

## Letter

## Offering Toughness and Protection, Arapaima Scales Provide Effective Defense against Predation

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We thank Huskey, Westneat, and Grubich<sup>1</sup> for the detailed account on the arapaima and piranha. Their article is not only informational but adds to our understanding of the complex relationship between evolution, environment, and predator-prey dynamics. We are by no means evolutionary biologists, but materials scientists, and the sole goal of our contributions has been to clearly demonstrate that the arapaima scales are a formidable biological structure with great toughness, among the highest among biological materials, with an impressive  $J_{Ic}$  fracture toughness of  $\sim 200 \text{ kJm}^{-2}$ . We unknowingly narrowed Currey's conclusion about the protection offered by the arapaima scale to piranhas. He states:<sup>2</sup> "The huge teleost freshwater fish *Arapaima gigas*, which can exceed 3 m in length, has somewhat similarly layered scales, which probably make it effectively immune to attack (Torres et al., 2008)." Torres et al.<sup>3</sup> preceded us in the publication of the results and were the first to analyze the structure of the scale and to suggest their outstanding toughness. Thus, these scales are a superb defense against predators.

One of us (MAM) has a 50-year experience in the Amazon basin rivers and has witnessed unprovoked piranha attacks against persons and dogs. It is true that appendages such as tails (in dogs) and fingers and toes (in humans) are favored biting sites because of their shape. Huskey et al.<sup>1</sup> explain this well by measuring the gape and angle of various piranhas. It is also true that one often finds tails of fish with some

cartilage removed by piranha bites. We recognize that the arapaima shape is not highly conducive to be attacked by piranha. However, this might also be an aspect of evolution. The aruana, related to the arapaima, is similarly covered by large scales.

In seasonal lakes and river channels, diurnal fish such as peacock bass are often devoured when caught on the line and pulled away from protective dead underwater trees and branches. However, pacu are not and their scales provide protection even when hooked. Since piranhas are diurnal, nocturnal fish (primarily siluroidei, scaleless catfish) are protected because of their habits. The arapaima is an obligate air-breather and has to periodically (every 10 to 20 min) breach the surface. Thus, it would provide an ideal prey if it did not have these outstanding elasmoid scales. The tongue is also highly mineralized, and we venture to state that this is also a protection from piranha attacks. Huskey et al.<sup>1</sup> imply that the South American alligator (cayman) is the primary predator of the arapaima, but we can hardly reconcile this with the highly mineralized tongue. The indigenous inhabitants attribute the protection from piranha to the scales.

Indeed, elasmoid scales have appeared several times during evolution in response to predator attacks.<sup>4</sup> They should not be confused with ganoid scales, which diverged evolutionary from them at a very early stage. The ganoid scales of the alligator gar of the Mississippi Basin serve as pro-

tection against self-predation and alligators, as we stated earlier.<sup>5</sup> There is a cost, in mobility and speed, for having an armor. Thus, we are unanimous to agree that the survival of the arapaima has been ensured by its scales. Were the arapaima river dwellers, they would not be such an easy prey. Piranhas are not active in running water and are most aggressive in seasonal lakes, when the food supply is diminished, toward the end of the dry season.

It is true that juvenile arapaima do not have the well-developed scales, but they are protected by both parents in the nest—for the first three months of their life. The arapaima female prepares a nest and lays the eggs in it. These are later kept in the mouth of the father. The hatching coincides with the beginning of the rainy season; when the forest becomes flooded, the hatchlings enter it, finding plenty of food and protection. The mother fiercely protects the offspring from predators in the seasonal lakes. When the waters recede again, the juveniles are already grown (and have a covering of tough scales); they reach a length of 800 mm within one year.<sup>6</sup> This is consistent with the growth rate provided by Huskey et al.<sup>1</sup> We agree with the conclusions presented by Huskey et al.<sup>1</sup> Indeed, we have personally measured the biting force of piranhas from Paraguay and Roosevelt rivers and present the detailed results as well as experimental procedures in a separate paper.<sup>7</sup> This bite force is surprisingly low and we

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show, using allometry, that it increases with the square of the head length. Our results, consistent with the ones presented by Huskey et al.<sup>1</sup> and Huby et al.,<sup>8</sup> reinforce our belief that the arapaima scales are an effective defense against predation by, among others, piranhas.

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