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Thermal tolerance of the invasive red-bellied pacu and the risk of establishment in the United States

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ABSTRACT

Indigenous red-bellied pacu, *Piaractus brachypomus*, populations are in decline due to overfishing. Once ignored by aquaculturists because of their perceived low economic value, renewed aquaculture efforts in Central and South America aim to relieve fishing pressures on natural pacu populations. In the southern United States pacu aquaculture for the aquarium trade has raised concerns that accidental release could lead to establishment of overwintering populations outside captivity—a threat accentuated by the average 6 °C increase in shallow-water temperatures predicted by the end of the century. In the present study, Critical and Chronic Thermal Methodology was used to quantify red-bellied pacu thermal tolerance niche requirements. The data suggest that red-belllied pacu are a thermophilic species capable of tolerating low and high chronic temperatures of 16.5 °C and 35 °C, respectively. Critical thermal minimum and maximum temperatures of fish acclimated near their chronic limits are 10.3 and 44.4 °C. Red-bellied pacu aquaculture in the United States is concentrated in subtropical Florida regions that encourage rapid growth and reproduction, but carry an increased risk of establishing reproducing populations in local freshwater systems. The thermal niche data show that the risk of bioinvasion can be reduced or eliminated by adopting an approach whereby aquaculture potential is integrated with environmental temperature constraints.

1. Introduction

The combined effect of rapid global warming and geographic expansion of thermophilic invasive species has been defined as one of the most dangerous current threats to biodiversity (Di Santo, 2015; Hellmann et al., 2008; Rahel and Olden, 2008; Walsh et al., 2016). A warming climate will likely cause temperature increases in freshwater systems that could affect physiological performance, distribution, phenology and size of many aquatic species (Burrows et al., 2011; Di Santo, 2016; Di Santo and Lobel, 2017; Gardner et al., 2011; Genner et al., 2010; IPCC, 2013). In addition, anthropogenic activities have facilitated the spread of invasive fishes through implementation of fast-growing aquarium and aquaculture practices (Eme and Bennett, 2008; Rahel, 2007). Fish introductions into novel aquatic ecosystems can be devastating to indigenous diversity. While numerous adverse effects of exotic fish introductions have been explored such as disruption of native ecosystems (Dabruzzi et al., 2017) and increases in exotic diseases or parasites (Daszak et al., 2000; Hoegh-Guldberg and Bruno, 2010; Marcogliese, 2001), the increased risk of survival and permanent establishment of non-native species in local ecosystems under global warming scenarios is currently understudied.

The recent increase in the number of exotic introductions in North American freshwater systems (Bajer et al., 2016; Larson et al., 2017) highlights a need for understanding the extent to which warming of freshwater bodies could provide suitable thermal conditions for survival and establishment of non-native fishes. Geographic regions supporting migration and establishment of thermophilic fishes are expected to increase as a consequence of warming (Bennett and Beitinger, 1997; Currie et al., 1998; McCauley and Beitinger, 1992; Semmens et al., 2004). For example, McCauley and Beitinger (1992) predicted that the ability to grow channel catfish, *Ictalurus punctatus*, in the United States would be extend northward by approximately 240 Km for each 1 °C increase in mean air temperature. It is likewise plausible that non-native aquaculture species could become a threat to local

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biodiversity as future temperature regimes become more amenable to colonization. Typically, fishes chosen for intense aquaculture production are hardy, tolerant species that thrive in marginal water conditions (e.g. low dissolved oxygen and high temperature), and therefore are less sensitive to changes in the environment when compared to wild indigenous fishes (Alcantara et al., 2003).

The red-bellied pacu, *Piaractus brachypomus* (Cuvier, 1818) is a Neotropical fish that has garnered some interest as an aquaculture species in the United States. Unlike their notorious relatives, the piranhas (genera *Serrasalmus*, *Pristobrycon*, *Pygocentrus*, and *Pygopristis*), with which they are often confused, pacu are fast growing frugivorous fish that tolerate marginal water quality (Lovshin et al., 1974) and prefer plant material to flesh. The species is a floodplain specialist distributed throughout the Amazon and Orinoco Rivers in the La Plata Basin of South America, and typically does not occur outside main floodplain channels (Correa et al., 2007). Red-bellied pacu have palatable flesh and are an important commercial species in their native habitat (Ferreira et al., 1996), but overfishing has resulted in population declines across their natural range. Once ignored by aquaculturists because of their perceived low economic value compared to the closely related tambaqui, *Colossoma macropomum* (Cuvier, 1816), renewed efforts to culture red-bellied pacu have been aimed at relieving overfishing pressures on natural populations (Alcantara et al., 2003; Avadí et al., 2014).

In the southern United States red-bellied pacu are cultured as an ornamental species for the aquarium trade (Chapman et al., 1997; Hill et al., 2009), with most exported fish cultured in the state of Florida (Chapman et al., 1997). While there are no indigenous pacu species in Florida, at least three species have been reported in state waters (Fig. 1), including red-bellied pacu, tambaqui, *Colossoma macropomum* (Cuvier, 1816), and caranha, *Piaractus mesopotamicus* (Holmberg, 1887). All three species are thought to have been introduced through aquarium releases or fish farm escapes. Major concerns over aquaculture of pacu in the United States are related to the risk of establishing permanent populations outside captivity. Within the U.S. there are frequent reports of pacu caught by anglers (Ćaleta et al., 2011), sometimes as far north as the Laurentian Great Lakes (Rixon et al., 2005). Low winter temperatures are believed to be the major factor preventing pacu from establishing permanent populations in the northern United States, however; overwintering in thermal refugia such as stenothermal springs (see Edwards, 1977) or heated effluents (Neill and Magnuson, 1974) may allow pacu to survive winters in cooler northern regions. In their native tropical habitat, red-bellied pacu are found at temperatures between 15 and 35 °C (Lovshin et al., 1974), similar to conditions experienced in South Florida and the southernmost region of Texas (Bennett et al., 1997). The purpose of this study was to gain a better understanding of red-bellied pacu thermal ecology by quantifying the species' thermal niche using standardized thermal methodologies. Specific study goals were to 1) identify areas of the southern United States most susceptible to pacu colonization, 2) couple tolerance and local environmental data to identify sites within Florida suitable for pacu aquaculture but with minimal risk of bioinvasion, and 3) predict how future global warming scenarios may affect pacu populations in the United States.

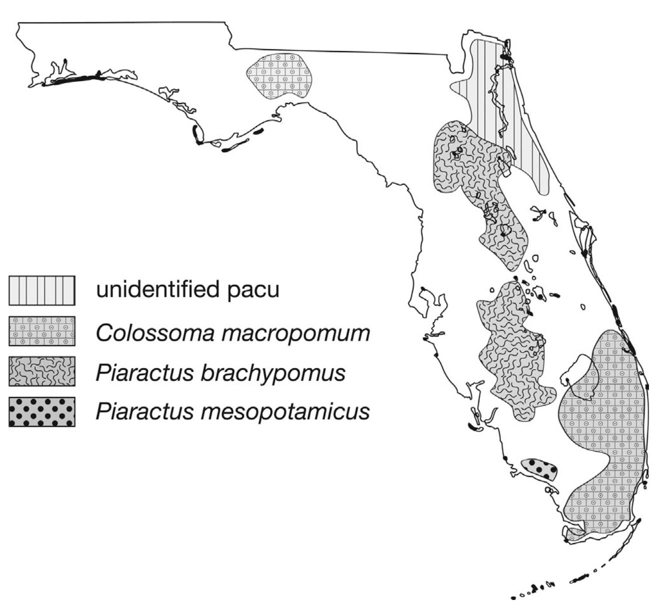

Fig. 1. Non-indigenous occurrence of different pacu species in Florida. According to the Florida Department of Environmental Protection pacu populations are thought to be introduced through aquarium releases or fish farm escapes and are listed as "permanent but not reproducing".

2. Materials and methods

2.1. Red-bellied pacu holding conditions

One-hundred juvenile red-bellied pacu with an average standard length of 6.6 ± 1.46 cm, and mass of 12.1 ± 6.32 g, were purchased from a local distributor. Fish were transferred to the University of West Florida, Marine Eco-Physiology Facility where they were randomly sorted into five temperature treatment groups. Each temperature treatment was comprised of four replicate 35-L, glass aquaria containing five fish each, (i.e., 20 pacu per treatment). Fish were maintained in aerated, biologically filtered, de-chlorinated tap water (conductivity 220–350 µmho/cm; pH 7.2–7.6). Water quality including pH, ammonia, nitrite, and nitrate was tested in each aquarium twice per week and 20% water changes were performed weekly, or more frequently if indicated by water quality testing results. Pacu were fed TetraMin® conditioning food daily throughout the acclimation period but were not fed 24 h before or during trials.

2.1.1. Thermal acclimation protocols

All treatment group aquaria were housed in a Kysor, model PS-6 environmental chamber at an air temperature of 10 °C and a 12 h light: 12 h dark diel photoperiod. Techne®, model TE-10A, 1000-W, circulating heaters maintained individual aquaria within ± 0.5 °C of their temperature set point. Treatment aquaria water temperatures were initially set at 20.0 ± 0.5 °C, and adjusted to their final set-point temperatures once fish began actively feeding. Temperatures in two of the treatment groups were increased by 1 ºC/day until reaching set-point temperatures of 25.0, and 30.0 °C. A third treatment group remained at 20.0 °C. Water temperatures in the two remaining treatment groups were increased or decreased by 0.5 °C per day until feeding cessation was observed. We used standard rates of increase and decrease in temperature that yield to meaningful prediction of thermal responses of organisms in the wild (Huey and Stevenson, 1979) and allow to compare thermal limits and niches across species. Treatment acclimation set-points of 16.5 and 35.0 °C (see Results) were then determined by reversing the direction of water temperature change in each treatment group until feeding resumed. Respective high and low feeding temperatures in each treatment were determined as the mean of the feeding cessation and feeding resumption points, and represent chronic maximum and chronic minimum temperatures that define the red-bellied pacu thermal acclimation range (Dabruzzi et al., 2017). All constant acclimation treatment groups were held at their final acclimation set-point temperatures for a minimum of 21 days before undergoing experimental trials.

2.2. Critical thermal methodology

Standard critical thermal methodology (CTM) was used to quantify critical thermal maximum (CTmax) and critical thermal minimum