Comparative Biochemistry and Physiology, Part A 189 (2015) 21–29

Contents lists available at ScienceDirect

Comparative Biochemistry and Physiology, Part A

journal homepage: www.elsevier.com/locate/cbpa

Surviving in a semi-marine habitat: Dietary salt exposure and salt secretion of a New Zealand intertidal skink

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ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form 7 July 2015
Accepted 7 July 2015
Available online 15 July 2015

Keywords:
Invertebrates
Physiology
Plasticity
Potassium
Regulation
Salt
Sodium
Stable isotopes
Stress
Suter's skink

ABSTRACT

Species that inhabit marine and intertidal ecosystems face osmoregulatory challenges, risking dehydration and increased ion concentrations in the body. Lizards need to either tolerate or regulate these increased ion concentrations. In this study, we aim to understand how Suter's skink (*Oligosoma suteri*), an intertidal skink restricted to shoreline habitats, is able to cope with the physiological stress of living in an extreme salt environment. We determined the diet, prey species' salt content, and nasal and cloacal salt excretion on Rangitoto and Motutapu Islands in northern New Zealand, where the skinks have contrasting access to terrestrial invertebrates. Analysis of stable isotopes suggests inter- and intra-population variability in Suter's skink diets. Intertidal invertebrates under washed up seaweed appear to compose a major part of the diet of the Rangitoto population, while the Motutapu population showed evidence for a mixed diet of terrestrial and intertidal invertebrates. Sodium content of prey species decreased with an increasing distance from the seawater. Field secretion of cations through nasal glands consisted primarily of Na^+, which is consistent with other marine and intertidal species. Sodium was also the primary cation in urine. In contrast, fecal cations consisted primarily of K^+. This first study into the salt secretion of an intertidal skink species provides evidence of Suter's skink's plasticity in secreting excess ions through nasal salt glands. This likely enables it to deal with the challenges of living in a semi-marine habitat.

1. Introduction

Reptiles have managed to settle in extreme habitats including the cold of the Arctic circle (Andersson, 2003; Pianka and Vitt, 2003; Meiri et al., 2013), the hot temperatures of the desert (Vitt and Caldwell, 2009), and the salt water of the ocean (Schmidt-Nielsen and Fange, 1958). Each of these habitats forces reptiles to deal with particular physiological challenges, one of which is coping with high ionic concentrations of body fluids.

Reptiles comprise 70–80% water, with Na^+, K^+, and Cl^- as some of the crucial ions for physiological functions (Vitt and Caldwell, 2013). In order to maintain homeostasis, thus maintaining their osmotic balance (Brischoux and Kornilev, 2014), ionic concentrations of body fluids need to remain within a specific range (Campbell and Mader, 2006). Reptiles can either tolerate or regulate their internal ion concentration (Hazard, 2004). Species like *Gopherus agassizii* and *Amphibolurus muricatus* are able to tolerate extreme fluctuations in internal ion concentrations until periodic rainfall allows them to secrete the stored excess ions (Bradshaw and Shoemaker, 1967; Peterson, 1996). However, many reptiles use salt glands to regulate internal ion concentrations (Dunson, 1976). Reptile salt glands are able to secrete the cations Na^+ and K^+ with Cl^- as the most important anion (Dunson, 1969; Hazard, 2001). The salt glands may secrete ions in response to each species' ecologically relevant dietary stimuli, with Na^+Cl^- as the most important dietary salt input for intertidal or marine species, and K^+ for terrestrial herbivorous species (Hazard et al., 2010).

Many opportunistic lizard species exploit the resources of marine and intertidal ecosystems, despite the physiological challenges (Davenport, 2011). Feeding on intertidal resources has been documented for, e.g., *Uta stansburiana* (Hazard et al., 1998), *U. tumidarostra* (Grismer, 1994), *Podarcis dugesii* (Davenport and Dellinger, 1995), *P. atrata* (Castilla et al., 2008), and *Eumeces longirostris* (Davenport et al., 2001). Lizards feeding on marine or intertidal resources are particularly prone to exposure from high ion loads (Hazard, 2004; Hazard et al., 2010). Those species that enter seawater will likely face the most extreme salt environment among terrestrial lizards.

To our knowledge, the salt secretion of only two skink species has been studied: the semi-desert species *Eumeces schneideri* (Hazard et al., 2010) and the semiarid plains and woodlands inhabiting *Tiliqua rugosa* (Bradshaw et al., 1984). Neither of these is known to feed on

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http://dx.doi.org/10.1016/j.cbpa.2015.07.002
1095-6433/

intertidal invertebrates. Both skink species secrete a relatively stable combination of Na^+ and K^+, without the ability to exclude the secretion of either cation (Bradshaw et al., 1984; Hazard et al., 2010).

The few studies available on skink ion secretion suggest that these lizards might secrete excess ions in a different way compared to other lizard species, as they appear unable to substantially vary their secretion of cations (Hazard et al., 2010). Combined with the hypothesis that lizards secrete in response to each species' dietary stimuli, the question arises: how do skink species exposed to salty environments cope with a high ion input?

Suter's skink *Oligosoma suteri*, Boulenger (1906), is a small (SVL <108 mm, Hare et al. (2008)) nocturnal semi-aquatic species endemic to New Zealand and distinctive for its use of seawater to escape predators (Hare and Miller, 2009; Miller et al., 2010) and to forage for food (Towns et al., 2003). The species inhabits boulder beaches, rock talus above boulder beaches, rocks on rock platforms, and boulder areas covered by vines along the coast (Towns, 1975; Parrish and Gill, 2003). Suter's skink forages in the open, among rock pools (Whitaker, 1968), near rotting seaweed piles (Towns, 1975), and frequently enters rock pools to forage on intertidal invertebrates (Miller et al., 2010). Boulder beaches provide refuge to escape predation, but beaches with smaller boulders are susceptible to strong wave action and create a mobile rock cover on the shore (Morton and Miller, 1973). Therefore, boulder beaches might only be a temporary effective refuge (Towns et al., 2003). Suter's skink thus needs to be able to survive in a mobile and unstable habitat while facing the physiological challenges of living in a salty environment.

To understand how Suter's skink deals with the physiological stresses of long-term exposure to a salty environment, we studied two populations with different availability of terrestrial and/or intertidal resources. For both populations, we determined diet composition, strength of exposure to marine influences, and invertebrate salt content. We quantified Na^+ and K^+ content of nasal gland secretions, fecal matter and urine, and determined fecal water content. We assumed that Suter's skink regulates salt using nasal salt glands instead of tolerating increased ion concentrations. We hypothesize that Suter's skink is an opportunistic feeder, showing equal presence of terrestrial vs. intertidal resources in its diet when available; if there is limited access to terrestrial prey, the skinks will use intertidal resources as the main dietary component. We also hypothesize that cations in intertidal invertebrates will comprise a predominance of Na^+ whereas those in terrestrial invertebrates will comprise a predominance of K^+. As a consequence, both study populations of skinks will likely secrete relatively more Na^+ than K^+, but when there is increased access to terrestrial invertebrates, the skinks will secrete relatively less Na^+, as we expect an equal presence of terrestrial vs. intertidal resources in the diet when terrestrial resources are available.

2. Materials and methods

2.1. Study area

We collected Suter's skinks from Rangitoto Island Scenic Reserve and Motutapu Island Recreation Reserve (-36.786742° N, 174.860115° E) in the Hauraki Gulf Marine Park northeast of Auckland, New Zealand. Suter's skinks were captured at Cable Bay on Motutapu Island, and at Wreck Bay on Rangitoto between January and April 2014. Rangitoto is a forested volcanic island (2311 ha) connected to the farmed sedimentary Motutapu Island (1509 ha) by a short causeway. The Rangitoto study site is backed by a mosaic of Pohutukawa, *Metrosideros excelsa*, dominated forest and scrub, which is typical of vegetation throughout the island (Wotherspoon and Wotherspoon, 2002). Patchy forest cover and bare volcanic rock provide little opportunity for skinks to forage on terrestrial invertebrates, but with ample opportunity to forage on intertidal invertebrates. The Motutapu study site is bordered on the landward side by grasses and herbs, which leads to pasture grazed by cattle (Towns, 1975). This provides an opportunity for Suter's skink to forage on both terrestrial and intertidal invertebrates. One fresh water stream crosses the study site at Motutapu, but no fresh water is available at Rangitoto. Suter's skink populations occur on both islands and are expanding following removal of eight invasive mammal species in 2009 (Griffiths et al., 2014).

2.2. Study design

2.2.1. Trapping of animals

We captured Suter's skinks in 4 L plastic pitfall traps (Towns, 1975; Towns et al., 2001) stratified over three habitat types: (I) the seaweed zone, (II) the border zone between beach and vegetation, and (III) the vegetation zone. For Motutapu, we also used a strip of rank pasture grasses adjacent to the fence separating the pasture and beach (Fig. 1), as a fourth habitat type (IV), as Suter's skinks could also be found there (Artyom Polkanov, *pers. comm.*, January 2014). Within each habitat type, pitfall traps were placed opportunistically, with an equal distance between the traps wherever possible. All traps were baited using canned fish food or sliced banana. Traps were set for less than 24 hours and only during the hours of darkness, since the species is nocturnal. We added wet seaweed to each trap to prevent dehydration of the lizards and to provide shelter from potential predators. Small holes in the bottom of each trap provided the necessary drainage to

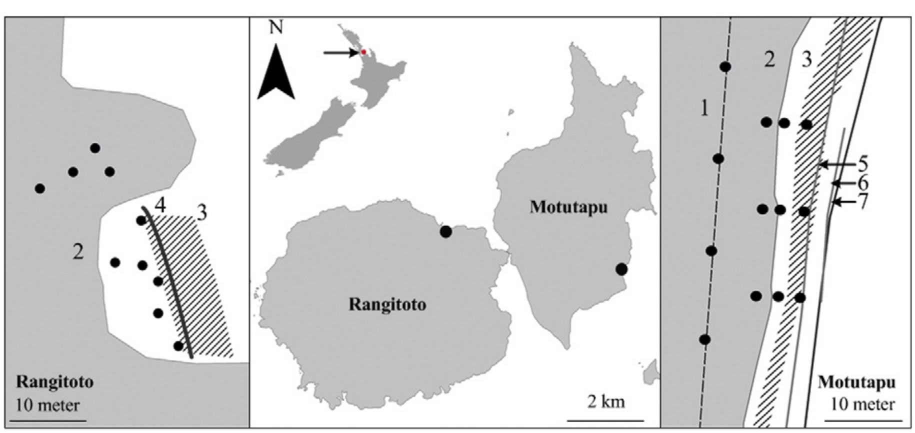

Fig. 1. Map of Rangitoto (left) and Motutapu (right) islands, their location within New Zealand, and the location of both study sites used. Black circles represent pitfall trap locations. On the left panel, the Rangitoto study site is shown, on the right, the Motutapu study site. The cattle fence (1) at Motutapu is displayed with four pitfall traps behind them. The darker area (gray) comprised the vegetation zone (2) and the dashed area is the average zone of seaweed (3), the line (5) at the left panel corresponds to high water levels at Rangitoto, and for Motutapu, average high water levels are shown for 31-01-2014 (5), 21-03-2014 (6), and 29-01-2014 (7).