RESPONSES OF FISH TO ENVIRONMENTAL CHANGE

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Introduction

Literature from the last several decades shows both an increased interest in fundamental questions about how fish respond to their environments as well as advances in instrumentation and techniques to address these questions. Many times, these questions have been prompted by practical problems regarding fisheries production (either for sportsfishing or commercial harvest), impacts of construction projects or contaminant inputs, or aquacultural efficiency. The fish biology community has contributed an impressive array of scientific advances over these last decades regarding biochemical, morphological, physiological, behavioral, and ecological responses of fishes to environmental change. My objective in this short paper is to describe some research findings from my laboratory in the Department of Wildlife and Fisheries Biology at the University of California, Davis, regarding some practical applications of these responses.

Responses of Fish for Use in Mosquito Control

The first questions concerned optimal use and production of mosquitofish for mosquito-borne disease control, in California rice fields. Mosquitofish (Gambusia affinis) are small (up to 5 g wet weight) livebearing fish, which have been introduced for mosquito control (by preying on mosquito larvae) in many aquatic habitats around the world. Although there are documented cases where mosquitofish have either failed to control mosquitoes or have severely disrupted the native aquatic community (usually by preying on young life history stages of resident fishes), they work well in agroecosystems in California's highly modified Sacramento and San Joaquin Valleys (reviewed by Swanson et al. 1994). Data were available concerning water conditions and mosquito larval densities (especially those of the encephalitis carrier, Culex tarsalis, and the malaria carrier, Anopheles freebomii) in various rice fields. Using laboratory investigations, we were to determine: 1. How many mosquito larvae a mosquitofish of a certain size would need to eat to stay alive and move about (to determine adequate rice field fish stock densities), and 2. How photoperiod (or daylength) might be modified to inexpensively speed up mosquitofish production in the early spring (when Culex was abundant).

We assessed the first question on food demands by using a bioenergetic model. Building on the pioneering efforts of Canadians, F.E.J. Fry, J.R. Brett, and others; former graduate students, Michael Massingill, Alison Linden, Daniel Castleberry; former assistant, Trent Wragg, and I measured oxygen consumption rates of mosquitofish (as measures of metabolism or food demand) under various rice field conditions. We used flow-through and static respirometry (Cech 1990) in a temperature-regulated water bath and altered dissolved oxygen concentrations by using a gas-stripping column incorporating counterflows of water and nitrogen gas (Fry 1951). We multiplied the daily oxygen consumption rates under the various conditions by an oxycalorific coefficient (relating energy yield from oxygen consumption, reviewed by Brett and
Groves 1979) and divided by the energy content of dry *Culex* larvae (determined by bomb calorimetry) to calculate the number of mosquito larvae (Cech et al. 1980).

So how does a 0.5 g mosquito fish respond to increases in water temperature or decreases in dissolved oxygen? The former increases food and oxygen demand (and, presumably, predation rate) in an exponential fashion, while the latter decreases demand at the warmer temperatures (Fig. 1). This is due to the mosquito fish’s high absolute demands at the warmest temperatures and the limitations on its aerobic metabolism imposed by environmental hypoxia (Cech et al. 1985). By measuring the changing rice field water conditions during the rice growing season, we can calculate the number of fish needed to control mosquitoes. Often this is most important at the beginning of the rice season when *Culex* are present and before fish numbers have increased due to in-field reproduction (Botsford et al. 1987).

![Graph showing the relationship between temperature and number of large instars/day](image)

**Figure 1.** Mean (+SE) number of large (3rd or 4th) *Culex* mosquito instar larvae required per day by a 0.5 g mosquito fish (*Gambusia affinis*) in a "resting" state at various temperatures while exposed to dissolved oxygen concentrations approximating 100% (open bars), 25% (wide-hatched bars), or 15% (narrow hatched bars) of air saturation. Asterisks indicate significant (p < 0.01, t-test) decreases compared with 25% of air saturation values. Figure redrawn from Cech et al. (1980).

How can we produce enough mosquito fish to stock the fields early in the rice season? Former undergraduate students, William Coles and Brent Bridges, colleague Robert Schwab, and I addressed the second question by measuring the birth rate of mosquito fish held under different photoperiods. Mosquito fish were held in replicate flow-through aquaria at 25°C in light-tight photoperiod-regulated chambers, and visibly pregnant female fish were placed into two-compartment, birthing cubicles within the aquaria for quantification of newborn mosquito fish. In our first experiment, mosquito fish showed accelerated reproductive development when exposed to constant photoperiods of 13L:11D or 15L:9D, compared with either a constant 11L:13D or a naturally increasing photoperiod starting at the winter solstice. However, nutritional limitations of the fish flake diet apparently increased female mosquito fish mortality.
ca. 1 wk prior to parturition (Cech et al. 1992).

By supplementing the diet with tubificid worms (higher in protein, lipids, and calories than fish flakes), 15L:9D fish showed an 11-12 wk accelerated reproductive output, compared with naturally increasing photoperiod fish with the supplemented diet (Cech et al. 1992). Thus, mosquitofish respond to a changed environmental light regime, and some California Mosquito Abatement Districts now use artificial photoperiods (timers on production room lights) to speed production of fish for early season stocking for biological mosquito control.

Responses of Intertidal Fish for Potential Culture

Former undergraduate student David Edwards and I were interested in effects of tidal changes on an intertidal fish of the California coast. We used respiratory metabolic rate measurements to quantify physiological tolerances of monkeyface prickback, *Cebidichthys violaceus* to aerial exposure. As an adult, this fish lives subtidally in rocky habitats, feeds almost exclusively on algae, and represents a favorite quarry of "poe-poling" anglers. The juveniles live in the intertidal zone, feeding on invertebrates and algae. At low tide, they can be found under rocks, either in pools or on moist sand. We found that these juvenile prickbacks consume significantly less O₂ during air exposure than when immersed in sea water. This metabolic depression is apparently a total one, rather than representing a shift to anaerobic pathways, because we measured no significant increase in mean muscle lactate concentration (Edwards and Cech 1990). Presumably the metabolic depression results from the total quiescence observed in these fish when air-exposed, matching their observed behavior when found at low tide.

There has already been interest in culturing these fish. Some California mariculturists see these prickbacks as an interesting aquarium fish in cold marine displays and as a food fish which might be raised quite inexpensively, e.g. on algal diets. Further investigations regarding metabolism, feeding, digestive efficiency, and growth of monkeyface prickbacks are needed. Some original designs for optimal culture systems could also be desireable to take advantage of the juveniles' decreased metabolism while respiring air. For example, aquatic phases for feeding could be alternated with aerial phases for optimal assimilation while flushing their culture systems of metabolic wastes.

Temperature-induced Movements in Fish

Fish, of course, also show behavioral responses to environmental changes. Former graduate student, Todd Hopkins, and I investigated seasonal distribution and abundance of the bat ray, *Myliobatis californica*, in Tomales Bay, California, as part of Dr. Hopkins' dissertation research. With the help of several student helpers, we monthly sampled Tomales Bay by setting 9 longlines of 20 hooks each. Bat rays were mostly very abundant in the Bay, except for the winter months when water temperatures dropped below 10°C. We're quite sure that the rays moved out of the Bay, rather than just stopped biting on our hooks because all 6 sonic-tagged rays' signals also disappeared at this time. Five of the 6 came back the following spring (Hopkins 1993). Laboratory studies showed quite low metabolic rates and small Bohr effects of their hyperbolically shaped blood-oxygen binding curves at low temperatures (Hopkins 1993), so ecological factors (e.g. susceptibility to predation) may best explain why the bat rays (and the other elasmobranch fish) left the Bay during the coldest months.

The biogeochemists studying the Bay are keenly interested in how many rays are residing and feeding there at different times of year. Not only do they forage (presumably in proportion to water temperature) on benthic invertebrates which are so plentiful there, but their vigorous excavations of these molluscs and worms, resuspend a significant amount of sediment which may
significantly affect nutrient stoichiometry (Smith et al. 1991). The practical significance of these findings may lie in future decisions regarding regulation of either freshwater or treated wastewater inputs into the Bay. California's limited water supply and increasing human population continuously forces water planning decisions. Recent decisions regarding marine and estuarine water quality standards will hopefully protect these areas for some time.

Conditioning Responses of Fish to Water Currents

As a final example of responses of fish to environmental changes, former graduate student, Paciena Young, and I showed that striped bass, *Morone saxatilis*, respond morphologically and physiologically to water current. As part of her dissertation research, Dr. Young showed increased growth rates, swimming performance, and red and white muscle development in young-of-the-year striped bass when exercise-conditioned for 60 d at 1.2 to 2.4 body lengths/s (bl/s) (Young and Cech 1993). The practical value of these studies to striped bass aquaculturists is readily apparent, once the monetary costs of current generation in rearing tanks or of net pen maintenance in river or tidal currents are established and compared with the benefits in growth.

In subsequent experiments, we examined persistence of these effects after exercise conditioning at several velocities was terminated. The gain in growth after swimming at moderate velocities was still significant at 56 d post-conditioning for fish conditioned for 60 d at moderate (1.5-2.4 bl/s) or fast (2.4-3.6 bl/s) velocities (Young and Cech 1994). Interestingly, there seemed to be a 14 d post-conditioning, compensatory growth spurt in the fish conditioned at the fast velocity (Young and Cech 1994). Although compensatory increases in growth have been described for fish previously held under fasting (or energy limitation) conditions, this is the first case, to our knowledge, where an exercise (or energy redirection) compensation of growth has been described.

These data might be especially interesting to a private or public hatchery operation raising striped bass for mitigative stocking in natural waters for population enhancement. Eleven years of such stocking without using exercise conditioning techniques failed to measurably increase striped bass abundance (Stevens 1992) in California's San Francisco Bay Delta region, which has manifold problems (e.g. restricted freshwater inputs and insufficiently restricted chemical inputs). Recent efforts to maximally protect native winter-run chinook salmon (*Oncorhynchus tshawytscha*) have stopped (introduced) striped bass enhancement in California. Thus, expected benefits of exercise conditioning may be initially gained in Atlantic coast states where native striped bass populations have also declined in coastal waters. Presumably, conditioning velocities could be optimized for swimming and growth characteristics which take advantage of local conditions of current, food availability, and predator densities. Ideally, fish raised under various exercise regimes could be marked (e.g. with coded wire tags) for subsequent evaluations of conditioning benefits to the fishery.

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