Symbiotic nutrient cycling enables the long-term survival of Aiptasia in the absence of heterotrophic food sources

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Keywords

Aiptasia | heterotrophy | NanoSIMS | nitrogen limitation | photosymbiosis | Symbiodiniaceae

Author contributions

N.R conceived and conducted the experiment and performed the sample and data analysis. N.R. and A.M. wrote and revised the manuscript.

Conflict of interest

The authors declare no competing interests.

Funding

N.R. and A.M. are supported by the Swiss National Science Foundation, grants 200021_179092 and 205321_212614

Data availability

All associated data are available at zenodo.org.

Abstract

Phototrophic Cnidaria are mixotrophic organisms that can complement their heterotrophic diet with autotrophic nutrients assimilated by their algal endosymbionts. Metabolic models suggest that the translocation of photosynthates and their derivatives from the algae may be sufficient to cover the metabolic energy demands of the host. However, the importance of heterotrophy to the nutritional budget of these holobionts remains unclear. Here, we report on the long-term survival of the photosymbiotic anemone Aiptasia in the absence of heterotrophic food sources. Following one year of heterotrophic starvation, these anemones remained fully viable but showed an 85 % reduction in biomass compared to their regularly-fed counterparts. This shrinking was accompanied by a reduction in host protein content and algal density, indicative of severe nitrogen limitation. Nonetheless, isotopic labeling experiments combined with NanoSIMS imaging revealed that the contribution of autotrophic nutrients to the host metabolism remained unaffected due to an increase in algal photosynthesis and more efficient carbon translocation. Taken together, our results suggest that heterotrophic feeding is not essential to fulfilling the energy requirements of the holobiont on a one-year timescale. But, while symbiotic nutrient cycling effectively retains carbon in the holobiont over long time scales, our data suggest that heterotrophic feeding is a critical source of nitrogen required for holobiont growth under oligotrophic conditions.

Introduction

Photosymbiotic Cnidaria, such as corals and anemones, dominate shallow hard-bottom substrates in the oligotrophic tropical ocean (Pandolfi 2002). The key to their evolutionary and ecological success under these conditions lies in their association with endosymbiotic algae of the family Symbiodiniaceae (Stanley 2006; Stanley and van de Schootbrugge 2009). Efficient nutrient exchange in these symbioses couples the heterotrophic metabolism of the host with the autotrophic metabolism of their algal symbionts (Yellowlees et al. 2008; Cunning et al. 2017). Consequently, photosymbiotic Cnidaria are considered mixotrophic as they can acquire nutrients via heterotrophy and autotrophy alike (Fox et al. 2018; Radice et al. 2019). Under oligotrophic conditions, this confers an ecological advantage that enables these animals to outcompete other benthic organisms restricted to either heterotrophic or autotrophic nutrient sources (Muscatine and Porter 1977; McCook 2001).

In the stable symbiosis, the algal symbionts translocate a large proportion of their photosynthates in the form of sugars and sterols to their host (Falkowski et al. 1984; Burriesci et al. 2012; Tremblay et al. 2014; Hambleton et al. 2019). This carbon translocation fuels the host metabolism and may be sufficient to cover the host's energy demand under optimal environmental conditions (Davies 1984; Rinkevich 1989; Tremblay et al. 2012). The translocated photosynthates have been referred to as 'junk food' because their low nitrogen content limits their potential for anabolic incorporation (Falkowski et al. 1984; Dubinsky and Jokiel 1994). Hence, the utilization of autotrophic nutrients by both symbiotic partners depends, in part, on their access to inorganic nitrogen sources from the surrounding seawater (Davies 1984; Morris et al. 2019; Rädecker et al. 2021). However, under the oligotrophic conditions that prevail in the tropical ocean inorganic nitrogen availability is limited (O'Neil and Capone 2008).

In contrast, heterotrophic nutrient sources have a proportionally higher nitrogen content allowing efficient anabolic assimilation (Hughes et al. 2010). There is ample evidence demonstrating the nutritional benefits of heterotrophic feeding, e.g., in the form of organic nitrogen or vitamins for both symbiotic partners (Goreau et al. 1971; Porter 1976; Houlbrèque and Ferrier-Pagès 2009). As such, high rates of heterotrophic feeding may enable corals to compensate for reduced autotrophic nutrient availability following bleaching; i.e., the stress-induced breakdown of the cnidarian-algal symbiosis (Grottoli et al. 2006; Anthony et al. 2009). However, as our understanding of potential prey dynamics (e.g., zooplankton abundance) and cnidarian grazing on coral reefs remains limited (Lowe and Falter 2015), the importance of heterotrophic nutrients for sustaining the stable cnidarian-algal symbiosis is less clear.

Here, we performed a starvation experiment using the photosymbiotic sea anemone Aiptasia to study the role of heterotrophic nutrient acquisition in symbiosis. For this, we reared Aiptasia for one year in the absence of any heterotrophic nutrient sources. This permitted us to examine the effects of heterotrophic starvation on the symbiosis in light of the underlying carbon and nitrogen cycling and explore the limits of autotrophic nutrient acquisition in the photosymbiotic Cnidaria.

Material & Methods

Animal husbandry & experimental design

The experiments and measurements were performed on the photosymbiotic cnidarian model organism Aiptasia, i.e., *Exaiptasia diaphana* (Puntin et al. 2022). We used the clonal host line CC7 with its native algal symbiont community dominated by the *Symbiodinium linucheae* strain SSA01 (Sunagawa et al. 2009; Grawunder et al. 2015). Animal cultures were reared in 2 L acrylic food containers filled with artificial seawater (35 PSU, Pro-Reef, Tropic Marin, Switzerland). Artificial seawater was freshly prepared in the dark to minimize any potential microbial contamination. Culture stocks were kept at a constant temperature of 20 ˚C under a 12 h: 12 H light-dark cycle (photosynthetic

active radiation = 50 µE m^{-2} s^{-1}) using an Algaetron 230 incubator (Photo System Instruments, Czech Republic). Animals were fed once a week with freshly hatched *Artemia salina* nauplii (Sanders GSLA, USA) followed by a complete water exchange and removal of biofilms.

For the experiment, all animals were reared under the same conditions as outlined above for one year. However, while half of the animals were fed weekly with *Artemia* nauplii (regularly fed control), the other half was reared in the absence of any food sources (heterotrophically starved). Apart from this, all culturing parameters were kept identical, including the weekly cleaning and water exchange.

Phenotypic characterization

Following the one-year experiment, treatment responses were recorded. First, photos of representative phenotypes for each of the treatments were taken with an OM-1 camera and a 60 mm f2.8 macro objective (OM System, Japan) using identical illumination and exposure settings. Then, three animals were collected from each treatment group, transferred to a pre-weighed 1.5 mL Eppendorf tube, and homogenized in 500 µL Milli-Q water using a PT1200E immersion dispenser (Kinematica, Switzerland).

Host and algal symbiont fractions were immediately separated by centrifugation (3000 g, 3 min) and the host supernatant was transferred into a new pre-weighed 1.5 mL tube, flash-frozen in liquid nitrogen, and stored at -20 °C for later analysis. The algal symbiont pellet was resuspended in 500 µL Milli-Q water and rinsed by one additional centrifugation and resuspension step. Algal symbiont concentrations were quantified in three technical replicates per sample based on cell shape and chlorophyll autofluorescence using a CellDrop cell counter (DeNovix, USA). The protein content in the defrosted host supernatant was quantified in three technical replicates using the Pierce Rapid Gold BCA Protein Assay Kit (Thermo Scientific, USA) according to the manufacturer's instructions. Algal concentrations and host protein content were extrapolated to the initial sample volume and normalized to holobiont biomass. Holobiont biomass was approximated as dry weight. For this, host and symbiont fractions were dried at 45 °C until the weight was stable and the initial weight of empty tubes was subtracted from the final weight. The weight of host and symbiont fractions was corrected for aliquots taken for sample measurements to approximate the dry weight of the holobiont as a whole, i.e., host + symbiont fraction.

Isotope labeling & NanoSIMS imaging

To study treatment effects on symbiotic interactions, we quantified inorganic carbon and nitrogen assimilation and translocation in the symbiosis. For this, three animals from each treatment were transferred to 50 mL glass vials. For isotopic labeling, vials were filled with minimal artificial seawater medium (35 PSU, pH 8.1, 355.6 mM NaCl, 46.2 mM $MgCl_2$, 10.8 mM Na_2SO_4, 9.0 mM $CaCl_2$, 7.9 mM, KCl; (Harrison et al. 1980)) containing 2.5 mM $NaH^{13}CO_3$ and 10 µM $^{15}NH_4Cl$. Animals were incubated for 6 h in the light at their regular culture conditions before being transferred to a fixative solution (2.5 % glutaraldehyde and 1 % paraformaldehyde in 0.1 M Sorensen's phosphate buffer). Samples were fixed for 1 h at room temperature followed by 24 h at 4 °C before being stored in a preservative solution (1 % paraformaldehyde in 0.1 M Sorensen's phosphate buffer) at 4 °C until further processing. Within four days of fixation, samples were dissected and individual tentacles were processed for resin embedding. As such, samples were dehydrated in a series of increasing ethanol concentrations (30 % for 10 min, 50 % for 10 min, 2 x 70 % for 10 min, 3 x 90 % for 10 min, and 3 x 100 % for 10 min) and transferred to acetone (100 % for 10 min). Dehydrated samples were gradually infiltrated with SPURR resin (Electron Microscopy Sciences, USA) at increasing concentrations (25 % for 30 min, 50 % for 30 min, 75 % for 1 h, and 100 % overnight) and the resin was polymerized at 65 °C for 48 h. Embedded samples were cut into semi-thin sections (200 nm) using an Ultracut E ultramicrotome (Leica Microsystems, Germany), transferred onto glow-discharged silicon wafers, and sputter-coated with a 12 nm gold layer using an EM SCD050 (Leica Microsystems).

These samples were analyzed with a NanoSIMS 50L instrument (Hoppe et al. 2013). To remove the metal coating, target sample areas were pre-sputtered for 5 minutes with a primary beam of ca. 6 pA. Data were collected by rastering a 16 keV primary ion beam of ca. 2 pA Cs^+ focused to a spot size of about 150 nm across the sample surface of 40 x 40 µm with a resolution of 256 x 256 pixels and a pixel dwell time of 5 ms. The secondary ions $^{12}C_2^-$, $^{12}C^{13}C^-$, $^{12}C^{14}N^-$, and $^{12}C^{15}N^-$ were simultaneously collected in electron multipliers at a mass resolution of about 9000 (Cameca definition), sufficient to resolve potentially problematic mass interferences. For each sample, seven to eight areas were analyzed in five consecutive image layers. The resulting isotope maps were processed using the ImageJ plug-in OpenMIMS (https://github.com/BWHCNI/OpenMIMS/wiki). Mass images were drift- and dead-time corrected, the individual planes were added and $^{15}N/^{14}N$ maps were expressed as hue-saturation-intensity images, where the color scale represents the isotope ratio. ^{15}N assimilation was recorded as atom % excess (in comparison to unlabeled controls) by drawing regions of interest (ROIs) based on $^{12}C^{14}N^-$ maps around individual symbiont cells as well as gastrodermal tissue (excluding symbiont cells) in each of the images (see data file (Rädecker and Meibom 2022)). Due to the clonal nature of Aiptasia and the identical environmental conditions of animals within the same treatment, individual ROIs were considered independent measurements across animal replicates for the purpose of this study.

Statistical analyses

Treatment effects on phenotypic responses, i.e., biomass, host protein content, and symbiont density, were analyzed using two-sided unpaired Student's *t*-tests. Isotope ratios from NanoSIMS analysis were square root transformed to meet model assumptions and analyzed with linear models (LM) using the respective symbiotic partner (host/symbiont) and treatment (fed/starved) as explanatory variables. To test individual differences between groups LMs were followed up with a Tukey HSD post hoc comparison.

Results

Holobiont biomass loss in the absence of heterotrophic nutrients

After one year of husbandry in the absence of heterotrophic food sources, Aiptasia remained viable but had ceased any detectable asexual propagation via pedal lacerates. Starved animals showed pronounced phenotypic differences compared to their regularly fed counterparts. Specifically, starvation resulted in a reduction in body size, a paler appearance, and a loss of 85 % of their dry weight (Fig. 1A,B; Student's *t*-test, $t = 4.71$, $p = 0.042$). This decline in holobiont biomass was, at least in part, driven by a strong decline in host protein content and algal symbiont density, which both decreased by more than 80 % on average when normalized to holobiont biomass (Fig. 1C,D; for host protein: Student's *t*-test, $t = 5.39$, $p = 0.014$; for algal symbiont density: Student's *t*-test, $t = 3.85$ $p = 0.047$ for algal symbiont densities).

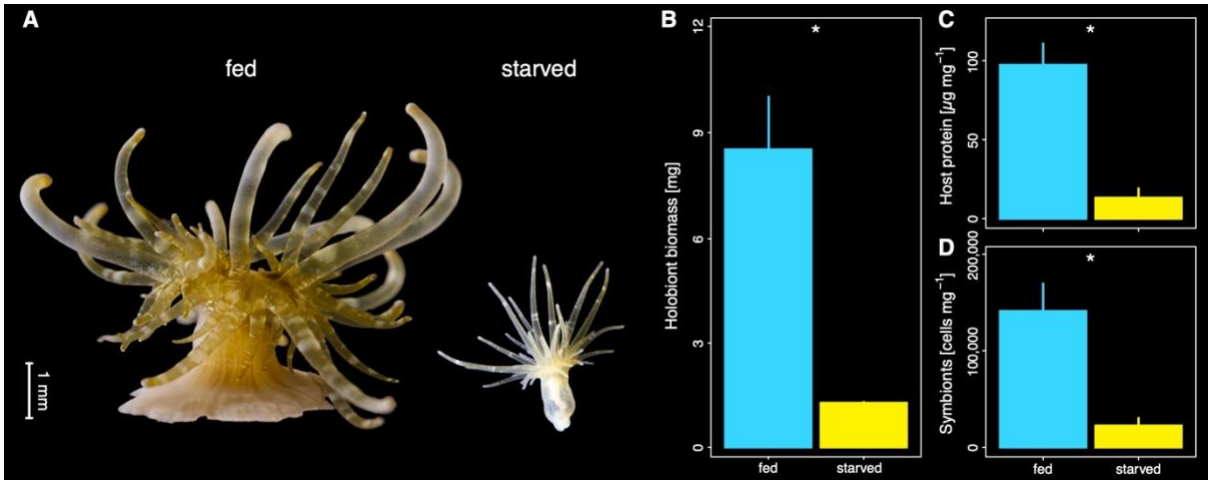

Fig. 1 | Phenotypic response to heterotrophic starvation in Aiptasia. (A) Representative photos illustrating the phenotype of animals that were regularly fed (left) or reared for one year without heterotrophic food sources (right). **(B)** Holobiont biomass expressed as dry weight of fed and starved Aiptasia. **(C)** Protein content of the host tissue per holobiont biomass of fed and starved Aiptasia. **(D)** Algal symbiont density per holobiont biomass of fed and starved Aiptasia. Asterisks indicate significant effects between treatments (*$p < 0.05$).

Enhanced photosynthetic performance of algal symbionts sustains host metabolism during heterotrophic starvation

NanoSIMS imaging revealed that metabolic interactions in the cnidarian-algal symbiosis remained remarkably stable during heterotrophic starvation despite the pronounced phenotypic response of the Aiptasia holobiont. Consistent with previous reports (Rädecker et al. 2018), ^{13}C enrichment from ^{13}C-bicarbonate assimilation/translocation was highest in the algal symbionts with host ^{13}C enrichment primarily observed in lipid bodies (Fig. 2A,B; host/symbiont differences: LL, $F = 666.53$, $p < 0.001$). Despite drastic declines in algal symbiont densities during heterotrophic starvation, overall ^{13}C enrichment remained stable in the gastrodermal tissue of the host (Tukey's HSD, $p = 1.000$). This was likely explained by the enhanced photosynthetic performance of algal symbionts reflected in a nearly 50 % increase in their ^{13}C enrichment (Fig. 2C; Tukey's HSD, $p < 0.001$).

The constant availability of photosynthates in the symbiosis during heterotrophic starvation was reflected in the maintained anabolic assimilation of ^{15}N-ammonium by both symbiotic partners. Consistent with previous studies, the algal symbionts acquired the highest ^{15}N enrichments from ammonium assimilation (Pernice et al. 2012; Rädecker et al. 2018), but the host also exhibited clearly measurable ^{15}N enrichments in both epidermal and gastrodermal tissue layers (Fig. 2D,E; host/symbiont differences: LM, $F = 660.32$, $p < 0.001$). Thus, heterotrophic starvation did not alter the ability for ammonium assimilation of either symbiotic partner (Fig. 2F; Tukey's HSD, $p = 0.968$ for host gastrodermis, $p = 0.901$ for algal symbionts).

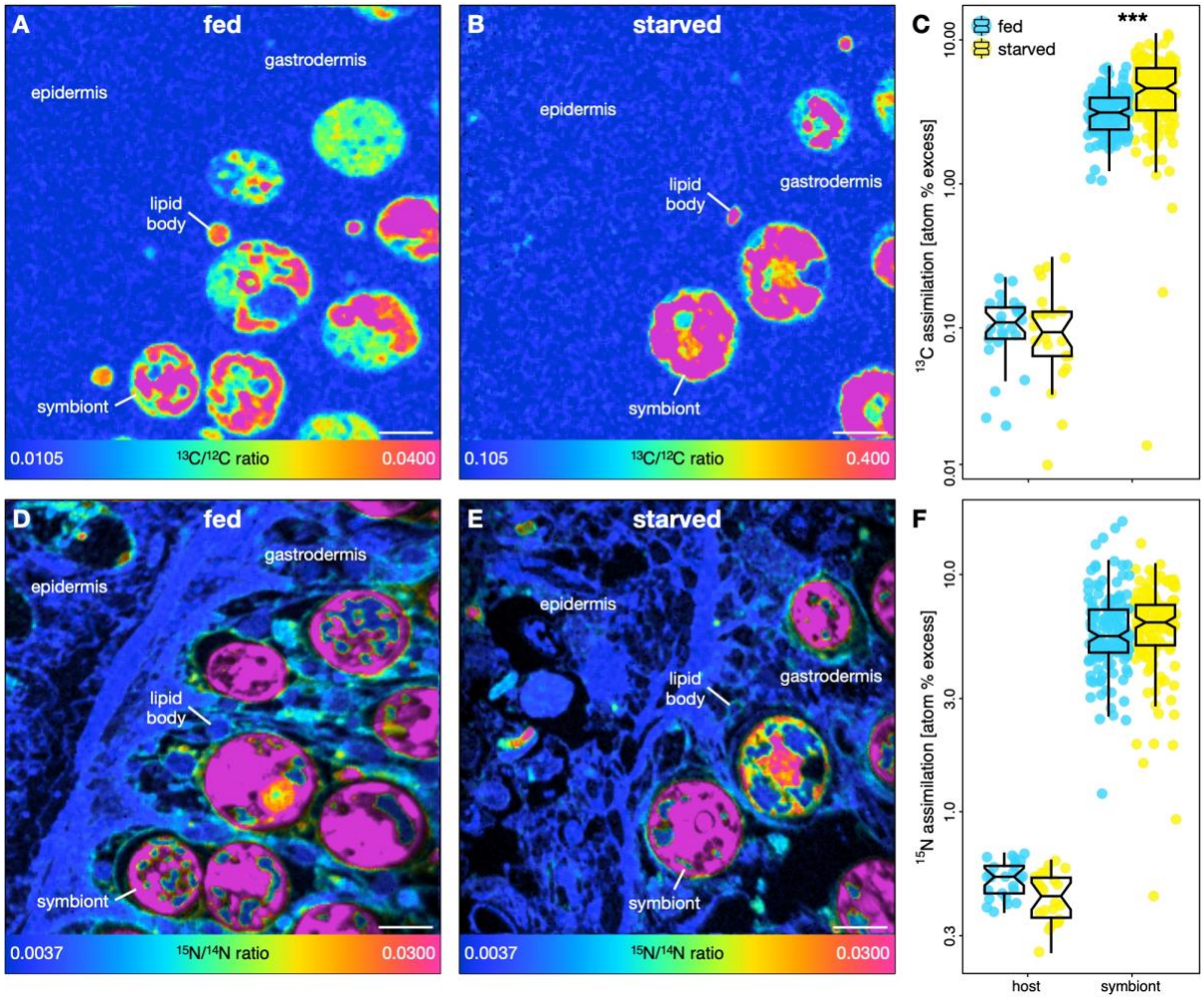

Fig. 2 | NanoSIMS imaging of symbiotic carbon and nitrogen cycling in fed and starved Aiptasia. (A,B) Representative NanoSIMS images illustrating $H^{13}CO_3^-$ assimilation and translocation as $^{13}C/^{12}C$ isotope ratio maps in regularly fed and starved Aiptasia. **(C)** Corresponding boxplots and data points of ^{13}C enrichment for the host gastrodermis and the algal symbiont cells. **(D,E)** Representative NanoSIMS images illustrating $^{15}NH_4^+$ assimilation as $^{15}N/^{14}N$ isotope ratio maps in regularly fed and starved Aiptasia. **(F)** Corresponding boxplots of ^{15}N enrichment for the host gastrodermis and the algal symbiont cells. NanoSIMS ratio maps are shown as hue saturation images with blue representing no/low enrichment and pink representing the highest level of enrichment. Note the logarithmic scale for **C**,**F**. Scale bars are 5 µm. Asterisks indicate significant effects between treatments (***$p < 0.001$).

Discussion

The association with autotrophic endosymbiotic algae has enabled heterotrophic Cnidaria to thrive in the oligotrophic tropical ocean (Muscatine and Porter 1977; Stanley 2006). The long-term starvation experiment presented here emphasizes the remarkable trophic plasticity that this symbiosis confers upon these cnidarian holobionts. Because of the highly efficient symbiotic nutrient exchange and recycling, Aiptasia were able to survive without heterotrophic feeding for at least one year. At the same time, starved animals showed clear signs of nutrient limitation, including reduced biomass, host protein content, and symbiont density, underscoring the long-term importance of heterotrophic feeding for body mass maintenance and growth.

Autotrophic nutrient recycling can sustain the cnidarian-algal symbiosis for extended periods of time

Recent work suggests that the lack of heterotrophic feeding could shift the cnidarian-algal symbiosis towards parasitic interactions that reduce the capacity of the host to survive starvation (Peng et al. 2020). However, here we show that, even after one year of complete heterotrophic starvation, the translocation of photosynthates by algal symbionts remained sufficient to maintain the basal

metabolic requirement of the host. Indeed, patterns of host ^{13}C enrichment (Fig. 2A-C) were not affected by heterotrophic starvation indicating that photosynthate availability for the host was not impaired despite an 85 % reduction in algal symbiont biomass in the holobiont (Fig. 1B). This implies that carbon translocation by individual algal cells must have significantly increased in response to heterotrophic starvation. Indeed, we observed a 50 % increase in ^{13}C enrichment among the algal symbionts in starved animals (Fig. 2C), clearly indicating enhanced photosynthetic performance required for higher relative translocation rates. Similar, albeit less pronounced, trends were previously reported in a three-month starvation experiment using Aiptasia (Davy and Cook 2001). These authors proposed that the increase in algal photosynthetic performance in starved animals was the result of reduced intra-specific competition for CO_2. Indeed, reduced algal symbiont densities likely reduce competition for CO_2 (Rädecker et al. 2017; Krueger et al. 2020). However, in starved animals, this effect could, in part, be masked by the reduced catabolic CO_2 production in the holobiont due to the lack of heterotrophic prey digestion by the host. Our data point to an additional mechanism that could promote enhanced photosynthate release by algal symbionts in the absence of heterotrophy: nitrogen starvation.

Nitrogen limitation shapes the starvation response of Aiptasia

In the stable symbiosis, low nitrogen availability limits the anabolic incorporation of photosynthates in the algal symbiont metabolism (Rädecker et al. 2021; Cui et al. 2022a, 2022b). This nitrogen limitation is thus not only crucial in regulating algal growth but also ensures the translocation of excess photosynthates to the host (Muscatine and Porter 1977; Falkowski et al. 1984). The host passively modulates *in hospite* nitrogen availability for algal symbionts through ammonium assimilation and release in its glutamate metabolism (Rahav et al. 1989; Rädecker et al. 2021; Cui et al. 2022a). Here, we found a proportional decline of algal symbiont density and host protein content in heterotrophically starved Aiptasia. Given that both algal growth and host protein synthesis depend on nitrogen availability, the data suggest that starvation caused severe nitrogen limitation. This is consistent with previous work documenting increases in the carbon-to-nitrogen ratio and lipid content of Symbiodiniaceae in unfed Aiptasia (Cook et al. 1988; Cook and Muller-Parker 1992; Muller-Parker et al. 1996). Strongly reduced nitrogen availability could thus drive the enhanced translocation of photosynthates by the algal symbionts observed here and explain the long-term survival of Aiptasia during heterotrophic starvation.

Interestingly, the reduced nitrogen availability did not cause changes to the ammonium assimilation rates by either symbiotic partner; both continued to efficiently assimilate ammonium from the surrounding seawater in the absence of heterotrophic nutrients. Because ammonium assimilation depends on the availability of carbon backbones from the TCA cycle (Cui et al. 2022b), this observation also suggests that starved holobionts did not experience severe carbon limitation. Yet, the starved holobionts showed severe shrinkage and a significant decline in biomass indicative of malnutrition in the present study. Under the current experimental conditions, environmental ammonium assimilation was thus not sufficient to fulfill the nitrogen requirements of the holobiont. In our experiments, the availability of seawater ammonium was possibly limited by the rate of water exchange (once per week as for the entire animal culture stock). It is thus plausible that higher ammonium concentrations would have allowed the heterotrophically starved Aiptasia to maintain a larger fraction of their original biomass. Yet, in the environmental context of the oligotrophic ocean, photosymbiotic animals are likely similarly limited in their access to environmental ammonium (O'Neil and Capone 2008). In this context, our findings illustrate the importance of heterotrophic feeding by the host for the long-term maintenance of the cnidarian-algal symbiosis biomass. While symbiotic nutrient exchange and recycling may be sufficient to cover the carbon and energy demands of the symbiotic partners on a time scale of at least one year, heterotrophic feeding is not only required for long-term survival but also required for propagation and net growth of the holobiont.

Conclusion

We illustrated the immense trophic plasticity of the cnidarian-algal symbiosis by rearing Aiptasia for an entire year in the complete absence of heterotrophic feeding. Our findings reveal that efficient symbiotic nutrient exchange and recycling are sufficient to sustain the basic metabolic requirements of both symbiotic partners over extended periods of time. Yet, under long-term exposure to highly oligotrophic conditions, the assimilation of environmental inorganic nitrogen will be insufficient to support the nutritional requirements of the holobiont. Heterotrophic feeding thus represents an essential source of nitrogen for holobiont growth. Under oligotrophic conditions, mixotrophy thereby provides a nutritional advantage to photosymbiotic cnidarians that in part explains their ability to outcompete other organisms restricted to either autotrophic or heterotrophic nutrient acquisition.

Acknowledgments

We are grateful to Dr. Claudia Pogoreutz and Gaëlle Toullec for their help with animal culture maintenance. We thank Jean Daraspe for his help with sample processing and Dr. Stéphane Escrig and Florent Plane for their assistance and support with NanoSIMS measurements.

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