Transactions of the American Fisheries Society
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/utaf20

Low-Temperature Tolerance and Critical Thermal Minimum of the Invasive Oriental Weatherfish Misgurnus anguillicaudatus in Idaho, USA
Alexander N. Urquhart & Peter Koetsier

Department of Biological Sciences, Boise State University, 1910 University Drive, Boise, Idaho, 83725-1515, USA
Published online: 11 Dec 2013.


To link to this article: http://dx.doi.org/10.1080/00028487.2013.829124

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the “Content”) contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions
Low-Temperature Tolerance and Critical Thermal Minimum of the Invasive Oriental Weatherfish *Misgurnus anguillicaudatus* in Idaho, USA

Alexander N. Urquhart and Peter Koetsier*

Department of Biological Sciences, Boise State University, 1910 University Drive, Boise, Idaho 83725-1515, USA

Abstract

The Oriental Weatherfish *Misgurnus anguillicaudatus* is invasive to many countries around the world, but very little is known about the life history or environmental tolerances of this cryptic fish. As part of a larger study of its life history, we conducted an experiment designed to determine the critical thermal minimum (CTmin) of Oriental Weatherfish collected from water bodies near Boise, Idaho, USA. In each of three experimental trials, 16 fish were placed into individual tanks in an environmental chamber where over the course of 20 d the ambient air temperature was lowered to 0°C. Air temperature was then held at 0°C for 102–134 h. Individual tank temperatures decreased over the course of each trial such that fish were exposed to temperatures ranging from 20°C to −3.64°C. Tank temperatures reaching below the ambient air temperature set-point were attributed to cold air currents within the environmental chamber. Six of 48 fish died due to temperature-related factors. Thirty-eight of the remaining 42 fish survived exposure below the freezing point of freshwater, and 2 fish survived full enclosure in ice with direct contact between skin and ice. In the absence of an observed lethal temperature at which 50% of fish died (LT50), we used logistic regression and observational data to extrapolate a CTmin of −1.8°C. The ability of Oriental Weatherfish to survive at subfreezing temperatures and being embedded in ice indicates a physiological adaptation to cold that may include systemic antifreeze proteins. Tolerance for low temperature and resistance to freezing add to a growing list of characteristics that make the Oriental Weatherfish a highly successful invasive species.

Worldwide, the biodiversity of aquatic ecosystems is challenged by the threat of exotic organisms (Olden et al. 2004; Villéger et al. 2011). In the United States alone, over 138 nonnative fish species have been introduced (Pimentel 2005), many of which have established self-sustaining, wild populations that can disrupt native communities and cause loss of native biota through habitat modification, competition, predation, and introduction of pathogens (Mills et al. 1994; Dextrase and Mandrak 2006). One such successful invader is the Oriental Weatherfish *Misgurnus anguillicaudatus* (Cobitidae). The Oriental Weatherfish is native to Southeast Asia, its range extending from Myanmar to southern Russia and including the Japanese archipelago (Franch et al. 2008). Within this range, the fish primarily occupies lotic systems and is commonly found in canals and irrigation ditches, but it also migrates into rice paddies and other temporary ponds to spawn (Kubota 1961; Naruse and Oishi 1996). Because of its frequent and ongoing commercial distribution as an ornamental fish, as a food source, and as live bait, the Oriental Weatherfish has been introduced into many countries (Chang et al. 2009; Strecker et al. 2011). Established wild populations are now reported in the Philippines, Turkmenistan, Germany, Spain, Italy (Freyhof and Korte 2005; Simon et al. 2006; Franch et al. 2008), and several parts of Australia (Keller and Lake 2007). Within North America, wild populations have been found in Mexico (Contreras-Balderas and Escalante-Cavazos 1984) and in at least 13 states in the USA.

*Corresponding author: pkoet@boisestate.edu
Received March 20, 2013; accepted July 18, 2013
Published online December 11, 2013
The high colonization potential of the Oriental Weatherfish results, in part, from its potentially high propagule pressure (via aquaculture escapes and aquarium releases: Strecker et al. 2011), but also may involve its tolerance to a wide range of environmental conditions. The fish is found in both lotic and lentic systems, has a wide physiological tolerance to dissolved oxygen levels (McNeil and Closs 2007), and can survive long periods of desiccation (Koetsier and Urquhart 2012). The ranges Oriental Weatherfish has invaded suggest that this “tropical” fish may tolerate a broad thermal environment as well. Oriental Weatherfish has been found in habitats with water temperatures ranging from 2°C to 38°C (Linternans and Burchmore 1996; Logan et al. 1996; Strecker et al. 2011). However, specific temperatures occupied by the fish vary between study locations, and empirical data regarding direct temperature tolerance are lacking. In its native habitat, optimal water temperatures are thought to be between 20°C and 30°C (Kubota 1961), and 25°C is considered the ideal temperature for egg development (Suzuki and Yamaguchi 1977). To our knowledge, no empirical studies have successfully determined the maximum/minimum water temperatures for the fish in the habitats it has invaded (but see Logan et al. 1996).

Given the broad latitudinal range in which populations of Oriental Weatherfish have been found, minimum water temperature may be a key abiotic factor for limiting the spread of this fish. As part of a series of studies designed to ascertain the niche boundaries of the fish in Idaho, we initiated research to identify the lowest temperature Oriental Weatherfish can survive. To accomplish this, we set up a laboratory experiment to determine the critical thermal minimum (CTmin) for a local wild population of Oriental Weatherfish. We found that not only could the fish survive water temperatures near 0°C, but also it could withstand short-term encasement in ice with no ill effects.

METHODS

From May 2008 to June 2009, we collected 311 Oriental Weatherfish from irrigation canals and ponds, sites with seasonal connections to the Boise River (southwest Idaho). Fish were captured in vinyl-coated, steel-mesh minnow traps (42 cm × 22 cm with a 2.5-cm opening at the apex of an inverted cone in each end) baited with 30 g of dry, commercial dog food. During the collection period, sampling sites were exposed to ambient, seasonal temperatures; during winter months, these sites were often covered with a thick layer of surface ice (3–4 cm). Traps were relocated as necessary due to seasonal fluctuations in water levels and winter draining of irrigation canals and ponds.

We checked traps every 3 d and transported any live fish to a laboratory holding facility where they were acclimated to an ambient temperature and placed into one of two communal holding aquaria. Aquaria were constructed of clear acrylic material (43 × 73 × 37.5 cm; 117.7 L) with mesh-screened tops and fitted with filters and air stones. Approximately 3 g of commercial pellet fish food was added to each aquarium by automated feeders twice daily and fish fed ad libitum. Fish densities in these communal aquaria (approximately 1.3 fish/L) were similar to densities reported for Oriental Weatherfish populations in its native range (Katano et al. 2003) but much lower than those reported in aquaculture operations (W. Youji, Huazhong Agricultural University, China, unpublished data). Aquaria were cleaned of excess algae and half of the water volume was changed weekly. Fish were housed in these conditions until being utilized in a series of ecological and behavioral experiments. Any fish that were included in an experiment and survived was placed in a “used fish” aquarium and excluded from any subsequent experiments. Air temperature in the holding facility was kept at 20°C, and fish were exposed to ambient water temperature (approximately 18–22°C) and the natural lighting regime for at least 1 month prior to being utilized in this study.

Our experimental design consisted of 16 small, clear acrylic tanks (18 × 28 × 17 cm) placed on four shelves (four tanks per shelf) within an environmental chamber (internal dimensions 71 × 135 × 56 cm). The chamber was outfitted with full-spectrum lighting and a two-channel microprocessor unit programmed to control temperature and photoperiod (Figure 1). Each tank was partially filled with 3.0 L of artificial pond water (0.03 g/L NaHCO₃, 0.35 g/L NaCl, and 0.007 g/L CaCl in deionized H₂O; pH 8.0, conductivity 800 μS/cm), which mimicked solute concentrations of freshwater and allowed us to minimize variation between experimental tank conditions. Each tank was outfitted with a single air stone and a thermocouple temperature probe connected to an electronic data logger (21 × micrologger, AM416 multiplexer; Campbell Scientific). The photoperiod was set at 12/12 h light/dark, and the air temperature inside the chamber and the water temperature of each tank were recorded hourly, for the duration of each trial. We completed three sequential trials such that the first began on October 9, 2009, and the third trial was completed on January 2, 2010.

At the start of each trial, a random number generator was used to identify from which of the two communal tanks we would select a fish. We hand-netted a single fish and used the same randomization method to determine whether to include or release that fish. In this manner, we selected 16 fish and added one to each of the 16 experimental tanks within the environmental chamber. Fish were not fed and water was not changed in the experimental tanks during each trial to avoid adding any additional confounding factors to our experimental design. In previous experiments, we found Oriental Weatherfish to be highly tolerant of extremely poor water conditions and low food resources (e.g., Koetsier and Urquhart 2012).

At the beginning of each experimental trial, the internal air temperature of the environmental chamber was held at 20°C for the first 24 h then decreased by 2°C over the course of 1 h. Air temperature was then held constant for the next 23 h. Following this regimen, air temperature inside the chamber was lowered by...
FIGURE 1. Experimental setup for determining the CTmin of Oriental Weatherfish taken from water bodies near Boise, Idaho. An environmental chamber was outfitted with four shelves, each holding four acrylic fish tanks. Each tank contained one randomly selected fish, 3 L of artificial pond water, a single air stone, and a thermocouple temperature probe. Photoperiod was controlled at 12/12 h light/dark; air temperature was lowered inside the chamber over 14 d and then held at 0°C for 102–134 h. (a) full spectrum fluorescent lights; (b) excurrent cold air vent; (c) aquarium air pumps; (d) chamber control unit; (e) tank arrangements on each of four shelves.
2°C every 24 h until reaching 6°C, after which it was decreased by 1°C every 24 h until reaching 0°C on day 14. Air temperature was held at 0°C for 102 h in trial 1, and 110 h in trial 2, it was then increased to 10°C for 24–48 h in both trials to thaw any ice that had formed within the tanks. Because mortality rates were low in our first two trials, we increased the time for holding at 0°C to 134 h in trial 3.

Fish were observed once or twice daily for viability; the time of each observation was recorded along with the appearance of the fish and the general state of the water in each tank (e.g., liquid, partially frozen, or completely frozen). Fish viability was assessed by visually checking for opercular movement or by gently probing each fish with a stainless steel rod to elicit a swimming response. In the cases where ice prohibited probing, we tapped on or gently shook the tank and observed any responsive movement. Whenever a fish was found dead, the time of death was determined as the time it was last observed to be alive. Minimum temperature for the dead fish was determined as the lowest temperature experienced up until the last living observation. For fish that were encased in ice, minimum temperature was determined as the lowest temperature reached by the ice surrounding the fish at any time when the fish was so encased. For time spent at or below 0°C, experimental tank temperatures were rounded to the nearest whole degree, and whole-hour time increments were summed such that the cumulative time that any fish spent in water below 0.5°C was included. Dead fish were removed at the time of discovery (if not inaccessible due to ice) to prevent decay. The condition of each dead fish was visually inspected to determine probable cause of mortality (other than temperature exposure).

At the termination of each trial, surviving fish were removed from the experimental tanks and held at 20°C in a communal tank for at least 72 h. Because it appeared that no further mortality would result from thermal stress after this period, these fish were moved to a “used fish” aquarium.

During the experiment, four fish showed signs of a fungal infection consistent with Saprolegniasis (D. Burton, Idaho Department of Fish and Game, personal communication). Two of these fish died during the experiment and were excluded from the analyses because the fungus had become a confounding factor. The other two fish did not die and signs of their fungal infection abated during the postexperiment 20°C observation period. These two fish were included in subsequent analyses because, regardless of any additional stress due to fungal infection, temperature exposure did not kill these fish.

We compared the lowest mean temperatures of the experimental tanks between trials by using ANOVA and compared fish mortality between experimental trials using logistic regression. To determine whether fish mortality was due to the low temperature experienced by the fish or to the cumulative time spent below freezing temperature, we modeled minimum temperature, cumulative time at or below 0°C, and an interaction of these against fish mortality, using logistic regression analysis. We used corrected Akaike’s information criterion (AICc) values to select the combination of these variables that best predicted fish mortality (Cody and Smith 2006; Guy and Brown 2007).

In our experiment, temperature did not reach a lower lethal point at which 50% of the fish died (LT50). In the absence of such data, we used logistic regression analysis to model the probability of death occurring at each temperature to which the fish were exposed (Berkson 1951; Tsutakawa 1982). Using the resulting linear equation, we calculated the temperature at which log-odds (logit) of dying were equal to log-odds of survival. This temperature became our predicted LT50 and allowed us to calculate the 95% CI to determine the range in which the true CTmin for sampled Oriental Weatherfish existed.

**RESULTS**

Eight of 48 fish died during the course of this experiment, two of which were excluded from analyses due to confounding fungal infection. Fish mortality differed between experimental trials ($X^2 = 8.35, P < 0.05$): five of the six fish included in analyses died in trial 3 compared with a single death in trial 1 and no deaths in trial 2. Minimum temperature also differed between trials ($F_{2,43} = 6.97, P < 0.05$): the mean minimum temperature of tanks in trial 3 ($−1.30°C, SE = 0.47°C$) was lower than that in trial 1 ($−0.50°C, SE = 0.31°C$) and trial 2 ($−0.45°C, SE = 0.24°C$; Figure 2).

High variability in tank temperatures within experimental runs was attributed to air currents within the environmental chamber. These differential currents caused some tanks to experience higher evaporative water loss and may have led to faster cooling of individual tanks. This evaporative water loss and resulting concentration of soluble biological wastes may have contributed to tank water remaining liquid below the typical freezing point of freshwater. However, there was no indication

![FIGURE 2. Median and quartile plots of minimum water temperatures in each of three experimental trials. Whiskers display maximum and minimum values. Experimental tanks in trial 3 reached significantly lower water temperatures ($F_{2,43} = 6.97, P = 0.002$) than the tanks in trial 1 or trial 2; therefore, trials were not treated as replicates. An asterisk indicates statistically significant difference.](image-url)
that tank location (shelf or tank position) affected minimum temperature \( (F_{15,30} = 1.56, P > 0.05) \) or the amount of freezing \( (F_{15,30} = 1.29, P > 0.05) \) within each tank. Between-trial differences in mean minimum temperature were attributed to the longer hold time at 0°C ambient air temperature during the third trial: the extended hold time allowed individual tanks to reach a lower temperature than in the other trials. As a result of these trial effects, experimental trials were not treated as replicates; instead, results for all tanks in all trials were pooled for further analyses.

Because of the low mortality in this experiment (13%), we could not determine a LT50 using standard methods. However, logistic regression of minimum temperature versus fish mortality allowed us to calculate a LT50 as follows: \( y = -3.604x - 6.331 \), where \( y \) represents the log-odds ratio of death to survival, and \( x \) represents minimum temperature experienced by a fish. When \( y = 0 \), the probability of death is equal to the probability of survival. Therefore, this \( x \)-intercept point also represents the theoretical temperature where 50% of the fish should die. Using this point as the LT50, the CTmin of Oriental Weatherfish used in this experiment was estimated as \(-1.76°C (SE = 1.05°C)\), with a 95% CI \( \pm 2.06°C \).

Model selection using AICc values (Table 1) identified both minimum temperature and cumulative time at or below 0°C as possible causes of fish mortality, such that probability of dying increased with a decrease in temperature and an increase of time exposure at or below 0°C. However, these variables were highly correlated \((r = -0.74)\), in that tanks reached lower temperatures as the length of time below 0°C increased.

All fish in this experiment were exposed to temperatures below 0.45°C and all but four tanks reached temperatures below 0°C. Minimum temperature experienced by surviving fish (mean = \(-0.54°C\), SE = 0.08°C) differed significantly from that of fish that died (mean = \(-2.12°C\), SE = 0.37°C; \(X^2 = 5.90, P < 0.05\)). Time exposure at or below 0°C also differed significantly between surviving fish and fish that died (\(X^2 = 5.06, P < 0.05\)), such that surviving fish spent less time in subfreezing temperatures (1–145 h, mean = 62.4 h, SE = 6.3 h) than did the fish that died (100–183 h, mean = 149.8 h, SE = 13.8 h). Thirty-five fish survived temperatures between 0.00°C and −1.00°C, and five of these survived within this range for longer than 100 h (Figure 3). Only one fish exposed to this temperature range died. Six of seven fish exposed to temperatures between −1.00°C and −2.00°C also survived.

Most of the experimental tanks froze along the top and tank margins such that fish were enclosed within a small liquid water refuge surrounded by ice on all sides. All fish in this condition survived with no apparent ill effects. Several fish survived direct contact with ice when they became partially trapped with water surrounding other parts of their bodies (Figure 4). For example, the head of one fish was encased in ice but the rest of its body was surrounded by liquid water for at least 24 h (based on the time this condition was first noted) and survived. Seven fish became wholly encased and in direct contact with ice for between 34 h and 109 h. Two of these fish survived encasement for 34 and 54 h, respectively. The other five fish died while encased for 78 h or more.

### DISCUSSION

Oriental Weatherfish in our experiment survived extended exposure to subfreezing temperatures and several fish survived partial or full entrapment and direct contact with ice. Four fish showed signs of damage potentially caused by thermal stress (e.g., fungal infections). Two of the infected fish survived so we could not unequivocally attribute the infection to temperature exposure. However, thermal stress can lower immune response and contribute to pathogen infections (Bly et al. 1997; Engelsma et al. 2003; Goodwin et al. 2009; Ibarz et al. 2010). Thus, continued exposure to the subfreezing temperatures may have indirectly increased the rate of fish mortality.

Because of high variation in minimum temperatures and low fish mortality during our experiment, we were unable to reach a directly observed LT50. Further, our calculated CI for the lethal temperature spanned a large range (95% CI \( \pm 2.06°C \)). However, no fish exposed to temperatures below −1.99°C survived, and no fish died from exposure to temperatures above −0.94°C. Coupling these apparent limitations with our model-extrapolated CTmin (−1.76°C), we deem it reasonable to assess a range of water temperature between −1°C and −2°C as the approximate lowest limit for survival of Oriental Weatherfish from our sampled population.

The freezing point of intracellular fluid in most fishes is approximately −0.7°C (Helfman et al. 2009). However, some fish have adapted physiological mechanisms to survive subfreezing temperatures. For example, colligative properties of solutes in blood plasma and intracellular fluid can lower the freezing point of body fluids (DeVries and Cheng 2005). However, these fish (e.g., Theragra sp., Liparis sp., Limanda sp.) risk direct contact with ice, which catalyzes the formation of ice crystals and causes instantaneous freezing of tissues (Scholander and Maggert 1971; Hoar 1983). In contrast, other fishes (e.g., Pleuronectes

### Table 1: Model selection of parameters affecting mortality of Oriental Weatherfish exposed to minimum water temperatures.

<table>
<thead>
<tr>
<th>Model</th>
<th>AICc</th>
<th>ΔAICc</th>
<th>K</th>
<th>Weight</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum, time ≤ 0°C</td>
<td>18.88</td>
<td>0.00</td>
<td>4</td>
<td>0.5777</td>
<td>−4.95</td>
</tr>
<tr>
<td>Minimum, time ≤ 0°C,</td>
<td>21.34</td>
<td>2.46</td>
<td>5</td>
<td>0.1685</td>
<td>−4.92</td>
</tr>
<tr>
<td>minimum · time ≤ 0°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>21.53</td>
<td>2.66</td>
<td>3</td>
<td>0.1531</td>
<td>−7.48</td>
</tr>
<tr>
<td>Time ≤ 0°C</td>
<td>22.37</td>
<td>3.49</td>
<td>3</td>
<td>0.1007</td>
<td>−7.90</td>
</tr>
<tr>
<td>Null</td>
<td>39.90</td>
<td>21.02</td>
<td>2</td>
<td>0.0000</td>
<td>−17.81</td>
</tr>
</tbody>
</table>

Note: AICc values indicate that both minimum temperature and time spent at or below 0°C affected minimum temperature, such that the probability of dying increased as the water temperature decreased and as the time of exposure to subfreezing temperature increased; LL = log-likelihood.
sp., *Hemitripterus* sp., *Myoxocephalus* sp.) have evolved production of antifreeze proteins (AFPs), which noncolligatively prevent ice formation within body fluids, allowing the fish to survive even direct skin contact with ice (Fletcher et al. 2001; DeVries and Cheng 2005). Additionally, AFPs can be induced by environmental conditions, and vary in concentration both geographically and by season (Goddard et al. 1992, 1999; Raymond and Hassel 2000). Published reports of AFP presence in fish have predominantly focused on Arctic and Antarctic marine species. However, Yamashita et al. (2003) found AFPs in freshwater Japanese Smelt *Hypomesus nipponensis*, indicating that freshwater fish may also produce these proteins when needed.

We were surprised to find that several fish that came into direct contact with ice in our experiment survived. These fish fully recovered when thawed and showed no indication of damage. Although determining the colligative properties of body fluids or systemic presence of AFPs was beyond the scope of this study, our results suggest that the Oriental Weatherfish has some physiological mechanism that allows it to survive in subfreezing temperatures and tolerate direct contact of skin and ice.

Because the freezing point of freshwater is 0°C, and freshwater is densest at 4°C, most freshwater fishes never encounter temperatures low enough to freeze body fluids. However, the Oriental Weatherfish burrows into the substrate during seasonal habitat drying (Kubota 1961; Koster et al. 2002; Tsui et al. 2002; Ip et al. 2004) and can survive in dry soil for several months (Koetsier and Urquhart 2012). Many of the fish included in the present experiment were collected from irrigation canals that are drained in late autumn and remain dry throughout the winter months. While collecting fish for this study, we received anecdotal accounts from farmers who claimed to have found live, active Oriental Weatherfish when removing soil from drained...
irrigation ditches during the winter. If Oriental Weatherfish are utilizing their burrowing capabilities to remain localized during winter habitat drying, survival of periodic subfreezing soil temperatures may be a necessary part of their overwintering strategy.

In southwest Idaho, subfreezing air temperatures are common during the winter. Ground temperatures may reach 0°C at 8 cm below the surface, but deeper soil temperatures seldom drop below 0°C (NRCS 2012). Kubota (1961) found that, in its native range, the Oriental Weatherfish burrows less than 10 cm into the substrate as a survival strategy when rice paddies and streams dry in the winter. Within this region, however, year-round soil temperatures exceeded 5°C, never approaching 0°C. If this characteristic behavior and depth is retained within invaded regions, then subfreezing temperatures may cause winter mortality. As a result, natural selection would favor freeze-resistant physiological mechanisms in populations of Oriental Weatherfish. In contrast, if fish burrow to a depth below that of frozen substrate, they may avoid periodic ice formation. However, to our knowledge no published study of burrowing depth exists outside of the fish’s native range. In habitats where substrate temperatures reach freezing temperatures below 10 cm depth, Oriental Weatherfish may encounter ice, and the compounding effect of thermal and desiccation stresses may limit overwinter survival. Overwintering success may therefore be limited to permanent water bodies, which may act as source populations for the recolonization of temporary ponds and ditches. In permanent aquatic habitats that do not dry up or completely freeze during winter, Oriental Weatherfish survival may resemble that of other freshwater fishes, that is, simply remaining at or near the bottom of the water body most overwintering freshwater fishes remain in liquid water near the bottom of a water body and never encounter temperatures low enough to freeze body fluids (DeVries 1971; Helfman et al. 2009).
Successful invasive fish species have been characterized as being long-lived, with early maturation, high fecundity, and broad environmental tolerance (Townsend 1996; Marchetti et al. 2004; Vila-Gispert et al. 2005). The Oriental Weatherfish shares many of these traits. The fish may live beyond 7 years in the wild (Suzuki 1983; Urquhart 2013), reaches sexually maturity by age 1 year (Kubota 1961; Lei and Wang 1990), and is capable of very high reproductive output, spawning multiple times over a protracted mating season (Suzuki 1983; Urquhart 2013). Additionally, the Oriental Weatherfish is highly tolerant of variable environmental conditions. The fish uses a range of behavioral and physiological characteristics to support hypoxic water conditions and aerial exposure, including surface air breathing (Chew et al. 2001; McNeil and Closs 2007). It can survive months of habitat drying and can resist desiccation by burrowing into the substrate and waiting out these conditions in a small excavated chamber below the ground surface (Koetsier and Urquhart 2012). The present study adds to this list by indicating the ability of Oriental Weatherfish to survive subfreezing water (and perhaps soil) temperatures, including direct exposure to ice.

Ecological impacts of invasive populations of the Oriental Weatherfish are uncertain. However, given the widespread locations of introduced populations, its standing as a commercially available aquarium fish, and its display of traits characteristic of other successful invasive fishes, we predict that the fish will continue to invade new regions. Additionally, our data suggest that minimum water temperature may not limit further range expansion. Consequently, we suggest that future studies focus on the specific ecological impacts of the Oriental Weatherfish on native fish and invertebrate communities within habitats where it has become established.

ACKNOWLEDGMENTS

We thank D. Daw and J. Tabbutt for their assistance in the field and laboratory. We also thank Idaho Department of Fish and Game personnel at the Eagle Island Hatchery and the South-west Regional and Research Offices for access to collection locations, methodology, and insights. Most importantly, we thank James Long, Professor Emeritus of Boise State University for introducing us to this novel fish species. All field and laboratory procedures were carried out in accordance with the American Fisheries Society publication, Guidelines for the Use of Fishes in Research (2004).

REFERENCES


