill upstream storage reservoirs. Managing to aggressively minimize delivery of storage water during the summer and initiate storage as early in the fall as possible could provide additional water for winter flows, as has been done successfully with Island Park Reservoir. Furthermore, coordinated system-wide management, as well as development of additional managed recharge capacity, could provide options for maintaining a minimum winter flow of 1,800 cfs without risk of spilling water out of the upper Snake River system.

Maximize spring flows to maintain ecological processes in the stream channel and floodplain. Results from the flow analysis show that both RHT and YCT recruitment increase with increased spring-time flows, at least when these flows are below 25,000 cfs. The increase in recruitment is likely due to additional bank habitat becoming available for juvenile trout during high water. Ideally, freshet flows would exceed 25,000 cfs, mobilizing substrate, dislodging RHT eggs, and providing flood plain habitat and forage for juvenile YCT trout. Unfortunately, this is not likely to happen due to flood management constraints (see below). It is still recommended that spring flows be as great as possible, for as long as possible, to maintain channel and floodplain processes that provide trout habitat in the long run.

Achieving freshet flows >25,000 cfs may not be possible under flood management constraints. Due to flood control restrictions, flows below Palisades Dam may never reach the levels necessary to mobilize substrate and dislodge RHT eggs during the spring freshet period. Even in average- to above-average water years such as 2008, 2009, 2010, and 2011, freshet flows never exceeded 25,000 cfs. Additionally, it would take many years with flows above 25,000 cfs to be able to conduct a statistical test of sufficient power to determine whether freshet flows were effective at decreasing RHT recruitment. As such, it is recommended that efforts to increase angler harvest of RHT continue and that additional research into YCT/RHT interactions and life-history strategies be conducted to find effective alternatives to the freshet in favoring YCT over RHT.

Future Research

Modify and update DeVita's model. These modifications would first include replacing existing flow-dependent relationships with the new ones reported here. Second, the model should be re-calibrated to the 2004-2017 time period to reflect dynamics since implementation of the three-prong approach. Third, the number of degrees of freedom in the calibration could be reduced by two by eliminating the freshet effect, if it is apparent that freshet flows will never reach 25,000 cfs anyway. This would increase precision in calibration of the remaining parameters.

Run simulation scenarios with updated DeVita model. Using the updated DeVita model, run predictive simulations to understand how different scenarios of winter flow, angler harvest rate, etc. may affect RHT and YCT populations. Results from simulation scenarios would be useful for optimizing multifaceted management strategies.

Investigate sources of YCT recruitment. The reasonably good performance of DeVita's model in predicting the YCT population provides some evidence that the YCT population is segregated into tributary- and river-spawning subpopulations. However, the distribution of the YCT population among these two groups is an unknown model parameter estimated only through calibration. Our understanding of YCT recruitment, as well as of current YCT-RHT dynamics, would be improved through empirical estimation of relative sources of YCT recruitment, both between river and tributaries and among the tributaries themselves. This understanding would not only improve the predictive model but would also allow prioritization of tributary restoration and habitat enhancement.

Investigate YCT and RHT population trends in the lowest reach of the SFSR (Twin Bridges to confluence of Henry's Fork River). While RHT are displacing YCT in the upper reaches of the SFSR (Conant reach), RHT have not begun to significantly invade or displace YCT in the lower sections of the SFSR. In addition, warmer temperatures and minimal access to tributaries make the lower reach appear more suitable for RHT than YCT. Yet, YCT abundances remain stable and RHT abundances remain low. Moller and Van Kirk (2004) provided evidence that the shape of the hydrologic regime in this reach of the South Fork is less altered than that in the upper reach, possibly limiting RHT reproductive success. Additional years of data and increased understanding of groundwater-surface water interactions, which are relevant to the hydrology of the lower South Fork, could provide more understanding of relationships between flow and trout population dynamics than were possible in the early 2000s.

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Tables

Table 1. AICc results for the top eight models predicting RHT recruitment using mean flow during RHT spawning (April 1-May 15), mean flow during RHT emergence (June 15 – July 31), mean flow winter flow (December 1 – February 28), max flow during the year, and mean winter temperature (temperature during coldest 90-day period).

Model	Parameters	LogL	AICc	Δ AICc	Weight	Cumulative weight
Winter Flow + Emergence Flow	5	-30.55	75.38	0.00	0.36	0.36
Winter Flow + Max Flow	5	-32.28	77.29	1.91	0.14	0.50
Winter Flow + Winter Temp	5	-31.61	77.50	2.12	0.13	0.63
Winter Flow	4	-33.50	77.66	2.28	0.12	0.75
Winter Temp	3	-35.44	77.87	2.49	0.10	0.85
Null	2	-37.05	78.81	3.43	0.07	0.92
Emergence Flow	3	-36.48	80.46	5.08	0.03	0.97
Spawning Flow	3	-36.85	80.70	5.32	0.02	0.99

Table 2. AICc results for the top ten models predicting YCT recruitment including mean flow during YCT spawning (May 24-July 7), mean flow during RHT emergence (June 15 – July 31), mean flow winter flow (December 1 – February 28), max flow during the year, and mean winter temperature (temperature during coldest 90-day period).

Model	Parameters	LogL	AICc	Δ AICc	Weight	Cumulative weight
Winter Flow	5	-22.13	58.55	0.00	0.21	0.21
Emergence Flow	3	-25.73	58.97	0.42	0.17	0.37
Winter Temp	3	-26.02	59.14	0.59	0.15	0.53
Spawning Flow	3	-26.03	59.16	0.60	0.15	0.68
Null	2	-27.35	59.40	0.85	0.13	0.81
Winter Flow + Emergence Flow	5	-23.20	60.70	2.14	0.07	0.88
Spawning Flow + Max Flow	4	-25.59	61.08	2.53	0.06	0.94
Winter Flow + Spawning Flow + Winter Temp	6	-23.63	63.68	5.13	0.02	0.96
Winter Flow + Max Flow	5	-25.73	64.46	5.91	0.01	0.97
Spawning Flow+Emergence Flow+Winter Temp	5	-25.23	64.74	6.19	0.01	0.98

Table 3. Maximum freshet flow (flow between May 1- June 30), number of days with flows greater than 19,000 cfs, number of days with flows greater than 25,000 cfs, ratio of mean flow during Rainbow/Hybrid Trout spawning (April 1-May 15) to maximum freshet flow, and winter flow (mean flow December 1 – February 28), for the South Fork Snake River, ID, since the beginning of the three-prong approach management strategy, 2004-2017.

Year	Max freshet flow (cfs)	# days with flow >19,000 cfs	# days with flow >25,000 cfs	Spawning-freshet ratio	Winter flow (cfs)
2004	19000	0	0	0.2867	946
2005	14900	0	0	0.2071	897
2006	19500	1	0	0.5447	1392
2007	18500	0	0	0.2611	1472
2008	18200	0	0	0.199	801
2009	23600	10	0	0.5377	921
2010	23200	5	0	0.1495	1525
2011	23100	21	0	0.6634	1630
2012	13800	0	0	0.6609	3138
2013	18000	0	0	0.2668	947
2014	18400	0	0	0.4731	1170
2015	17000	0	0	0.5588	1282
2016	17100	0	0	0.3598	904
2017	24100	25	0	0.677	1328

Table 4. AICc results for the top ten models predicting YCT recruitment using mean South Fork Snake River tributary flow and air air temperature in July, August, and September during YCT Age-0 and Age-1 life-stages.

Model	Parameters	LogL	AICc	Δ AICc	Weight	Cumulative weight
Age-0 Aug Temp	3	-22.28	51.71	0.00	0.44	0.44
Age-0 July Temp*Age-0 Aug Temp	4	-21.82	53.64	1.93	0.17	0.61
Age-0 Aug Temp*Age-1 Aug Temp	4	-21.82	53.65	1.93	0.17	0.77
Age-0 July Temp	3	-24.63	56.41	4.70	0.04	0.82
Age-0 July Temp*Age-0 July Flow	5	-21.75	56.66	4.95	0.04	0.85
Age-0 Aug temp* Age-0 Aug Flow	5	-21.77	56.69	4.98	0.04	0.89
Null	2	-26.78	58.10	6.39	0.02	0.91
Age-1 Aug Temp	3	-25.65	58.44	6.72	0.02	0.92
Age-0 July Temp* Age-1 July Temp	4	-24.46	58.93	7.21	0.01	0.93
Age-1 Sept Flow	3	-26.08	59.30	7.59	0.01	0.94

Figures

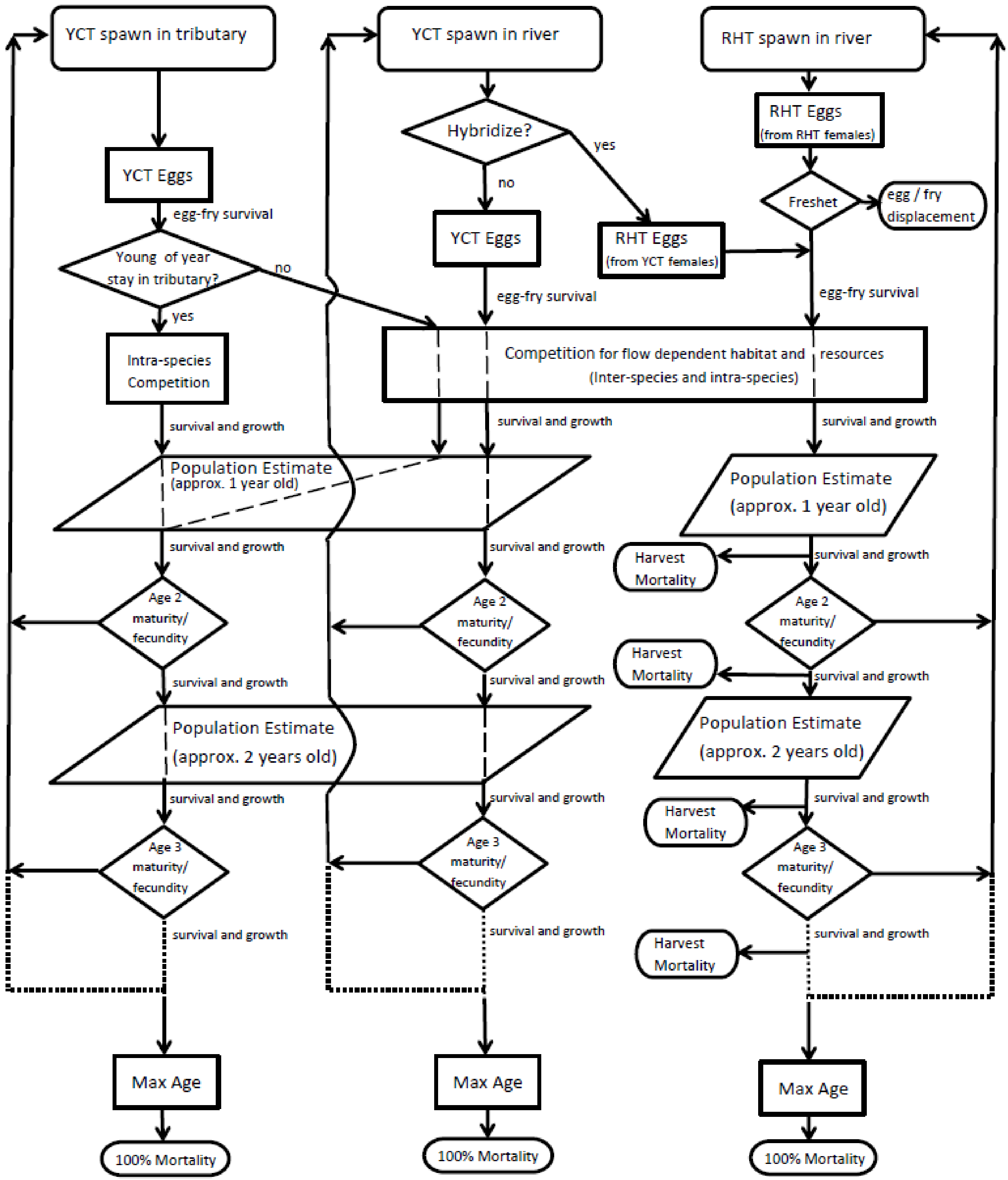

Figure 1. Figure 1. Flow chart of the DeVita (2014) simulation model.

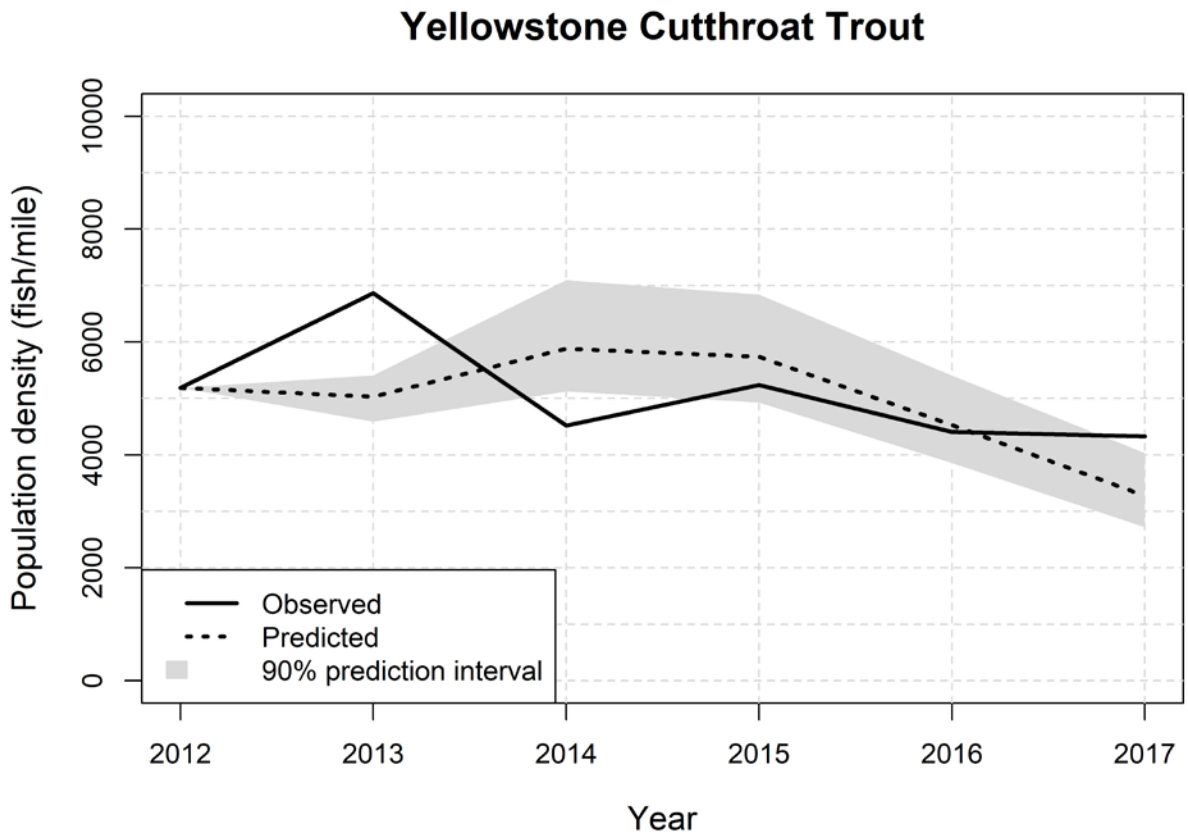

Figure 2. Observed and model-predicted Yellowstone Cutthroat Trout population density in the Conant Reach of the South Fork Snake River, 2013-2017.

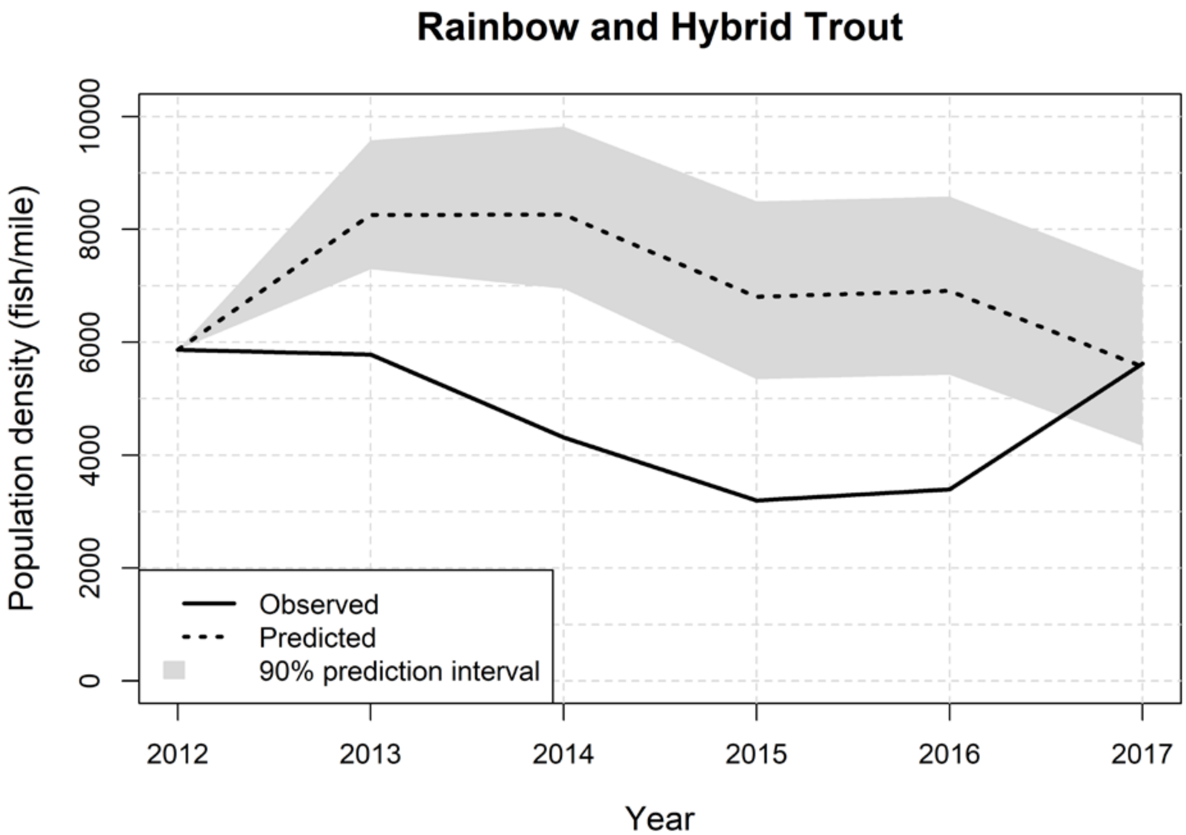

Figure 3. Observed and model-predicted Rainbow and Hybrid Trout population density in the Conant Reach of the South Fork Snake River, 2013-2017.

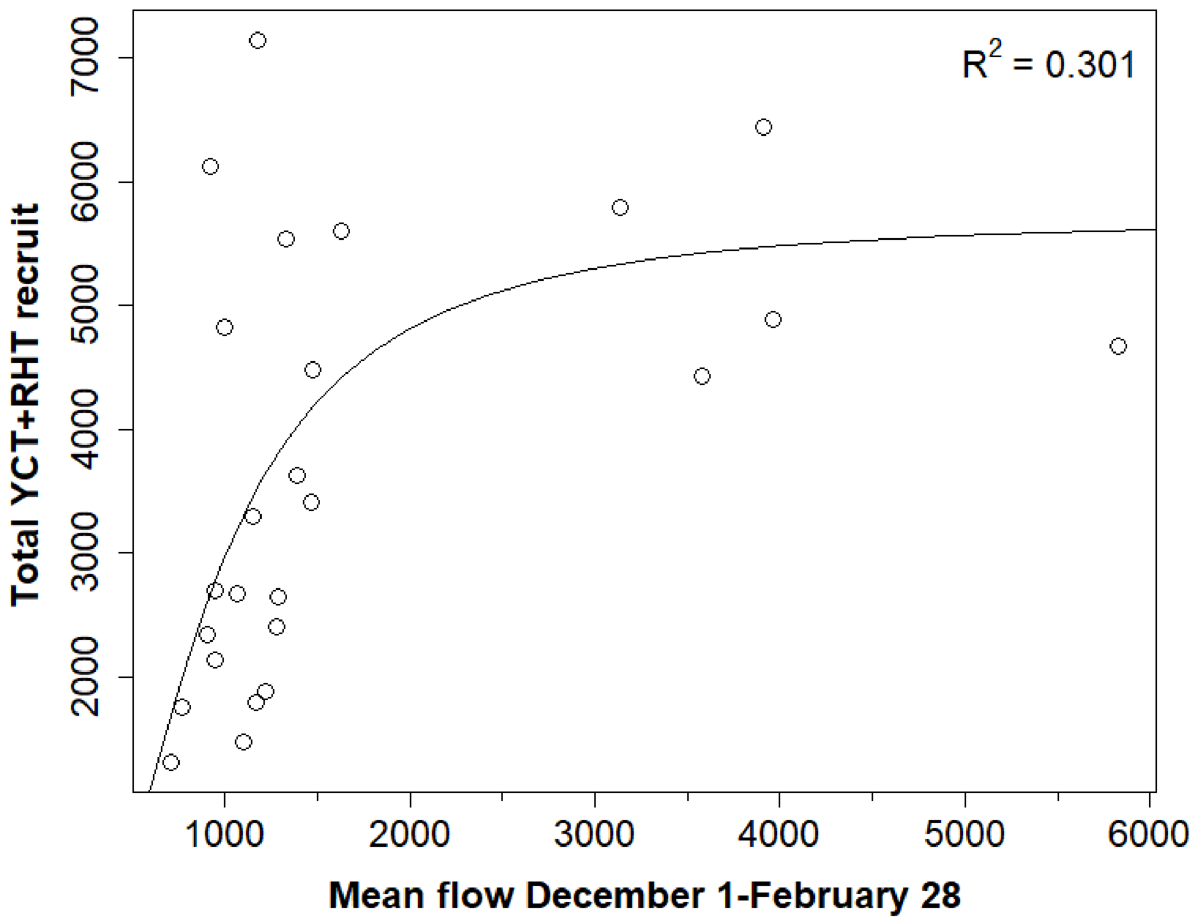

Figure 4. Total Rainbow/Hybrid and Yellowstone Cutthroat Trout recruitment as a function of mean winter flow (December 1- February 28) on the South Fork Snake River, with logistic model fit to the data, 1988-2017.

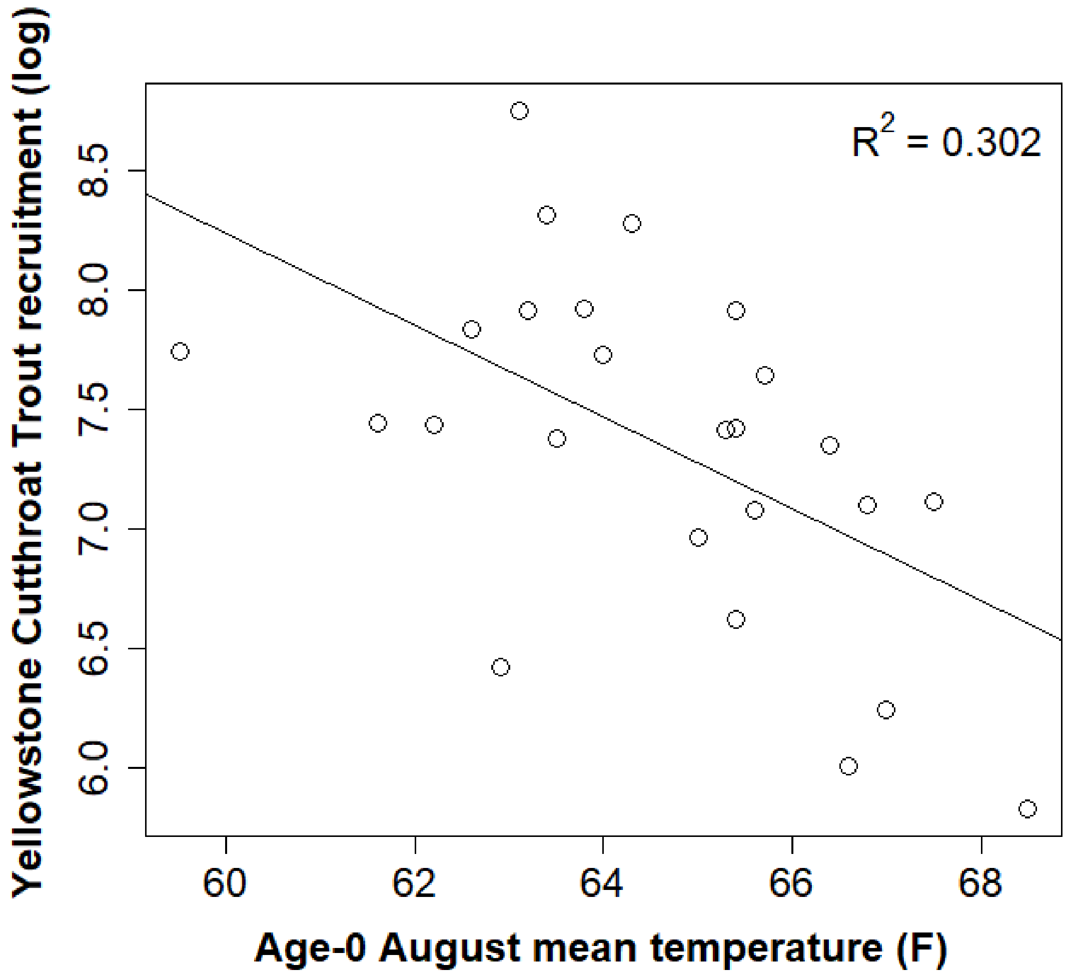

Figure 5. South Fork Snake River Yellowstone Cutthroat Trout recruitment as a function of August mean air temperature during a cohort's first (age-0) summer, 1989-2017.

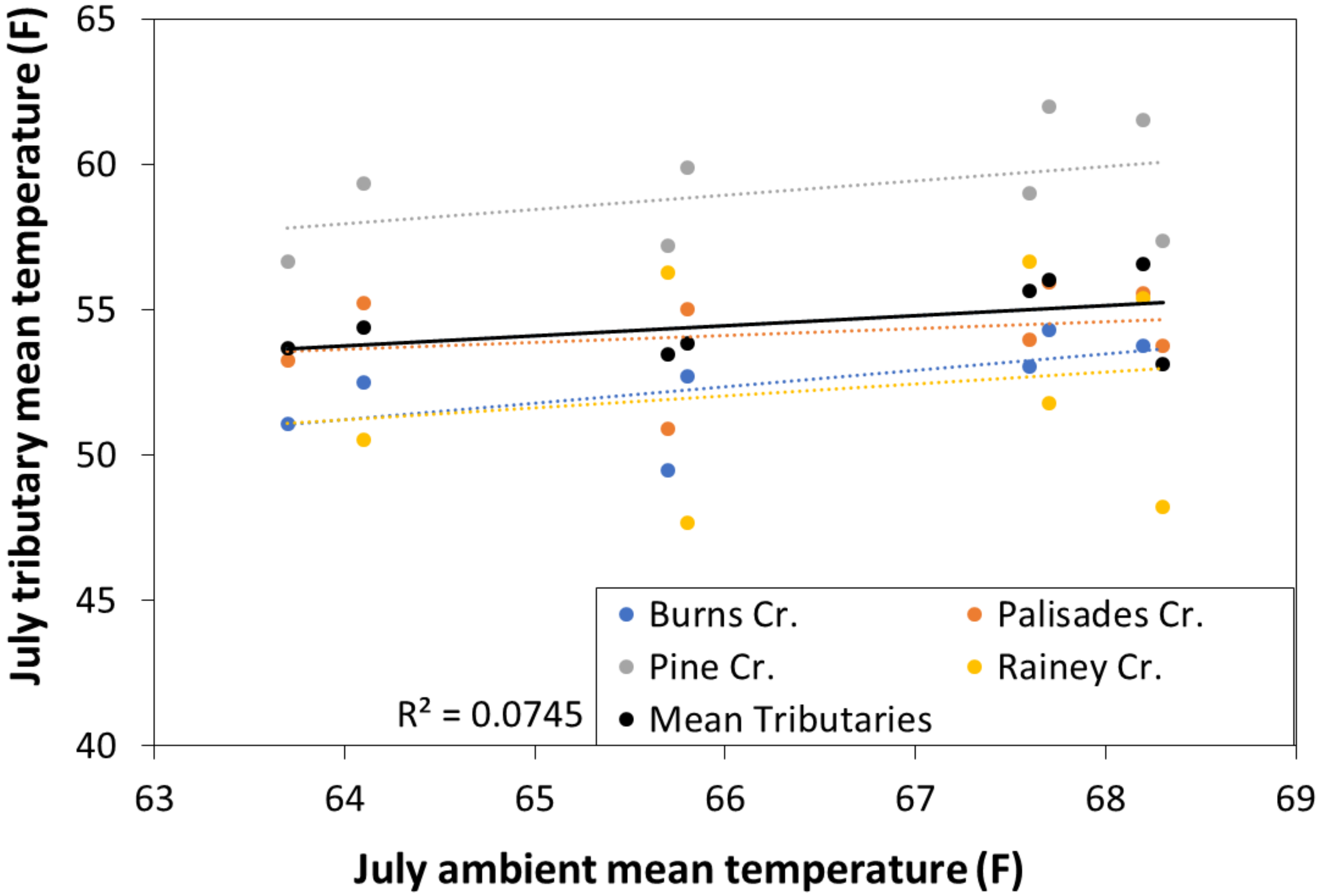

Figure 6. July mean water temperature of four primary Yellowstone Cutthroat Trout spawning tributaries of the South Fork Snake River versus July ambient air temperature at the Bureau of Reclamation (BoR) Agrimet station in Rexburg, ID to 2010-2017. R^2 value is for the regression line fit to the mean July temperature averaged over all tributaries.

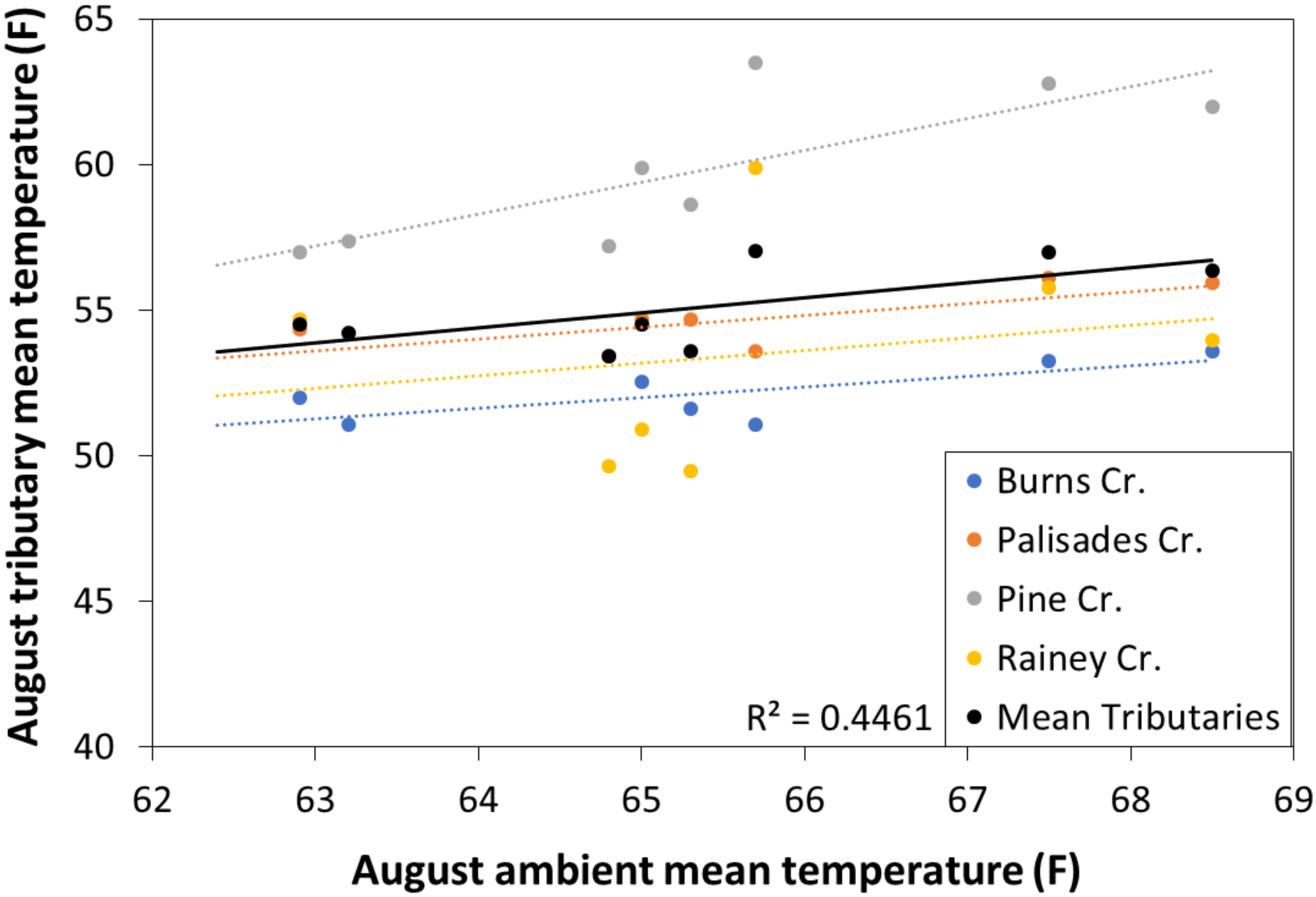

Figure 7. August mean water temperature of four primary Yellowstone Cutthroat Trout spawning tributaries of the South Fork Snake River versus July ambient air temperature at the Bureau of Reclamation (BoR) Agrimet station in Rexburg, ID to 2010-2017. R^2 value is for the regression line fit to the mean August temperature averaged over all tributaries.