



Limb and Tail Loss and Regeneration in the Nauta Mushroomtongue Salamander (*Bolitoglossa altamazonica*) in the Madre de Dios Region, Peru

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The regeneration of body parts as adults is rare among vertebrates, with members of the order Caudata possessing the most extensive regenerative capabilities. They are able to regenerate complex organs or structures such as the heart (Oberpriller and Oberpriller 1974), intestines (O’Steen 1958), jaws (Ghosh et al. 1996), lens (Reyer 1956), and limbs (Scadding 1981; Sessions and Larson 1987; Arenas Gómez et al. 2017). Additionally, they can regenerate the tail, a characteristic also present in many lizard species. However, while lizards regenerate unsegmented cartilage tubes that are easily distinguishable from intact tails, salamanders can regenerate almost perfect copies of the original tail that are segmented and include neural and hemal arches (Lozito and Tuan 2016). Most studies on regeneration in amphibians focus on *Ambystoma mexicanum* (Ambystomatidae) and *Notophthalmus viridescens* (Salamandridae), which are often

used as model organisms (Arenas Gómez and Delgado 2021). However, relatively few studies address the regenerative capabilities of other families (Scadding 1981; Sessions and Larson 1987; Arenas Gómez et al. 2017).

Salamanders in the family Plethodontidae possess characteristics uncommon in other families, such as the absence of lungs and the ability to respire entirely through the skin, a projectile tongue used for catching small invertebrate prey, and the ability to autotomize the tail. Plethodontids undergo direct development and lack larval stages (Arenas Gómez et al. 2017). *Bolitoglossa* is a diverse plethodontid genus and the most geographically widespread genus of salamanders, distributed from northern Mexico throughout much of Central and South America to the Amazon Basin in Peru and Brazil and the mountainous regions of central Bolivia (Brcko et al. 2013). Species of *Bolitoglossa* are nocturnal, generally arbo-



Fig 1. An adult Nauta Mushroomtongue Salamander (*Bolitoglossa altamazonica*) with an amputated left hind limb showing signs of regeneration and a regenerating tail. Photograph by Daniel Ash.

real, and have extensively webbed digits and a prehensile tail, which allow them to climb and utilize arboreal habitats (Arenas Gómez et al. 2017).

Bolitoglossa altamazonica (Nauta Mushroomtongue Salamander) is a small, slender species that occurs in tropical primary and secondary forests on the eastern side of the Andes and throughout the western Amazon Basin. Adults have SVLs of 33–54 mm, and tails approximately 70–120% of SVL (Brcko et al. 2013). They often are up to 1.8 m above the ground on the leaves of herbaceous vegetation, although they occasionally occur in leaf litter and inside bamboo stems, where they may sleep during the day (Brcko et al. 2013).

At 2046 h on 19 September 2022, during a routine herpetological survey in secondary forest at the Manu Learning Centre, a biological station operated by the Crees Foundation for Manu, in the Manu Biosphere Reserve of Peru (12.78742 S, 71.40008 W; elev. 502 m asl), we encountered an adult *B. altamazonica* (36.0 mm SVL, 20.1 mm tail length, 0.4 g) perched 102 cm high above the ground on a leaf (Fig. 1). It was lacking part of its left hind limb, which had been severed above the elbow. The limb appeared to be in the process of regeneration, with the palette starting to form and dorsoventral flattening occurring. Furthermore, the individual apparently had previously autotomized and was regenerating its tail, which was discolored and shorter in length than non-autotomized tails. Upon release, the salamander walked on a leaf, using the stump of its rear left leg. We do not know the cause of the loss of the limb, but the signs of regeneration indicated that it likely was not a congenital malformation.

According to the growth stages of limb regeneration in *Bolitoglossa ramosi* (Arenas Gómez et al. 2017), dorsoventral flattening and palette development occur at approximately 70 days post-amputation. However, the rate of regeneration is unknown in its congener, *B. altamazonica*. The locomotion of the individual described above did not appear to be negatively impacted by the loss of its limb. Available literature fails to address the prehensibility of regenerated tails. Since the fully regenerated tail is almost identical to the original (Lozito and Tuan 2016), it might retain its prehensibility. We did not observe this individual climbing, but since we found it on the leaf well above the ground, it evidently was capable of arboreal movement despite missing a foot and its original tail.

A possible consequence of appendage loss in salamanders, especially caudal autotomy, is the cost on respiration. Given that plethodontid salamanders are lungless and respire through the skin, the loss of a large proportion of respiratory surface area could have a substantial impact on respiratory and metabolic capacities. Smits and Brodie (1995) found that in *Oedipina uniformis*, another plethodontid species, the respiratory cost of tail autotomy was insignificant. However, this has yet to be investigated in the genus *Bolitoglossa*. In addition to the effects of appendage loss, little is known about

the effects of regeneration itself in any species of *Bolitoglossa* that could include energy costs and implications for reproduction and survival. Studies on other plethodontid salamanders, such as *Batrachoseps attenuatus* and *Plethodon cinereus*, indicated that tail regeneration could potentially delay maturity, inhibit reproduction, and reduce reproductive output, suggesting that, when the tail is lost, the allocation of energy for caudal regeneration is prioritized over development and reproduction (Maiorana 1977; Yurewicz and Wilbur 2004). Conversely, an experiment by Houck (1982) found that tail loss in male *Desmognathus ochrophaeus* did not reduce reproductive success, despite these salamanders using their tails during courtship. While *B. altamazonica* shares certain morphological and molecular characteristics with other plethodontid salamanders, substantive differences exist. Therefore, further research is required to gain a better understanding of the regenerative capabilities of *B. altamazonica* and the impacts and costs of appendage loss and regeneration on survival, development, locomotion, and reproduction.

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