The Influence of Size and Growth Rate on Outmigration Timing in Coho Salmon (*Oncorhynchus kisutch*) Smolts

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ABSTRACT

Coho salmon (*Oncorhynchus kisutch*) are on the brink of extinction in central California. The period of salmon migration from feshwater to the marine environment greatly influences prospects for survival in the ocean and subsequent migration to freshwater to reproduce. Smolt scales and other body size parameters from the spring 2009 outmigration of coho salmon on Lagunitas Creek (Marin County, CA) were analyzed to determine the influence of body size and growth rate on migration timing. Fork length was negatively and significantly correlated to the date of migration (r^2 = 0.04, p = 0.013). The residuals from the regression of number of circuli on fork length, which can be used as a proxy for growth rate, were negatively and significantly correlated to the date of migration (r^2 = 0.10, p < 0.0001). Although both growth rate and absolute size were significantly related to migration date, growth rate appears to exert a stronger influence because it is explains more of the variation in migration date. Faster growing coho are able to leave freshwater earlier, and in doing so they confer several advantages upon entering the marine environment that increase their chance of survival.

KEYWORDS

Lagunitas Creek, scales, residual analysis, migration patterns, circuli

INTRODUCTION

Coho salmon (*Oncorhynchus kisutch*), an important component of California's native biodiversity, are on the brink of extinction in California (Miller 2010). The causes of this decline have been attributed to a variety of factors, including dam construction, diversion of water, over-harvesting in the ocean, greater variability in ocean conditions, and climatic events (Carlisle et al. 2008). In 1996 all coho populations in the West Coast were designated as threatened under the Endangered Species Act (Federal Register 1996) and divided into several Environmentally Significant Units (ESUs). An ESU is a population or group of populations that are (1) reproductively isolated from other populations of the same species and (2) comprise an important component in the evolutionary legacy of the species (Waples 1991). The California Central Coast ESU (CCC ESU), which is located in California between Punta Gorda and the San Lorenzo River (NMFS 2008), is of particular interest for this study. As the largest and most stable coho population in the CCC ESU, the Lagunitas Creek system is where coho salmon have the greatest chances for survival (Moyle 2008). Coho population numbers within the CCC ESU have significantly dropped from between 50,000 and 125,000 individuals in the 1940s to only 6,000 individuals in 1996 (Federal Register 1996). Because of these severe declines, the status of CCC ESU coho was changed from threatened to endangered under the ESA in 2005 (Carlisle et al. 2008). In order to better manage these endangered populations, it is crucial to understand factors impacting their survival.

Studying the emigration period of coho salmon allows for better understanding of migration patterns and timing. Coho salmon life history normally occurs over a three year span, during which time they live in both freshwater and marine environments, and have two critical migration periods that characterize their life history. Coho are born in freshwater, where they remain for one year before migrating to the ocean. After eighteen months in the ocean, coho return as adults to their natal freshwater habitat spawn (CDFG accessed 14 Mar 2009). The period of transition between freshwater and saltwater is considered to be a "critical period" because an individual's prospects for survival and subsequent migration to freshwater to reproduce are dependent on the first year in the marine environment (Quinn 2005). Coho migrate to the ocean because there is a greater abundance of food resources, which allow for faster growth and ultimately prepare salmon for migration back upstream. Migration from the ocean back to freshwater streams offers adult coho safer spawning and rearing sites than the marine environment (Beamish 2005). Scheuerell et al. (2009) found that Chinook (*O. tshawytscha)* and steelhead (*O. mykiss)* that migrated to the ocean earlier tended to exhibit higher survival rates. Pearcy (1992) found that migration occurs at a time that optimizes the availability of food in the ocean and minimizes the abundance of predators. In other words, salmon enter the marine environment when conditions for growth and survival are optimal.

Analysis of fish scales is often a useful method of determining body size, which is an important factor to consider when studying coho migration. Fish scales grow much like tree rings; however, in fish the circuli (dark concentric rings) are laid down sub-monthly for juvenile salmonids. The distance between circuli reflects the amount of growth during that period, and has been shown to correlate strongly with scale growth rate in coho salmon (Holtby et al. 1990; Fischer and Pearcy 2005). Similarly, Fisher and Pearcy (1990) found that the rate of circuli formation was significantly and positively correlated to the rate of overall growth of coho salmon smolts. Many studies have focused on the influence of size during the migration period on survival (e.g. Matthews and Ishida 1989, Quinn and Peterson 1996, Brakensiek and Hankin 2007), but relatively few have studied how body size and growth rate may be related to the specific timing at the onset of migration, especially in California populations of coho salmon.

The purpose of this study is to determine the influence of absolute body size and growth rate on the migration timing of coho salmon smolts from Lagunitas Creek (Marin County, CA) using scale samples collected from Lagunitas Creek coho smolts during the spring 2009 migration. I hypothesize that growth rate will have a significant impact on the timing of downstream migration timing, and absolute body size will not significantly impact migration timing.

METHODS

Study site

Lagunitas Creek, located within the California Central Coast ESU (Fig. 1) is a perennial stream that originates in Mt. Tamalpias and flows 40 km northwest into Tomales Bay before entering the Pacific Ocean. The creek, located to the east of the San Andreas Fault, drains an area of 211 km^2 (Niemi and Hall 1996). Vegetation on the stream banks consists primary of willow (*Salix sp.)* and alder (*Alnus sp.*). Four dams along the creek regulate streamflow and create reservoirs, which provide water for more than 170,000 people in Marin County.

Maximum mean daily discharge ranges from 1,200-3,800 cfs during winter to about 3 cfs during summer (CDFG 2002, King 2004).

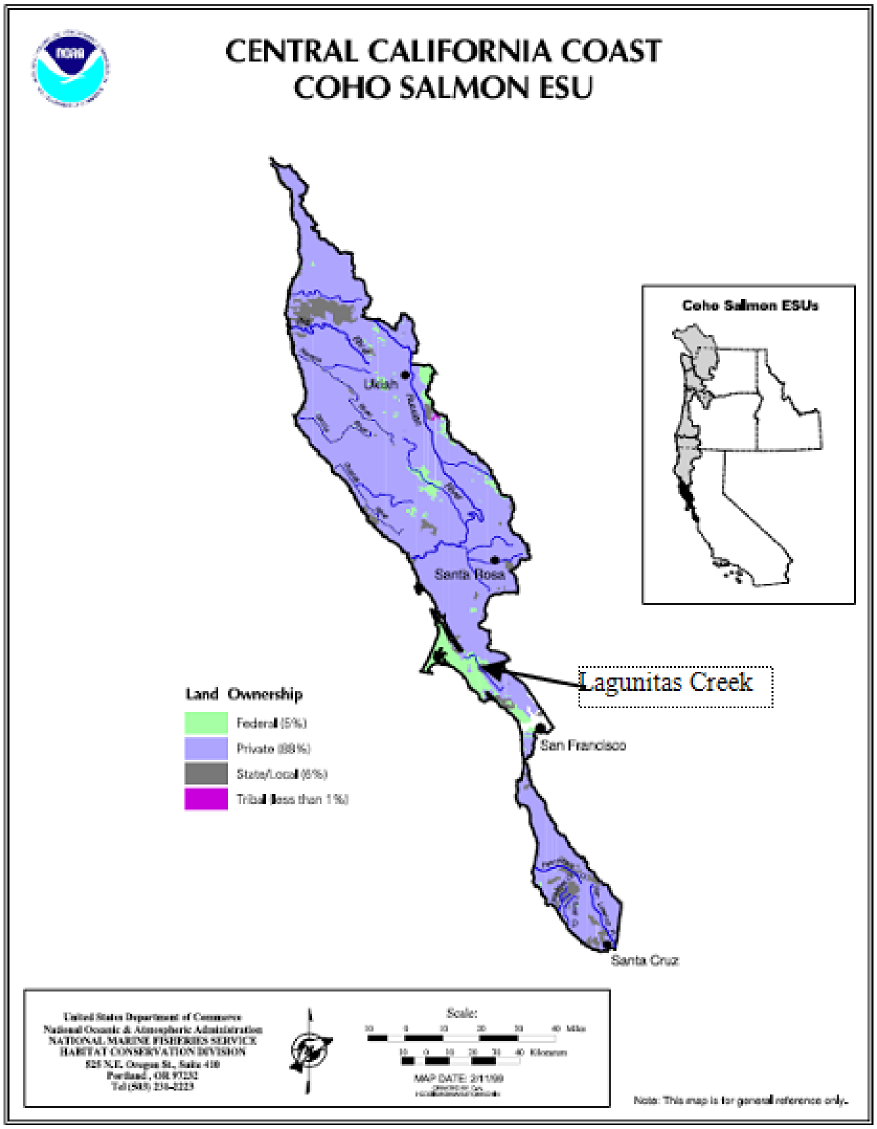

Figure 1. Map of California Central Coast Evolutionarily Significant Unit. Lagunitas Creek is indicated with an arrow. (National Marine Fisheries Service, 1999).

Scale Collection

I used fish scale analysis to estimate growth rates. Scales are easily collected and prepared and do not require lethal sampling. Fish scales and body size parameters from 156 coho smolts were collected from Lagunitas Creek as part of salmonid monitoring efforts by the Marin Municipal Water District (MMWD) and Stillwater Sciences. Because of endangered species permitting restrictions, I was unable to participate in the scale collection. Stillwater and MMWD caught the fish with a rotary screw trap, which is a passive trapping method used to capture fish moving downstream. Stillwater and MMWD monitored the coho smolts in Lagunitas Creek between March 27, 2009 and June 2, 2009. Scales were collected daily during the first half of this period, and the weekly during the second half because the collectors felt that scale collection from fish of the same year was becoming redundant. Stillwater and MMWD collected scales from the region above the lateral line and between the dorsal and adipose fins by running a knife blade across the region two or three times.

Scale Processing and Measurement

I rinsed the scales with deionized water and used an ultrasonic cleaner to remove debris particles. I examined the cleaned scales under a dissecting microscope and gently removed any remaining debris with tweezers. After one final ultrasonic cleaning, I mounted the scales onto slides. I chose the least damaged scale from each smolt and photographed it using a digital camera (Canon EOS Rebel XS, Canon Inc., Lake Success, NY, USA) mounted to a microscope (Bond et al. 2008). I used ImageJ software and the MeasureCumulativeDistances macro (ImageJ, National Health Institute) to measure the number of circuli and the scale radius (measured as the distance between the first circulus and the scale edge along the 45 degree axis) (Fig. 2).

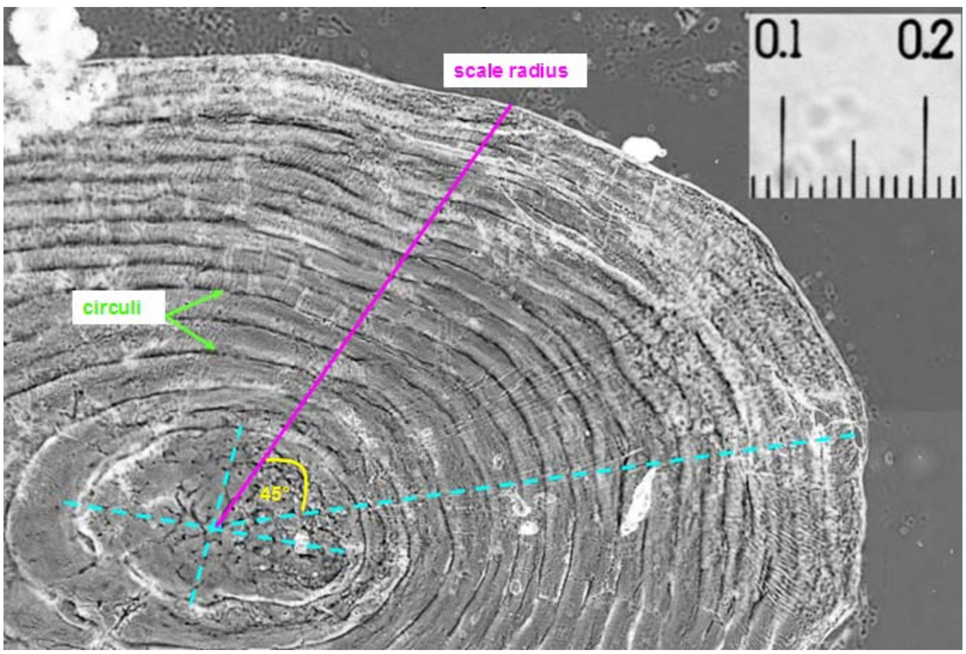

Figure 2. Measurements taken in ImageJ for each coho salmon smolt scale. Dotted lines represent lines that were drawn in order to find the scale radius.

Statistical Analysis

All statistical analyses were performed using the R Commander package in R statistical software (R 2.10.1, The R Project for Statistical Computing). I determined the relationship between fork length, scale length, and number of circuli in order to assess the strength of subsequent analyses using these data. To determine whether body size influences migration timing, I plotted each of the body size parameters against migration date. Finally, to determine the influence of growth rate on the date of migration, I plotted the residuals from the scatterplot of the number of circuli vs. fork length relationship. The residuals can be thought of as a proxy for growth rate because of a previous study by Fisher and Pearcy (1990), who found that the rate of circuli formation was highly correlated to the overall growth rate of coho smolts. Using this information, I assumed that for two smolts with the same fork length, the smolt with a greater number of circuli must have grown faster than the smolt with fewer circuli. Smolts with larger, more positive residual values were assumed to be faster growing than smolts with large, negative residual values. Residual analysis will allow for the comparison of smolts with different fork lengths. I assume that the scales are a random sample from the overall population of coho smolts on Lagunitas Creek that migrated to the ocean during spring 2009.

RESULTS

Scale length, number of circuli, and fork length were all significantly and positively correlated to one another (Fig. 3). However, these relationships were fairly weak. The strongest relationship was between the two scale measurements, number of circuli and scale length ($r^2 = 0.60$, $p<0.001$), while the weakest was between scale length and fork length ($r^2 = 0.22$, $p<0.001$). The relationship between number of circuli and fork length was also quite weak ($r^2 = 0.30$, $p<0.001$).

Scale length, number of circuli, and fork length were each significantly and negatively correlated to migration date (Fig. 4). Fork length was the most weakly related to migration date of the three parameters ($r^2 = 0.04$, $p = 0.013$). Scale length explained 11% of the variation in migration date, while the number of circuli explained 14% of migration date variation.

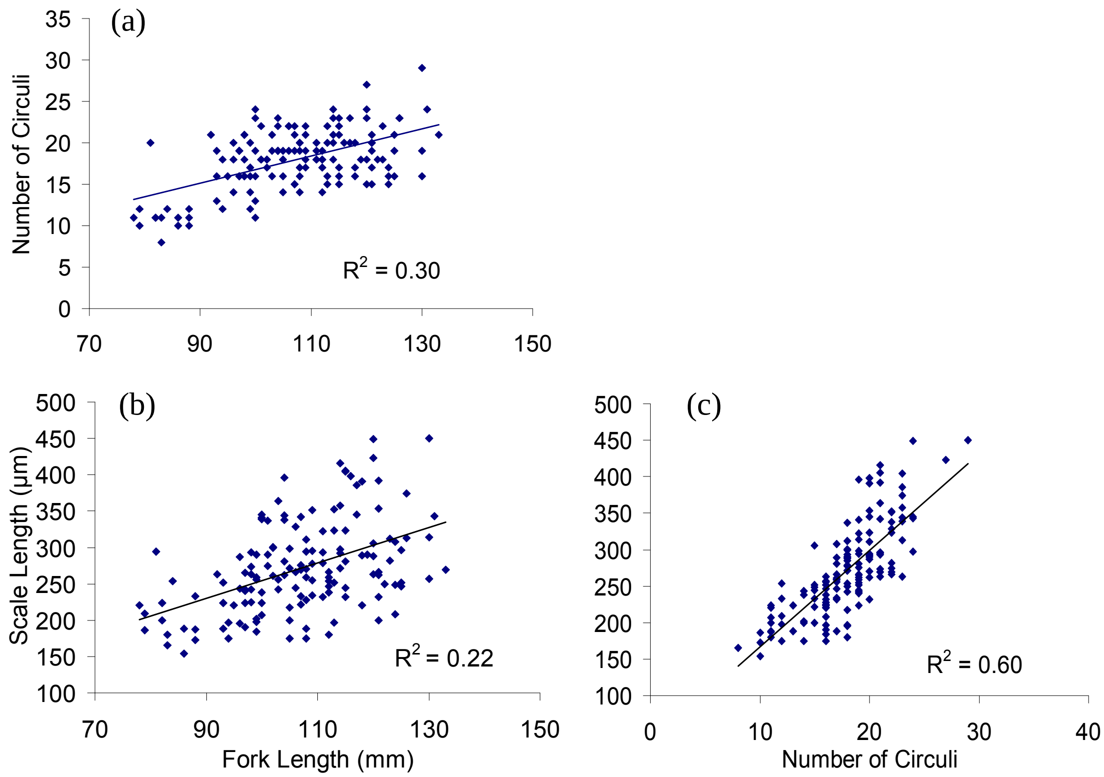

Figure 3. Relationships among size parameters. Scatterplots for (a) number of circuli vs. fork length, (b) scale length vs. fork length, (c) scale length vs. number of circuli.

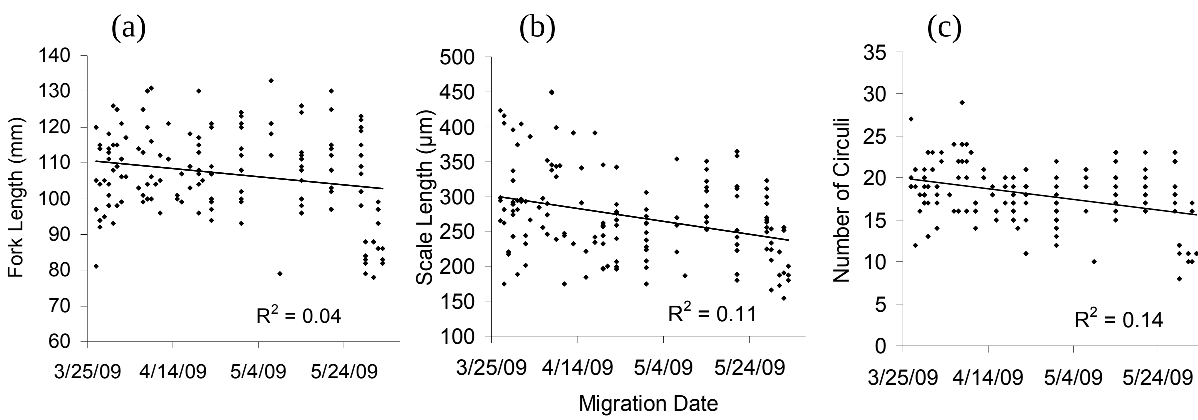

Figure 4. Relationships between size parameters and migration date. Scatterplots for (a) fork length, (b) scale length, and (c) number of circuli versus migration date.

The residuals from the regression of number of circuli on fork length, which can be used as a proxy for growth rate, were negatively and significantly correlated to the date of migration ($r^2 = 0.10$, $p < 0.001$, Fig. 5).

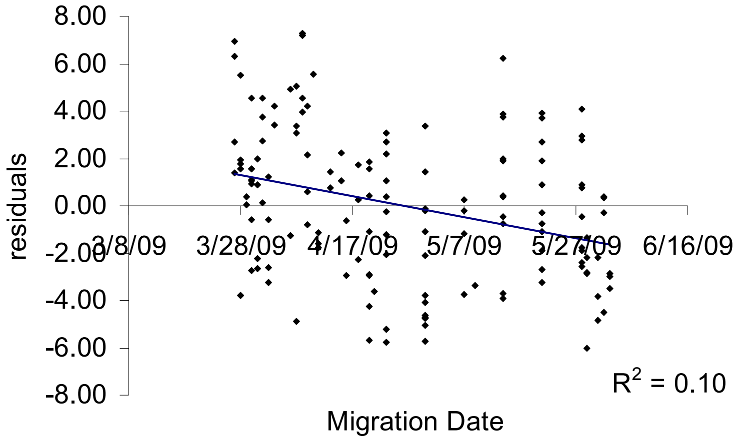

Figure 5. Residual Analysis. Residuals from fork vs. number of circuli plot (Fig.3a) vs. migration date. Residuals are a proxy for growth rate.

DISCUSSION

The life stage during which salmon migrate from freshwater to the marine environment is a crucial period that greatly influences chances for survival to adulthood (Pearcy 1992, Quinn 2005, Scheuerell 2009). It is therefore very important to understand the factors that influence this migration. In this study, the relative influence of absolute body size and growth rate on migration timing was determined for coho salmon smolts from the 2009 Lagunitas Creek outmigration using scale analysis.

I found that size parameters (fork length, scale length, and number of circuli) were significantly correlated with one another. However, because these relationships were weak, subsequent analyses of this data did not show strong correlations. Previous studies found stronger relationships between scale length and fork length. Fisher and Pearcy (2005) found that scale length and fork length were highly correlated (r = 0.97); however, they did use adult scales from salmon in Oregon. Because number of circuli and fork length were more strongly correlated than scale length and fork length, I used those residuals to determine the relationship between growth rate and migration date.

The relationships between the size parameters and migration date were all weakly correlated, but significantly so in the direction expected. Even though I was not able to calculate absolute measures of growth rate, residual analysis allows for the comparison of growth rates within the 2009 emigrating population. Residual analysis of the number of circuli versus fork length reveals that smolts migrating earlier tend to have larger residuals, and therefore, faster growth rates.

In this study, both fork length and growth rate are significantly related to migration date in the coho smolts. Growth rate, however, appears to exert a stronger influence on migration timing than absolute size because it is more highly correlated to migration date. Beckman et al. (1998) could not definitively differentiate between the influence of absolute size and growth rate in downstream migration timing of Chinook salmon (*O. tshawytscha)*. They did, however, conclude that juvenile Chinook with high spring growth rates were more inclined to migrate downstream. Dickhoff et al. (1997) suggests that growth may play a more important role in smoltification (which occurs simultaneously with migration) than body size. An individual growing slowly will smolt later in the season, while a fast-growing individual will tend to smolt and migrate downstream earlier. Beckman et al. (2003) found that the differences in growth rate among Chinook salmon affect their ability to become smolts.

Although there are many environmental factors that can influence the migration timing of coho salmon, such as water temperature and stream flow, these factors were not considered explicitly in this study. However, growth rate is equivalent to the difference between the energy that an individual takes in and the energy that an individual expends (Cross et al. 2002). For example, if the water temperature rises the fish must exert energy to maintain homeostasis, thereby reducing the amount of energy available to put into growth.

Faster growing coho are able to leave freshwater earlier, and in doing so they confer several advantages upon entering the marine environment. These advantages offer more opportunities for growth in the marine environment, because salmon grow much faster in the marine environment than in freshwater (Quinn 2005). Coho that grow faster are able to attain larger sizes, which allow them to escape the gape limitation of predators, as well as to eat larger prey. Finally, fast growing coho are likely to be more fit than slower growing coho, and thus would be able to swim faster to escape predators and catch prey (Quinn 2005). Overall, faster growth increases fitness and chances of survival (Hartman et al. 1982, Quinn and Peterson 1996, Scheuerell et al. 2009).

Limitations

One confounding factor of this study could be scale resorption. When a salmonid becomes calcium deficient, it can resorb its calcified scales in order to obtain the calcium that it needs (Bigler 1989). A coho individual that exhibited a faster growth rate but became calcium-deficient and had to resorb some of its scales might have a lower number of circuli than one might expect. At the same time, a slower growing fish that did not need to resorb its scales could have a larger number of circuli than the faster growing calcium deficient fish. Coho are also able to regenerate their scales, which could result in the presence of scales with a significantly smaller number of circuli. In the case of this study, the latter should not be an issue because regenerated scales were deliberately excluded from the mounted scales.

Another important source of error could have come from non-standardized scale collection technique. While Stillwater Sciences and the Marin Municipal Water District were instructed to remove the scales from the area above the lateral line and between the dorsal and adipose fins, there can be a great deal of variation in scale size and circuli number within this region. Scarnecchia (1979) found that scales taken from coho salmon far above the lateral line had significantly lower scale radius and number of circuli. Similarly, Martynov (1983) found that scale size and number of circuli vary greatly depending on where exactly the scales were removed from Atlantic salmon (*Salmo salar*). Circuli number decreased as the site of removal moved from the lateral line to the dorsal fin. To address this issue, future research should focus on only the largest and most complete scale collected for an individual smolt. This would presumably ensure that the scale is from nearest the lateral line between the dorsal and adipose fins. Even if the scales were taken from the exact same location on each fish, there would still be some inherent variability in the sizes of the scales. Biological variability can be individual-specific and is difficult to account for or quantify. Once again, measuring multiple scales may be the best way to address this issue.

Future Directions

Due to the overarching presence of high variability in this study, future studies should focus on using multiple scales per smolt or specifying the exact location for scale removal. Using scales from an identical location on each smolt in a study like this one could produce more highly correlated results and provide stronger evidence for the influence of growth rate on migration timing. Furthermore, using absolute calculations of growth rather than a proxy for growth rate could also substantiate the importance of growth rate. Finally, performing these two studies on multiple populations in the CCC ESU would provide a broad sense of the most important migration timing factors across an entire region rather than a single creek.

In studying the influence of absolute size and growth rate on migration timing, I was able to conclude that growth rate is more important in predicting when a coho salmon smolt will move downstream. This contributes to the general knowledge of the life cycle of coho salmon and the mechanisms driving its component life stages, as well as the need for environmental managers to protect water bodies used by coho. The numerous advantages of faster growth in coho salmon highlight the types of growth opportunities that managers should try to provide. Adequate food resources can be maintained by increasing flows and decreasing sedimentation (Allan and Castillo 2007), while water temperature can be maintained at physiologically advantageous levels by adjusting dam releases (Poole and Berman 2001). Sundstrom et al. (2005) suggests that food availability and the presence of predators may strongly influence chances for survival in the future. Furthermore, the authors propose that the large-scale removal of non-native predators may allow for the increase in growth rate for some species. Understanding the factors that influence coho smolt migration allows for the establishment of better management practices that create healthy environments and allow for declining California coho populations to recover (Miller 2010).

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