



## Symbiosis and cohabitation

How does an animal behave like a plant? Physiological and molecular adaptations of zooxanthellae and their hosts to symbiosis<sup>☆,☆☆</sup>Denis Allemand<sup>a,\*</sup>, Paola Furla<sup>b</sup><sup>a</sup> Centre scientifique de Monaco, laboratoire international associé “BioSensib” (LIA 647 / CSM & CNRS–UniStra), 8, quai Antoine-1<sup>er</sup>, 98000 Principauté de Monaco, Monaco<sup>b</sup> UMR 7138 EPS, Sorbonne Universités, UPMC Université Paris-6, université des Antilles, université Nice–Sophia-Antipolis, CNRS, laboratoire évolution Paris–Seine, institut de Biologie Paris–Seine (EPS-IBPS), Parc Valrose, 28, avenue Valrose, BP71, 06108 Nice cedex 02, France

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## ABSTRACT

Cnidarians (corals and sea anemones) harbouring photosynthetic microalgae derive several benefits from their association. To allow this association, numerous symbiotic-dependent adaptations in both partners, resulting from evolutionary pressures, have been selected. The dinoflagellate symbionts (zooxanthellae) are located inside a vesicle in the cnidarian host cell and are therefore exposed to a very different environment compared to the free-living state of these microalgae in terms of ion concentration and carbon content and speciation. In addition, this intracellular localization imposes that they rely completely upon the host for their nutrient supply (nitrogen, CO<sub>2</sub>). Symbiotic-dependent adaptations imposed to the animal host by phototrophic symbiosis are more relevant to photosynthetic organisms than to metazoans: indeed, the cnidarian host often harbours diurnal changes of morphology to adapt itself to the amount of light and possesses carbon-concentrating mechanisms, antioxidative defences and UV sunscreens similar to that present in phototrophs. These adaptations and the contrasting fragility of the association are discussed from both ecological and evolutionary points of view.

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## 1. Introduction: cnidarians, reinvented zoophytes?

The phylogenetic position of the Cnidarians within the animals was determined only during the 18th century, by a medical doctor from Marseilles, Jean-André Peyssonnel, who definitively discovered the animal nature of the red

coral [1]. Nevertheless, the name zoophytes (or phytozoans), *i.e.* a small composite organism with both animal and plant characteristics (Linnaeus 1758), remained attached to them until the beginning of the 20th century because of their morphology of animal-flowers. However, many traits of their physiology are in agreement with this term, since almost half of the cnidarians host photosynthetic microorganisms, commonly named zooxanthellae, conferring them plant properties [2], and leading to the birth of the concept of holobiont or metaorganism [3]. This association has not only deeply functionally marked these organisms, but also shaped an entire ecosystem, the coral reef, considered as “an oasis in a desert ocean” [4]. Indeed, coral reefs host, in less than 0.2% of the surface ocean, 30%

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of the known marine species [5]. This high biodiversity supports many ecosystem services, providing food for almost 500 millions of people, incomes from the tourism industry and coastal protection for a value estimated at about 375 billion US\$ [6]. Because of both their major ecological and human importance and the threats they undergo, Cnidarians have been extensively studied over the past two decades. In addition, their scientific interest is reinforced by their phylogenetic position as the sister clade of Bilateria. This chapter presents the state of knowledge in the rapidly growing field of research of coral symbiosis as well as the ecological and human consequences of its breakdown.

## 2. Cnidarians as holobionts

Described by Brandt at the end of the 19th century [7], zooxanthellae were referred initially to what was thought to be a single pandemic species, *Symbiodinium microadriaticum* [8], present in Cnidarians as well as in many other hosts (Mollusca, Platyhelminthes, Porifera, Foraminifera). With the development of new molecular tools, and recently next-generation sequencing, the genus *Symbiodinium* was finally divided into nine large groups, or clades, named as A to I [9,10]. Each clade is composed of many (up to 258) types (or subclades), as defined by ITS2 sequences [11,12]. Their diversification occurred during the Miocene, about 15 millions years ago [13], while coral symbiosis appeared during the Triassic [14]. In the 1980s, the concept moved to one *Symbiodinium* clade by host and it appears today that the association is far more complex, with a dynamic equilibrium between different clades and subclades per host according to environmental conditions [15] with occasionally possible parasitic relationship [16]. However, rarely host and symbiont genotypes have been analysed simultaneously, while evidences suggest that the genetic structuring of the host and symbionts are different [17]. Zooxanthellae are localized within gastrodermal (= endodermal) cells of the corals, surrounded by a host-derived membrane [18]. They occur at high density ( $> 10^6 \text{ cm}^{-2}$  of coral surface) within the endodermal cells of the oral tissue [18,19], and provide more than 90% of the coral's nutritional requirements [20].

While zooxanthellae are, by far, the best known coral symbionts, the coral holobiont is composed of many additional symbionts including protist (Apicomplexa), endolithic algae, eubacteria, Archaea, viruses, whose roles are still poorly known, but may include carbon fixation, nitrogen-fixation and cycling, sulphur cycling, synthesis of antibiotics. . . [21]. *Endozoicomonas* spp. (Gammaproteobacteria, Oceanospirillales) are dominant members of the microbiota of both tropical and temperate corals, but the presence of Spirochaetales (genera *Borrelia*, *Spirochaeta* and *Leptospira*, known to be parasitic in numerous land vertebrates) within the Mediterranean red coral was recently shown [22].

## 3. From surface recognition to cell-cycle control of the symbionts

While some corals transmit their symbionts directly to their eggs or brooded larvae (vertical – closed – transmission), for 85% of them, aposymbiotic larvae or early recruits

must acquire their symbionts from the environment (horizontal – open – transmission), which necessitates specific recognition mechanisms. These mechanisms depend on the corals' innate immunity system, which is as complex as that of Vertebrates [23–25]. Recognition as well as regulation of symbiont population have been extensively reviewed [26,27]. Briefly, recognition of symbionts may occur in the host mucus involving *Symbiodinium* glycans and host Pattern Recognition Receptors (PRR) like lectins [28,29], but also Toll-like receptors or Complement C3 receptor [30]. PRR binding to symbiont glycans induces the endocytosis of the alga and TGF $\beta$  pathway [31], leading to symbiont tolerance by inhibition of the maturation of the phagosome to lysosome by Rab5 proteins. Indeed, addition of an antibody raised against TGF $\beta$  resulted in the failure of the symbionts to successfully colonize the host. At this stage, incompatible zooxanthellae may be destroyed by apoptosis/phagocytosis [26].

The number of zooxanthellae by a cnidarian host cell is regulated to a number between 1 and 12 (average  $1.54 \pm 0.30$ ) depending on species and environment [32]. The doubling times of zooxanthellae is rapid in culture (2 to 5 days), while it is between 10 to 70 days *in hospite* [26]. However, the mechanisms controlling symbiont biomass are largely unknown. It may involve either post- or premitotic process: expulsion or apoptosis of excess symbionts, inhibition of symbiont division (by resource limitation, intracellular communication, acidification of the vesicle hosting the symbionts. . .). In *Hydra*, it has been shown that the nervous system of the host may control the symbiont population [33].

## 4. Holobiont as a super-organism but at a cost

### 4.1. The partners' contribution to symbiosis

Symbiosis is a powerful evolutive way to acquire new metabolic capabilities [34]. Concerning coral, the major consequence of the symbiosis is the partial autotrophy (mixotrophy) of the host conferred by the symbionts [18]. This process explains the Darwin Paradox because a part of the photosynthates is released in the form of mucus within the coral reefs at a high rate (about  $5 \text{ l} \cdot \text{m}^{-2} \cdot \text{yr}$ ), providing food for the whole reef [35]. In addition, zooxanthellae absorb coral waste, thus recycling the host catabolism products, which are re-metabolized by the algal cell into host reusable compounds. They also play a major role in the metabolic respiration of coral cells by supplying to the host energy substrates and oxygen [36,37]. They stimulate calcification of the host by an average factor of 3 by a process called "light-enhanced calcification", whose underlying mechanisms remain largely debated but may involve either synthesis of skeletal organic matrix precursors, supply of energy, or change in the chemical environment [38]. The benefits gained by the zooxanthellae allow them to protect themselves from predators as well as to develop in a stable "culture medium", the animal cytosol, controlled by animal metabolism, thus reducing their costs for ionic regulation [39].

#### 4.2. Constraints as evolutive drivers

Making photosynthesis within an animal cell is not without problem and led to a profound adaptation of the biology of both partners [39]. We will just give a brief summary here. The first one is the constraint of sun exposure to ensure optimal photosynthesis. The resistance to UV radiation is provided by compounds called Mycosporine-like Amino Acids (MAAs) synthesised by the symbionts and then transferred to the host [40]. In the host, the MAAs are then metabolized to up to seven new derived UV-absorbing compounds, providing the entire holobiont with an efficient barrier to UV. The second constraint concerns the necessity for the host to provide their intracellular symbionts with external carbon dioxide and ammonium for their photosynthetic and metabolic activities, as the quantities of  $\text{NH}_4$  and  $\text{CO}_2$  produced by the host and the symbionts are not sufficient [39]. The coral host uses for this purpose ammonium and bicarbonate carriers. To optimize the transport and fixation of  $\text{CO}_2$ , cnidarian takes benefit of several carbonic anhydrase isoforms [41], triggering not only the absorption, but also the accumulation of inorganic carbon in the symbionts, a process called Carbon-Concentrating Mechanisms or CCM [42]. The third constraint is the production of pure oxygen, leading to a cellular hyperoxia of about 60% within the coral cells [43]. Toxic for conventional animal cells, symbiotic corals developed a large set of antioxidant defences among them up to seven isoforms of superoxide dismutases and glutathione peroxidases [43,44] like in plants, or synthesized a large set of fluorescent proteins [45]. The fourth constraint is the large diurnal pH changes (about 2 pH units) induced by photosynthesis with the body fluids of the host [46,47]. These pH fluctuations are directly linked to the inorganic carbon absorption from the seawater in  $\text{HCO}_3^-$  form and the use of the  $\text{CO}_2$  form in the photosynthetic processes. To control the intracellular pH, specific expression of membrane carriers according to the state of symbiosis has been demonstrated [48,49]. The number of new metabolic capacities developed by the Cnidarians to deal with the symbiosis constraints demonstrated their large phenotypic plasticity. That symbiosis constraints-preconditioning could then suggest a relevant degree of tolerance on environmental changes. Recently, Ventura et al. [50] have for example demonstrated that the intrinsic plasticity of a sea anemone allows dealing with ocean acidification, maintaining constant the photosynthetic activity despite a modification of the seawater chemistry.

#### 5. Symbiosis disruption: biological, ecological and human consequences

Curiously, although the coral symbiosis tolerates a high level of oxidative stress and pH fluctuations, it is highly sensitive to a slight increase in temperature – 0.5 to 1 °C above mean SST – such as that produced by global warming, leading to a disruption of the association. Without its zooxanthellae, the cnidarian tissues become transparent and, in the case of corals, let show the white skeleton, a process called “coral bleaching”. The cellular

mechanisms behind this process are still widely discussed [51–54], but likely started with a burst of reactive oxygen species coupled to a defect in the Calvin cycle. The consequences of the temperature-induced modifications of the host and symbiont redox state are multiple including transcriptional modifications, protein and lipid damages and programmed cell death induction [55–60]. The final steps of the symbiont expulsion from the host tissues (*i.e.* exocytosis, host cell detachment, cell deaths of one or the two partners) and thus the respective roles of both partners are also debated and likely depend on the stress intensity and cnidarian species [54,61,62]. Mass coral bleaching descriptions started in the 1980s and are presently increasing, thus highlighting a worrying accentuation of its intensity and frequency [63]. During the 2016, a remote part of the Great Barrier Reef experienced an extreme mass bleaching event (> 90%), inducing coral mortalities of about 50% [63] and huge socioeconomic consequences [64]. Using IPCC projections, it is expected that in the near future, bleaching events will become annual and more than 90% of the world's reefs will be affected by 2050 [65,66].

#### 6. Conclusion: what is the future of symbiotic cnidarians?

Cnidarian symbiosis is an integrative field of research that combines disciplines as diverse as molecular and cell biology with field ecology, including conservation biology. This rapidly expanding field relies fundamental research in evolutionary biology and medical biology looking for new animal models of oxidative stress and aging [67,68]. As developed above, adaptation to symbiosis is a fantastic source of inspiration to understand and to analyse the processes of co-evolution and molecular interactions between two eukaryotes and several prokaryotes. Indeed, the “Coral Probiotic Hypothesis” [69] postulated that the coral microbiome may evolve so as to improve coral health and resilience. It is known that certain zooxanthellae strains facilitate the adaptation of their host to high temperatures [70]. It has been suggested that through shuffling of the dominant photosynthetic *Symbiodinium* clades within their tissues, some corals have become more tolerant to seawater temperature increases, thereby avoiding repeated bleaching events (adaptive bleaching hypothesis, [61]). While highly debated [62], this has led to develop a research leading to increasing coral resilience through host selection or symbiont manipulation, through a concept called “Assisted Evolution” [71] or Beneficial Microorganisms for Corals [72]. In addition, encouraging studies of cnidarian populations submitted to natural extreme-environmental, as intertidal pools or  $\text{CO}_2$  vents is essential to understand the limit of the phenotypic plasticity of the cnidarians and their host and to consider the possibility of symbiotic cnidarian adaptations to global changes. Despite the dynamism of this research area, future advances will be needed to fully understand the processes sustaining the fragile interactions and the role of the all the partners of the holobiont, including viruses [73]. Thus, a deeper understanding of the molecular and cellular mechanisms of bleaching is crucial for monitoring

the health and identifying the more resistant cnidarians. The challenge of this research will be to ensure a future for one of the most important ecosystems of our planet.

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## References

- [1] A. McConnell, The flowers of coral—some unpublished conflicts from Montpellier and Paris during the early 18th century, *Hist. Philos. Life Sci.* 12 (1990) 51–66.
- [2] A.E. Douglas, P.J. McAuley, P.S. Davies, Algal symbiosis in Cnidarian, *J. Zool. Lond.* 231 (1993) 175–178.
- [3] T.C.G. Bosch, M.J. McFall-Ngai, Metaorganisms as the new frontier, *J. Zool.* 114 (2011) 185–190.
- [4] E.P. Odum, G.W. Barrett, *Fundamentals of ecology*, Saunders, JSTOR Philadelphia, 1971.
- [5] J.W. Porter, J.I. Tougas, Reef ecosystems: threats to their biodiversity, in: S.A. Levin (Ed.), *Encyclopedia of Biodiversity*, Academic Press, San Diego, 2001, pp. 73–95.
- [6] R. Costanza, R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, M. Van Den Belt, The value of the world's ecosystem services and natural capital, *Nature* 387 (1997) 253–260.
- [7] T. Krueger, Concerning the cohabitation of animals and algae – an English translation of K. Brandt's 1881 presentation “Ueber das Zusammenleben von Thieren und Algen”, *Symbiosis* 71 (2017) 167–174.
- [8] H.D. Freudenthal, *Symbiodinium* gen. nov. *Symbiodinium microadriaticum* sp. nov., a zooxanthella: taxonomy, life cycle and morphology, *J. Protozool.* 9 (1962) 45–52.
- [9] X. Pochon, R.D. Gates, A new *Symbiodinium* clade (Dinophyceae) from soritid foraminifera in Hawai'i, *Mol. Phylogenet. Evol.* 56 (2010) 492–497.
- [10] M.A. Coffroth, S.R. Santos, Genetic diversity of symbiotic dinoflagellates in the genus *Symbiodinium*, *Protist* 156 (2005) 19–34.
- [11] N.M. Boulotte, S.J. Dalton, A.G. Carroll, P.L. Harrison, H.M. Putnam, L.M. Peplow, M.J. van Oppen, Exploring the *Symbiodinium* rare biosphere provides evidence for symbiont switching in reef-building corals, *ISME J.* 10 (2016) 1–9.
- [12] M. Ziegler, C. Arif, J.A. Burt, S. Dobretsov, C. Roder, T.C. Lajeunesse, C.R. Voolstra, Biogeography and molecular diversity of coral symbionts in the genus *Symbiodinium* around the Arabian Peninsula, *J. Biogeogr.* 44 (2017) 674–686.
- [13] X. Pochon, J.I. Montoya-Burgos, B. Stadelmann, J. Pawlowski, Molecular phylogeny, evolutionary rates and divergence timing of the symbiotic dinoflagellate genus *Symbiodinium*, *Mol. Phylogenet. Evol.* 38 (2006) 20–30.
- [14] L. Muscatine, C. Goiran, L. Land, J. Jaubert, J.P. Cuif, D. Allemand, Stable isotopes ( $^{13}\text{C}$  and  $^{15}\text{N}$ ) of organic matrix from coral skeleton, *PNAS* 102 (2005) 1525–1530.
- [15] J.E. Parkinson, I.B. Baums, The extended phenotypes of marine symbioses: Ecological and evolutionary consequences of intraspecific genetic diversity in coral–algal associations, *Front. Microbiol.* 5 (2014) 5.
- [16] J.L. Sachs, T.P. Wilcox, A shift to parasitism in the jellyfish symbiont *Symbiodinium microadriaticum*, *Proc. R. Soc. London, Ser. B* 273 (2006) 425–429.
- [17] I.B. Baums, M.K. Devlin-Durante, T.C. Lajeunesse, New insights into the dynamics between reef corals and their associated dinoflagellate endosymbionts from population genetic studies, *Mol. Ecol.* 23 (2014) 4203–4215.
- [18] G. Muller-Parker, C.F. D'Elia, C.B. Cook, Interactions between corals and their symbiotic algae, in: C. Birkeland (Ed.), *Coral reefs in the anthropocene*, Springer Netherlands, Dordrecht, The Netherlands, 2015, pp. 99–116.
- [19] E.A. Drew, The biology and physiology of alga-invertebrate symbioses. II. The density of symbiotic algal cells in a number of hermatypic hard corals and alcyonarians from various depths, *J. Exp. Mar. Biol. Ecol.* 9 (1972) 71–75.
- [20] L. Muscatine, P.G. Falkowski, J.W. Porter, Z. Dubinsky, Fate of photosynthetic fixed carbon in light – and shade – adapted colonies of the symbiotic coral *Stylophora pistillata*, *Proc. R. Soc. London, Ser. B* 222 (1984) 181–202.
- [21] D.G. Bourne, K.M. Morrow, N.S. Webster, Insights into the coral microbiome: underpinning the health and resilience of reef ecosystems, *Ann. Rev. Microbiol.* 70 (2016) 317–340.
- [22] J.A.J.M. van de Water, R. Melkonian, H. Junca, C.R. Voolstra, S. Reynaud, D. Allemand, C. Ferrier-Pagès, Spirochaetes dominate the microbial community associated with the red coral *Corallium rubrum* on a broad geographic scale, *Sci. Rep.* 6 (2016) 27277.
- [23] D.J. Miller, G. Hemmrich, E.E. Ball, D.C. Hayward, K. Khalturin, K. Agata, T.C.G. Bosch, The innate immune repertoire in Cnidaria – ancestral complexity and stochastic gene loss, *Genome Biol.* 8 (2007) R59.
- [24] C. Toledo-Hernández, C.P. Ruiz-Díaz, The immune responses of the coral, *Invertebrate Surviv. J.* 11 (2014) 319–328.
- [25] L.D. Mydlarz, L. Fuess, W. Mann, J.H. Pinzón, D.J. Gochfeld, Cnidarian immunity: from genomes to phenomes, the cnidaria, past, present and future, Springer, 2016, pp. 441–466.
- [26] S.K. Davy, D. Allemand, V.M. Weis, Cell biology of Cnidarian-dinoflagellate symbiosis, *Microbiol. Mol. Biol. Rev.* 76 (2012) 229–261.
- [27] D. Fransolet, S. Roberty, J.-C. Plumier, Establishment of endosymbiosis: the case of cnidarians and *Symbiodinium*, *J. Exp. Mar. Biol. Ecol.* 420–421 (2012) 1–7.
- [28] E.M. Wood-Charlson, L.L. Hollingsworth, D.A. Krupp, V.M. Weis, Lectin/glycan interactions play a role in recognition in a coral/dinoflagellate symbiosis, *Cell. Microbiol.* 8 (2006) 1993–1985.
- [29] J. Vidal-Dupiol, M. Adjeroud, E. Roger, L. Foure, D. Duval, Y. Mone, C. Ferrier-Pagès, É. Tambutté, S. Tambutté, D. Zoccola, D. Allemand, G. Mitta, Coral bleaching under thermal stress: putative involvement of host/symbiont recognition mechanisms, *BMC Physiol.* 9 (2009) 14.
- [30] P. Ganot, A. Moya, V. Magnone, D. Allemand, P. Furla, C. Sabourault, Adaptations to endosymbiosis in a Cnidarian-dinoflagellate association: differential gene expression and specific gene duplications, *PLoS Genet.* 7 (2011) e1002187.
- [31] O. Detournay, C.E. Schnitzler, A. Poole, V.M. Weis, Regulation of Cnidarian-dinoflagellate mutualisms: evidence that activation of a host TGF $\beta$  innate immune pathway promotes tolerance of the symbiont, *Dev. Comp. Immunol.* 38 (2012) 525–537.
- [32] L. Muscatine, C. Ferrier-Pagès, A. Blackburn, R.D. Gates, G. Baghdasarian, D. Allemand, Cell-specific density of symbiotic dinoflagellates in tropical anthozoans, *Coral Reefs* 17 (1998) 329–337.
- [33] S. Fraune, R. Augustin, T.C.G. Bosch, Exploring host-microbe interactions in *Hydra*, *Microbe* 4 (2009) 457–462.
- [34] N.A. Moran, Symbiosis as an adaptive process and source of phenotypic complexity, *PNAS* 104 (2007) 8627–8633.
- [35] C. Wild, M. Huettel, A. Klueber, S.G. Kremb, M.Y.M. Rasheed, B.B. Jørgensen, Coral mucus functions as an energy carrier and particle trap in the reef ecosystem, *Nature* 428 (2004) 66–70.
- [36] J.M. Shick, Diffusion limitation and hyperoxic enhancement of oxygen consumption in zooxanthellate sea anemones, Zoanthids and corals, *Biol. Bull.* 179 (1990) 148–158.
- [37] M.H. Long, P. Berg, D. de Beer, J.C. Ziemann, *In situ* coral reef oxygen metabolism: an eddy correlation study, *PLoS One* 8 (2013) e58581.
- [38] S. Tambutté, M. Holcomb, C. Ferrier-Pagès, S. Reynaud, É. Tambutté, D. Zoccola, D. Allemand, Coral biomineralization: from the gene to the environment, *J. Exp. Mar. Biol. Ecol.* 408 (2011) 58–78.
- [39] P. Furla, D. Allemand, M. Shick, C. Ferrier-Pagès, S. Richier, A. Plantivaux, P.-L. Merle, S. Tambutté, The symbiotic anthozoan: a physiological chimera between alga and animal, *Integr. Comp. Biol.* 45 (2005) 595–604.
- [40] M. Shick, S. Romaine-Lioud, C. Ferrier-Pagès, J.-P. Gattuso, Ultraviolet-B radiation shikimate pathway-dependent accumulation of mycosporine-like amino acids in the coral *Stylophora pistillata* despite decreases in its population of symbiotic dinoflagellates, *Limnol. Oceanogr.* 44 (1999) 1667–1682.
- [41] A. Bertucci, A. Moya, S. Tambutté, D. Allemand, C.T. Supuran, D. Zoccola, Carbonic anhydrases in anthozoan corals – A review, *Bioorgan. Med. Chem.* 21 (2013) 1437–1450.
- [42] D. Allemand, P. Furla, S. Bénazet-Tambutté, Mechanisms of carbon acquisition for endosymbiont photosynthesis in Anthozoa, *Can. J. Bot.* 76 (1998) 925–941.
- [43] S. Richier, P.-L. Merle, P. Furla, D. Pigozzi, F. Sola, D. Allemand, Characterization of superoxide dismutases in anoxia- and hyperoxia-tolerant symbiotic cnidarians, *Biochim. Biophys. Acta* 1621 (2003) 84–91.



- [44] A. Pey, T. Zamoum, R. Christen, P.-L. Merle, P. Furla, Characterization of glutathione peroxidase diversity in the symbiotic sea anemone *Anemonia viridis*, *Biochim.* 132 (2017) 94–101.
- [45] C.V. Palmer, C.K. Modi, L.D. Mydlarz, Coral fluorescent proteins as antioxidants, *PLoS One* 4 (2009) e7298.
- [46] P. Furla, S. Bénazet-Tambutté, J. Jaubert, D. Allemand, Functional polarity of the tentacle of the sea anemone *Anemonia viridis*: role in inorganic carbon acquisition, *Am. Physiol. Soc.* 274 (1998) R303–R310.
- [47] J. Laurent, S. Tambutte, E. Tambutté, D. Allemand, A. Venn, The influence of photosynthesis on host intracellular pH in scleractinian corals, *J. Exp. Biol.* 216 (2013) 1398–1404.
- [48] A. Bertucci, É. Tambutté, S. Tambutté, D. Allemand, D. Zoccola, Symbiosis-dependent gene expression in coral-dinoflagellate association: cloning and characterization of a P-type H<sup>+</sup>-ATPase gene, *Proc. R. Soc. London Ser. B* 277 (2010) 87–95.
- [49] D. Zoccola, P. Ganot, A. Bertucci, N. Caminiti-Segonds, N. Techer, C.R. Woolstra, M. Aranda, É. Tambutté, D. Allemand, J.R. Casey, S. Tambutté, Bicarbonate transporters in corals point towards a key step in the evolution of cnidarian calcification, *Sci. Rep.* 5 (2015) 9983.
- [50] P. Ventura, M.D. Jarrold, P.-L. Merle, S. Barnay-Verdier, T. Zamoum, R. Rodolfo-Metalpa, P. Calosi, P. Furla, Resilience to ocean acidification: decreased carbonic anhydrase activity in sea anemones under high pCO<sub>2</sub> conditions, *Mar. Ecol. Prog. Ser.* 559 (2016) 257–263.
- [51] V.M. Weis, Cellular mechanisms of cnidarian bleaching: stress causes the collapse of symbiosis, *J. Exp. Biol.* 211 (2008) 3059–3066.
- [52] M.P. Lesser, Coral bleaching: causes and mechanisms, in: Z. Dubinsky, N. Stambler (Eds.), *Coral reefs: an ecosystem in transition*, Springer Netherlands, 2011, pp. 405–419.
- [53] M.S. Roth, The engine of the reef: photobiology of the coral-algal symbiosis, *Front. Microbiol.* 5 (2014) 1–22.
- [54] T. Bieri, M. Onishi, T. Xiang, A.R. Grossman, J.R. Pringle, Relative contributions of various cellular mechanisms to loss of algae during Cnidarian bleaching, *PLoS One* 11 (2016) e0152693.
- [55] M.E. Warner, W.K. Fitt, G.W. Schmidt, Damage to photosystem II in symbiotic dinoflagellates: a determinant of coral bleaching, *PNAS* 96 (1999) 8007–8012.
- [56] D. Tchernov, M.Y. Gorbunov, C. de Vargas, S. Narayan Yadav, A.J. Milligan, M. Häggblom, P.G. Falkowski, Membrane lipids of symbiotic algae are diagnostic of sensitivity to thermal bleaching in corals, *PNAS* 101 (2004) 13531–13535.
- [57] S.R. Dunn, J.C. Thomason, M.D.A. Le Tissier, J.C. Bythell, Heat stress induces different forms of cell death in sea anemones and their endosymbiotic algae depending on temperature and duration, *Cell Death Differ* 11 (2004) 1–10.
- [58] S. Richier, C. Sabourault, J. Courtiade, N. Zucchini, D. Allemand, P. Furla, Oxidative stress and apoptotic events during thermal stress in the symbiotic sea anemone, *Anemonia viridis*, *FEBS J.* 273 (2006) 4186–4198.
- [59] A. Moya, P. Ganot, P. Furla, C. Sabourault, The transcriptomic response to thermal stress is immediate, transient and potentiated by ultraviolet radiation in the sea anemone *Anemonia viridis*, *Mol. Ecol.* 21 (2012) 1158–1174.
- [60] N. Traylor-Knowles, N.H. Rose, S.R. Palumbi, The cell specificity of gene expression in the response to heat stress in corals, *J. Exp. Biol.* 220 (2017) 1837–1845.
- [61] R.W. Buddemeier, D.G. Fautin, Coral bleaching as an adaptive mechanism: a testable hypothesis, *BioScience* 43 (1993) 320–326.
- [62] O. Hoegh-Guldberg, R.J. Jones, S. Ward, W.K. Loh, A.C. Baker, Is coral bleaching really adaptive? *Nature* 415 (2002) 601–602.
- [63] T.P. Hughes, J.T. Kerry, M. Alvarez-Noriega, J.G. Alvarez-Romero, K.D. Anderson, A.H. Baird, R.C. Babcock, M. Beger, D.R. Bellwood, R. Berkelmans, T.C. Bridge, I.R. Butler, M. Byrne, N.E. Cantin, S. Comeau, S.R. Connolly, G.S. Cumming, S.J. Dalton, G. Diaz-Pulido, C.M. Eakin, W.F. Figueira, J.P. Gilmour, H.B. Harrison, S.F. Heron, A.S. Hoey, J.A. Hobbs, M.O. Hoogenboom, E.V. Kennedy, C.Y. Kuo, J.M. Lough, R.J. Lowe, G. Liu, M.T. McCulloch, H.A. Malcolm, M.J. McWilliam, J.M. Pandolfi, R.J. Pears, M.S. Pratchett, V. Schoepf, T. Simpson, W.J. Skirving, B. Sommer, G. Torda, D.R. Wachenfeld, B.L. Willis, S.K. Wilson, Global warming and recurrent mass bleaching of corals, *Nature* 543 (2017) 373–377.
- [64] P.-Y. Chen, C.-C. Chen, L.F. Chu, B. McCarl, Evaluating the economic damage of climate change on global coral reefs, *Global Environ. Change* 30 (2015) 12–20.
- [65] K. Frieler, M. Meinshausen, A. Golly, M. Mengel, K. Lebek, S.D. Donner, O. Hoegh-Guldberg, Limiting global warming to 2 °C is unlikely to save most coral reefs, *Nat. Clim. Change* 3 (2013) 165–170.
- [66] L. Kwiatkowski, P. Cox, P.R. Halloran, P.J. Mumby, A.J. Wiltshire, Coral bleaching under unconventional scenarios of climate warming and ocean acidification, *Nat. Clim. Change* 5 (2015) 777–781.
- [67] S. Melov, Animal models of oxidative stress, aging, and therapeutic antioxidant interventions, *Int. J. Biochem. Cell Biol.* 34 (2002) 1395–1400.
- [68] E. Gilson, T.C. Bosch, Understanding why we age and how: evolutionary biology meets different model organisms and multi-level omics, *Bioessays* 38 (2016) 494–497.
- [69] L. Reshef, O. Koren, Y. Loya, L. Zilber-Rosenberg, E. Rosenberg, The coral probiotic hypothesis, *Environ. Microbiol.* 8 (2006) 2068–2073.
- [70] B.C. Hume, C. D'Angelo, E.G. Smith, J.R. Stevens, J. Burt, J. Wiedenmann, *Symbiodinium thermophilum* sp. nov., a thermotolerant symbiotic alga prevalent in corals of the world's hottest sea, the Persian/Arabian Gulf, *Sci. Rep.* 5 (2015) 8562.
- [71] M.J.H. van Oppen, J.K. Oliver, H.M. Putnam, R.D. Gates, Building coral reef resilience through assisted evolution, *PNAS* 112 (2015) 2307–2313.
- [72] R.S. Peixoto, P.M. Rosado, D.C. de Assis Leite, A.S. Rosado, D.G. Bourne, Beneficial Microorganisms for Corals (BMC): proposed mechanisms for coral health and resilience, *Front. Microbiol.* (2017) 8.
- [73] R.L.V. Thurber, A.M.S. Correa, Viruses of reef-building scleractinian corals, *J. Exp. Mar. Biol. Ecol.* 408 (2011) 102–113.