
OXFORD SCIENTIFIC/GETTY

Figure 1 | A partnership between coral and algae. The transparent coral contains intracellular algae that are visible as brownish-green dots.

Ecology

Corals have algal friends for dinner

Virginia M. Weis

Biologists have long sought to understand the factors that enable coral reefs to thrive. A careful analysis of nutrient cycling now points to an unexpected food source that helps to sustain corals during food scarcity. **See p.1018**

Healthy coral reefs are one of the most productive and biodiverse marine ecosystems on the planet. They are oases in crystal-clear waters that are almost devoid of nutrients — the equivalent of ocean deserts. Coral reefs defy logic in their ability to flourish in these locations with so few nutrients, and this puzzle has been called Darwin's Paradox after Charles Darwin's observations of this phenomenon more than 180 years ago[1]. On page 1018, Wiedenmann *et al.*[2] have come a lot closer to solving this puzzle.

The authors show that when no food is available, corals digest a portion of the algal population that they form a beneficial (symbiotic) relationship with, and such 'farming' of algae satisfies their need for nutrients in the case of nutrient limitation. This work suggests that this nutritional flexibility of the coral symbiosis is the key to the spectacular and enduring success of coral reefs.

Coral reefs depend on a symbiosis between corals (animals in a group, called cnidarians, that includes jellyfish and sea anemones) and billions of single-celled algae that live inside their host animal's cells (Fig. 1). This intimate symbiosis is based on a nutritional exchange. The algae have high rates of photosynthesis and move most of their products generated from photosynthesis to the host. The coral, in turn, provides the algae with inorganic nutrients in the form of inorganic carbon, nitrogen and phosphorus from its waste. Corals are the nutritional and structural foundation of coral-reef ecosystems. They deposit massive limestone skeletons that form the reef architecture and coral productivity is the centrepiece of the reef food web on which other organisms thrive.

What is the currency of nutrients exchanged between the two partners and how exactly are nutrients traded? These topics have been researched for close to 50 years. Dozens of studies have tried to understand both the nutrient 'accounting' — which explains how corals thrive in a desert-like environment — and the biology of how nutrients are acquired and moved between the partners[3]. Despite these decades of study, pieces of the puzzle have been described but a full picture that explains the success of corals in a nutrient-deficient environment has remained elusive.

Wiedenmann and colleagues grew nine coral species of interest in seawater tanks for months during which all nutrients flowing into the system were precisely controlled. The authors found that corals incubated in water containing inorganic nitrogen and phosphorus at the low concentrations typical of healthy reefs increased in size and the algal population increased as well, to keep up with coral growth. In these conditions, the partnership was acting together as an autotroph (generating its own food).

By contrast, when corals were kept in water virtually free of nutrients, after about two months, coral growth stagnated and remarkably, the algal population plummeted, causing the corals to have a bleached appearance because algae were lost. Wiedenmann and colleagues found that almost no algae were expelled into the water. Where were they going?

The authors looked for clues by tracing labelled compounds and they found that labelled nitrate was taken up by algae (the coral host lacks the machinery to take up and use nitrate). Labelled nitrate was also found in high concentrations in host tissues, indicating that nitrogen-containing compounds are transferred from the algae to their host. But how might this happen? The authors hypothesized that the algae were being consumed as food, farmed to satisfy the host's need for inorganic nitrogen and phosphorus.

To gather more evidence, Wiedenmann *et al.* examined the size of the algal population in healthy, growing corals. The authors calculated the growth rate of the algal population by counting the number of dividing cells, a measure called the mitotic index. Interestingly, when they modelled the population growth rate on the basis of the mitotic index, the expected rate was much higher than the measured rate from their experiments, obtained by counting algae over time. The authors deduced that these excess algae were being digested by the coral host.

Wiedenmann and colleagues also conducted an experiment to look for evidence of nutritional contributors to the differential coral growth in natural environments. They found that corals growing near dense seabird populations that produce high amounts of nutrient-rich guano droppings took up more inorganic nitrogen and grew faster than did corals that weren't near seabird colonies.

Nutritional flexibility of the coral–algal symbiosis might be the linchpin of the dominance of coral reefs in ocean deserts over the past 240 million years[4]. Corals can do it all. Most species can feed on other organisms and use their stinging tentacles to trap microscopic prey (zooplankton). Those corals in symbiosis with algae act as autotrophs, making sugars with energy from the Sun and recycling nitrogen and phosphorus, as well as acquiring them from the seawater. And in a pinch, when prey are not available to satisfy the corals' nutritional needs, such hosts might farm their algal population to fill the void. This scenario has evolutionary implications, given that the success of nutritional flexibility involving both partners provides evidence for the idea that the symbiotic partnership is the unit that undergoes natural selection[5], perhaps in addition to natural selection of the partners independently. The whole is therefore more than the sum of its parts.

Wiedenmann and colleagues provide strong evidence of algal farming, but there is still work to be done to definitively prove this phenomenon. Perhaps the direct evidence needed is to use an imaging method to show corals in the act of algal digestion. One study has captured images of this phenomenon for a single coral species[6]. The fact that this has not been commonly reported might mean that others have tried without success to convincingly document such a process. The authors of that imaging study[6] used electron microscopy for their work, a high-resolution but time-intensive and non-quantitative approach. Modern, state-of-the-art methods such as flow cytometry analysis of dissociated coral cells could enable high-throughput, quantitative and systematic sampling of coral tissue to look for evidence of algal degradation[7].

Finally, studies of corals in our time of extreme threats to the health of these reefs should be viewed through a lens of developing solutions to help reefs survive into the next century[8]. Knowledge of nutritional flexibility and algal farming could be used to aid understanding of the nutritional value of different algal species. It could also help to incorporate nutritional differences into strategies of breeding corals and symbionts that are more resilient to reef perturbation from temperature increases and nutrient stress. We need to marshal all available knowledge to help coral reefs remain the oases in desert oceans that are so crucial for the myriad services they provide to the planet and the people living nearby.

Virginia M. Weis is in the Department of Integrative Biology, Oregon State University, Corvallis, Oregon 97331, USA.
e-mail: virginia.weis@oregonstate.edu

1. Darwin, C. *The Structure and Distribution of Coral Reefs* (Smith Elder, 1842).
2. Wiedenmann, J. *et al. Nature* **620**, 1018–1024 (2023).
3. Morris, L. A., Voolstra, C. R., Quigley, K. M., Bourne, D. G. & Bay, L. K. *Trends Microbiol.* **27**, 678–689 (2019).
4. Stanley, G. D. *Earth Sci. Rev.* **60**, 195–225 (2003).
5. Bordenstein, S. R. & Theis, K. R. *PLoS Biol.* **13**, e1002226 (2015).
6. Titlyanov, E. A. *et al. Mar. Ecol. Prog. Ser.* **139**, 167–178 (1996).
7. Rosental, B., Kozhekbaeva, Z., Fernhoff, N., Tsai, J. M. & Traylor-Knowles, N. *BMC Cell Biol.* **18**, 30 (2017).
8. Kleypas, J. *et al. Biol. Conserv.* **257**, 109107 (2021).

The author declares no competing interests.
This article was published online on 23 August 2023.

Engineering

Drone-racing champions outpaced by AI

Guido C. H. E. de Croon

An autonomous drone has competed against human drone-racing champions — and won. The victory can be attributed to savvy engineering and a type of artificial intelligence that learns mostly through trial and error. **See p.982**

Artificial intelligence (AI) has already surpassed the performance of human champions in games such as chess[1], Go[2] and the car-racing video game *Gran Turismo*[3]. However, these achievements all took place in virtual environments. On page 982, Kaufmann *et al.*[4] make the leap to the real world with Swift — an autonomous AI-based drone system that can defeat humans in the sport of drone racing. Swift took on three human adversaries, all of whom are drone-racing champions, and clocked the fastest time on the racetrack.

The vehicles used in drone racing are usually controlled by human pilots who wear headsets that give them a 'first person' view through a camera attached to the drone. These pilots manoeuvre the drones deftly through a series of gates at speeds of 100 kilometres per hour