

6 Temperature-Driven Metabolic and Molecular Mechanisms

6.1 Changes in respiratory metabolic rate and energy expenditure

Temperature strongly modulates respiratory metabolism and whole-animal energy expenditure in abalone. In *Haliotis discus hannai* exposed to semidiurnal fluctuations (20 °C-26 °C), metabolic rates increased sharply at stable warm summer temperatures and fluctuated in parallel with short-term temperature changes, while ammonia excretion remained similar between fluctuating and stable conditions, indicating high maintenance costs and reliance on protein catabolism to fuel elevated demand (Kang et al., 2019). Under moderate heat stress (5 °C above ambient for six weeks), red abalone (*H. rufescens*) and pāua (*H. iris*) also showed 32% and 57% higher metabolic rates, respectively, confirming that acute warming elevates maintenance metabolism across species (Frederick et al., 2022). Interactions with oxygen availability further constrain thermal windows. In juvenile green abalone (*H. fulgens*), warming under hypoxia and hypercapnia caused respiration rates to fall below values expected from an exponential increase and triggered anaerobic metabolism, indicating a downward shift of the upper critical temperature and a narrowed thermal window (Tripp-Valdez et al., 2017; Tripp-Valdez et al., 2018). Seasonal studies on *Haliotis tuberculata* likewise show lower respiration and calcification in cool seasons and higher rates in warm seasons, emphasizing temperature as a primary driver of temporal variability in energy expenditure (Figure 1) (Chappon et al., 2018).

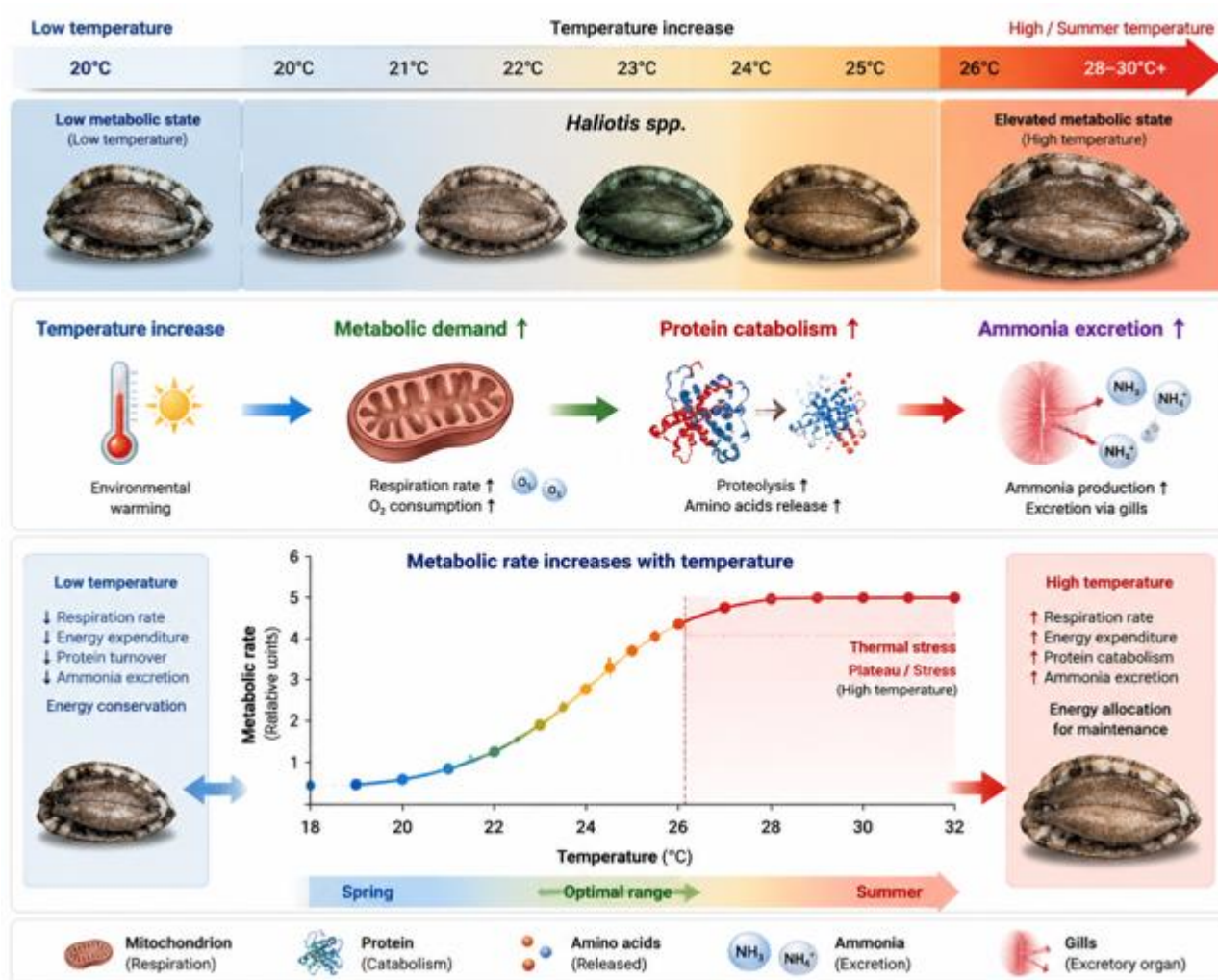


Figure 1 Temperature-driven metabolic regulation in *Haliotis* spp.

6.2 Enzyme activity and metabolic pathway regulation mechanisms

Thermal fluctuations reshape metabolic enzyme activity and pathway use. In *H. discus hannai* exposed to fluctuating temperatures, key metabolic enzymes (PDH, DLD, HIBADH, GDH) were downregulated despite high