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Saving California's native fishes: physiological and behavioural approaches

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Many of California's diverse, freshwater habitats have been modified, limiting the normal movements of many resident and migratory fishes. My students, colleagues and I used physiological and behavioural approaches to study the environmental requirements of native fishes that had low, or steeply declining, population sizes. Findings included swimming muscle 'remodelling' and decreases in sustained swimming performance in coho salmon as they developed towards their salt-water life-stage. These results, plus those on juvenile green sturgeon's decreases in swimming performance with salt-water readiness and this species' vulnerability to water diversions, should help natural resource managers set stream and river standards to ensure adequate flows for preserving our natural heritage of native fishes.

California, USA, has a wide variety of aquatic habitats, although its extensive agriculture, diverse industries and expanding human population (currently >39M) place heavy demands on its freshwater resources. To meet various human demands, hundreds of dams and reservoirs control the flows of California's rivers, and many viaduct/irrigation systems redistribute much of the State's water within and across watersheds. My colleague, Prof. Peter Moyle, and his students, have documented the population status of California's fishes. Unfortunately, 83% of California's 129 species of native, freshwater fishes face extinction or extirpation within the next century, with agriculture and dams as two of the leading causes of these population declines (Moyle *et al*., 2011).

California's extensively 'developed' water system and the associated effects on its fishes' movements and populations, make conservation of California's native freshwater and anadromous (sea-run) fishes a challenging activity. Dams provide valuable flood protection, water storage and 'green' (hydro-electric) power generation, and their reservoirs provide recreational activities for California's citizens, making them, and some related habitat alterations, permanent features of California's waterscapes. However, fish population declines, potential for earthquake-related effects, and contemporary and future climate changes demand science-based solutions to saving native biodiversity. Importantly, physiological and behavioural mechanisms link species' structural/genetic makeup to their patterns of resource use, population success and survival. My students, colleagues and I have been studying many of California's native fishes at our University of California, Davis, laboratory since 1975, emphasizing these mechanisms to better understand and conserve California's endemic fishes.

In one series of experiments we set out to study the Coho salmon (*Oncorhynchus kisutch*) an endangered, native, and anadromous species that spawns in coastal rivers and streams. The resulting, freshwater juveniles ('parr') transform (mediated by thyroid and other hormones) into silvery, seawater-capable 'smolts' which migrate to the Pacific Ocean during spring. We asked how much water is needed in these rivers and streams to facilitate the downstream movements of young salmon, and what mechanisms (active swimming or passive drift) do young coho use to move downstream? From bioenergetics and natural history standpoints, these young salmon should use the moving water's power to migrate.

My PhD student, Shana Katzman, and I implanted either thyroid-hormone-containing pellets to induce smoltification,

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or control pellets, into coho parr. Three weeks later, we found that the smolt-transformed coho had decreased, sustained swimming performance (to ~60 cm s^{-1}) in a laboratory swim tunnel, compared with that of the controls (~80 cm s^{-1}) (Katzman and Cech, 2001). This decreased, sustained swimming performance with increasing body size is opposite to the pattern shown in many fishes. Thus, an increased passive component of smolts' downstream movement (e.g. at water velocities >60 cm s^{-1}) seem likely. Interestingly, the smolts' mosaic swimming musculature also showed faster and stronger contractions, compared with those of the controls, when stimulated in a laboratory muscle preparation. These changes indicated a 'remodelling' from a mixture of red, key for sustained swimming, and white, key for 'burst' swimming, fibres to more of a pure white-fibre muscle tissue, which may increase survival potential (e.g. associated with capture of elusive prey and escape from larger predators) in salt-water environments. Furthermore, Katzman *et al.* (2010) set up a water-flow table with a gradient of faster to slower currents, and found that the coho preferred to swim in increasingly faster currents as the 3-month, springtime parr-smolt transformation period (April–June) progressed. Along with decreased sustained swimming performance, this faster-current-seeking behaviour presumably facilitates the smolt's passive movement downstream. We demonstrated that to conserve California's native coho salmon, stream conditions and flows adequate to passively move the smolts down to the estuaries during the spring migration period should be maintained.

A second series of experiments using physiological mechanisms to inform conservation comes from our work with the anadromous, green sturgeon (*Acipenser medirostris*), a threatened anadromous species, which spawns in the Sacramento and Klamath Rivers. My PhD student, Peter Allen and I wondered if these ancient, relatively unstudied, fish use similar physiological mechanisms to those found in more recently evolved bony fishes (e.g. salmon) when they move downstream and enter seawater as juveniles, after hatching in these rivers. Allen *et al.* (2011) showed that age-0 fish linearly increase their seawater tolerance, becoming fully seawater-tolerant at ~134 days post-hatch, when they are ~27 cm long. Concerning their movements downstream, Allen *et al.* (2006) showed that the swimming performance of these young fish increased (to ~50 cm s^{-1}) with increasing fish length during their early (freshwater-inhabiting) development. However, when they reached ~27 cm total length, their swimming performance declined over the next weeks (to <40 cm s^{-1}) during the autumn (when they reached ~45 cm total length, Fig. 1). This decline in their apparent ability to hold position in swift river currents presumably facilitates their passive emigration to the estuaries and ocean when rivers swell with runoff from seasonal rainfall events. Interestingly, if their growth and development is delayed (e.g. with exposure to colder water), such that they do not reach 27 cm length until winter, this transient decrease in swimming performance is not exhibited. After I retired in 2007, newly hired Prof. Nann Fangue took over the laboratory, and she continues research, with her students, on these interesting fish.

These results with juvenile green sturgeon, like those reported for coho salmon, argue for adequate downstream flows to assist swift, passive migratory movements of the young fish. However, we wondered about the migratory success of these small fish, especially regarding effects of unscreened openings of the many water-diversion pipes (e.g. for irrigation or municipal uses) in the river along their migratory paths. Prof. Fangue, Prof. Lev Kavvas (Dept. of Civil and Environmental Engineering), our students (including my PhD student, Tim Mussen) and I addressed this problem using a huge (501-kl) outdoor flume that incorporated a 46-cm-diameter, diversion-pipe opening. Thousands of similar water diversions are located in freshwater portions of the Sacramento and the San Joaquin Rivers and their confluence. Comparative studies of young Chinook salmon (*Oncorhynchus tshawytscha*) and green sturgeon in the large flume showed that young salmon were better able than sturgeon to detect and avoid strong (~74 cm s^{-1})

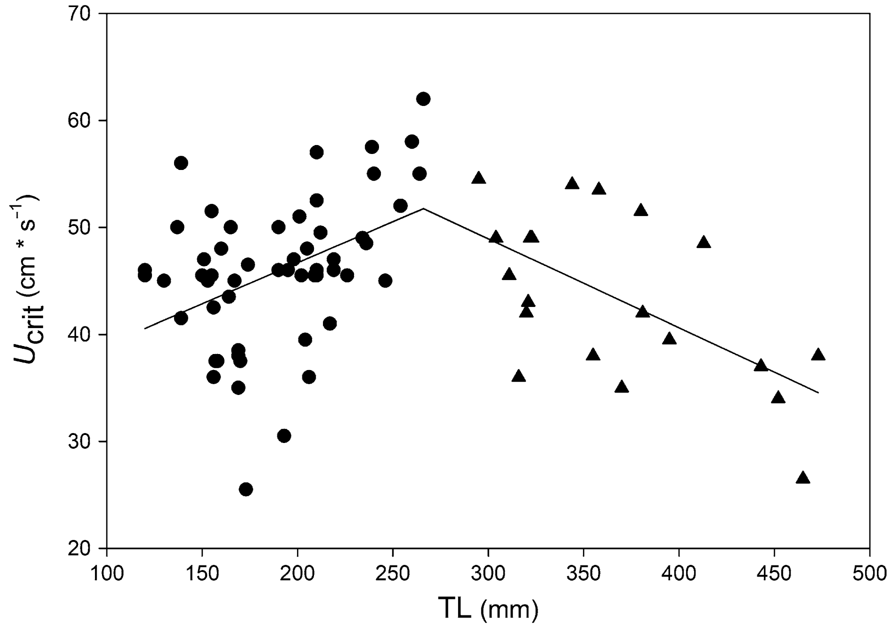

Figure 1: Green sturgeon swimming performance (Ucrit) and total length, when <100% seawater-tolerant (circles) and 100% seawater-tolerant (triangles). Adapted from: Allen *et al.* (2006).

diversion currents near the pipe's opening (Mussen *et al.*, 2013, 2014). Thus, it is possible that many young fish, especially green sturgeon, were inadvertently being removed from their migratory path, via unscreened diversion pipes. Our results showed that diverting river water during daylight hours may decrease the number of salmon removed from the river, and decreasing diverted water-flow rates, for longer time frames to move the same volume of water, may decrease green sturgeon removal (and consequent mortality).

The installation of fish screens at the entrances of many larger, water-diversion channels keeps small fishes from being removed from their environments, and more, even longer, screens are planned for future diversions. However, young fishes may suffer injuries or mortalities, via short or more prolonged contacts with the fish screen. My two Post-doctoral Researchers, Drs Tina Swanson and Cincin Young, led our fish-screen investigations on the endangered delta smelt (*Hypomesus transpacificus*) and young Chinook salmon, which move through the estuary. Delta smelt are endemic to the Sacramento–San Joaquin Rivers (confluence) estuary, and their populations have shown steep declines over the past 30 years. We used Prof. Kavvas' 'fish treadmill' apparatus to simulate a continuous fish screen with realistic approach (water diverted through the fish screen) and sweeping (river or tidal currents along the screen) velocities. We found that with 'high' approach and 'low' sweeping velocities, the smelt would often contact the fish screen, increasing their stress levels, bodily injuries and mortality (Swanson *et al.*, 2005, Young *et al.*, 2010). A model from these studies calculated the maximum length of a fish screen to minimize harm to the smelt, aiding conservation efforts associated with future fish screens. Juvenile Chinook salmon were much more resistant to contacts and consequently had lower mortality (Swanson *et al.*, 2004).

By limiting access to critical spawning and rearing areas, dams have negatively impacted sturgeon populations, worldwide. The white sturgeon (*A. transmontanus*), the other native sturgeon in California waters, generally avoids traditional fish-passage structures (i.e. 'ladders') designed for salmonids to by-pass dams. Our laboratory-flume studies on these huge (123–225 cm long) adult fish, showed that they are impressive swimmers (257 cm s^{-1}) over 24.4 m, up a 4% grade, if the sturgeon-compatible passage structure (i.e. flat floor with no jumps required) has aligned (rather than offset) 61-cm-wide slots for passage between five, paired energy-dissipating baffles (Cocherell *et al.*, 2011). We used this information in a review on the plight of sturgeon with restricted access to their historical spawning and rearing areas, and possible solutions (Jager *et al.*, 2016). The review was conceived with colleagues in a hotel bar when a snowstorm prevented our planned departure from the Detroit airport, for an extra evening. We concluded that many research challenges remain, to conserve native fishes.

Personally, I feel that we must do what we can to save native animals and plants. These marvellous organisms are the survivors of hundreds to hundreds of millions of years through time. Natural selection has shaped their structures and behaviours through many generations, leading to the exquisitely adapted organisms of today's world. My students and colleagues and I have sought to understand key mechanisms that some California fishes use to persist in their environments. Using approaches such as those described above, and those at other levels (e.g. cell and molecular) of organization, I hope that we can better inform policy makers, natural resource managers and the public concerning the best decisions to preserve critical populations and biotic communities. The timing of these decisions seems critical for species at low-population levels or for those whose population numbers are in steep declines. Let us move forward, before we lose key components of our natural heritage.

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