



Protists Within Corals: The Hidden Diversity

Camille Clerissi^{1*}, Sébastien Brunet², Jeremie Vidal-Dupiol³, Mehdi Adjeroud⁴, Pierre Lepage², Laure Guillou⁵, Jean-Michel Escoubas⁶ and Eve Toulza^{1*}

¹ Univ. Perpignan Via Domitia, IHPE UMR 5244, CNRS, IFREMER, Univ. Montpellier, Perpignan, France, ² McGill University and Génome Québec Innovation Centre, Montréal, QC, Canada, ³ IFREMER, IHPE UMR 5244, Univ. Perpignan Via Domitia, CNRS, Univ. Montpellier, Montpellier, France, ⁴ Institut de Recherche pour le Développement, UMR 9220 ENTROPIE & Laboratoire d'Excellence CORAIL, Université de Perpignan, Perpignan, France, ⁵ CNRS, UMR 7144, Sorbonne Universités, Université Pierre et Marie Curie – Paris 6, Station Biologique de Roscoff, Roscoff, France, ⁶ CNRS, IHPE UMR 5244, Univ. Perpignan Via Domitia, IFREMER, Univ. Montpellier, Montpellier, France

OPEN ACCESS

Edited by:

Virginia M. Weis,
Oregon State University,
United States

Reviewed by:

David Suggett,
University of Technology Sydney,
Australia
Kimberly B. Ritchie,
University of South Carolina Beaufort,
United States

*Correspondence:

Camille Clerissi
camille.clerissi@univ-perp.fr
Eve Toulza
eve.toulza@univ-perp.fr

Specialty section:

This article was submitted to
Microbial Symbioses,
a section of the journal
Frontiers in Microbiology

Received: 12 June 2018

Accepted: 13 August 2018

Published: 31 August 2018

Citation:

Clerissi C, Brunet S, Vidal-Dupiol J, Adjeroud M, Lepage P, Guillou L, Escoubas J-M and Toulza E (2018) Protists Within Corals: The Hidden Diversity. *Front. Microbiol.* 9:2043. doi: 10.3389/fmicb.2018.02043

Previous observations suggested that microbial communities contribute to coral health and the ecological resilience of coral reefs. However, most studies of coral microbiology focused on prokaryotes and the endosymbiotic algae *Symbiodinium*. In contrast, knowledge concerning diversity of other protists is still lacking, possibly due to methodological constraints. As most eukaryotic DNA in coral samples was derived from hosts, protist diversity was missed in metagenome analyses. To tackle this issue, we designed blocking primers for Scleractinia sequences amplified with two primer sets that targeted variable loops of the 18S rRNA gene (18SV1V2 and 18SV4). These blocking primers were used on environmental colonies of *Pocillopora damicornis sensu lato* from two regions with contrasting thermal regimes (Djibouti and New Caledonia). In addition to *Symbiodinium* clades A/C/D, *Licnophora* and unidentified coccidia genera were found in many samples. In particular, coccidian sequences formed a robust monophyletic clade with other protists identified in *Agaricia*, *Favia*, *Montastraea*, *Mycetophyllia*, *Porites*, and *Siderastrea* coral colonies. Moreover, *Licnophora* and coccidians had different distributions between the two geographic regions. A similar pattern was observed between *Symbiodinium* clades C and A/D. Although we were unable to identify factors responsible for this pattern, nor were we able to confirm that these taxa were closely associated with corals, we believe that these primer sets and the associated blocking primers offer new possibilities to describe the hidden diversity of protists within different coral species.

Keywords: holobiont, protists, symbiosis, metabarcoding, blocking primer, Scleractinia, *Pocillopora damicornis*

INTRODUCTION

Scleractinian corals build reefs all around the world. The ecological success of corals in the oligotrophic seawater of coral reefs mostly relies on the symbiosis with dinoflagellates (genus *Symbiodinium*). In particular, the symbiosis between corals and *Symbiodinium* takes place within coral cells, where the algal symbionts provide organic compounds to corals through their photosynthetic activity, and in turn receive nutrients and metabolic compounds from their host. *Symbiodinium* is a diverse genus divided into nine clades (Coffroth and Santos, 2005; Pochon et al., 2006; Quigley et al., 2014; Thornhill et al., 2017). Among these clades, five have been identified in coral cells (clades A, B, C, D, and F).

Corals are also associated with a high diversity of microorganisms (bacteria, archaea, fungi, endolithic algae, protozoa, and viruses) (Rohwer et al., 2002; Wegley et al., 2004; Thurber et al., 2017), and the complex formed by coral and the associated microorganisms corresponds to a single entity called the holobiont (Rohwer et al., 2002; Theis et al., 2016). Among them, the bacterial genus *Endozoicomonas* was found in high abundances within many coral species (Bayer et al., 2013; Neave et al., 2016, 2017). This genus was thought to be a beneficial symbiont to corals. Moreover, rare bacterial taxa (genera *Ralstonia* and *Propionibacterium*) were ubiquitous as well (Ainsworth et al., 2015). In addition to *Symbiodinium*, other unicellular eukaryotes (protists) were found to live with corals, including many Stramenopiles (Kramarsky-Winter et al., 2006; Harel et al., 2008; Siboni et al., 2010), several apicomplexans such as *Chromera* and coccidians (Toller et al., 2002; Moore et al., 2008; Janoušková et al., 2012; Kirk et al., 2013; Mohamed et al., 2018), different fungi (Amend et al., 2012), and different boring microflora (e.g., *Ostreobium*, *Phaeophila*, and *Porphyra*) (Tribollet, 2008b; Pica et al., 2016).

Unlike for *Symbiodinium*, the role of these microorganisms remains unknown within the holobiont. First, they might provide protection against pathogens through the secretion of antimicrobial compounds (Ritchie, 2006; Shnit-Orland and Kushmaro, 2009). Secondly, in addition to *Symbiodinium*, they might also provide metabolic compounds to corals (Kramarsky-Winter et al., 2006; Harel et al., 2008; Siboni et al., 2010). Thirdly, microbial communities might play an important role for coral heat tolerance (Ziegler et al., 2017), and for the ecological resilience of coral reefs (McDevitt-Irwin et al., 2017). As a consequence, these observations suggested that microbial communities contribute to coral health and homeostasis, through the presence of Beneficial Microorganisms for Corals (BMC) (Peixoto et al., 2017).

To date, however, most studies have focused on *Symbiodinium* and coral-associated bacteria. In particular, very little is known concerning the diversity and the role of other protists (Ainsworth et al., 2017), though several studies have shown that they play an important role in the structure and function of marine ecosystems (Thingstad et al., 2008; de Vargas et al., 2015). Previous analyses of protists mainly used non-destructive sampling techniques (microscope, culture) or low-throughput methods for environmental DNA (qPCR, cloning), though these methods were less effective at detecting diversity when compared to mass sequencing of the 18S rRNA gene for example. Because most DNA in coral samples was extracted from the host and the 18S rRNA gene is shared between corals and protists, to date high-throughput studies of protist diversity have been a challenge (Šlapeta and Linares, 2013).

To tackle this issue, we designed blocking primers for Scleractinia sequences in order to decrease their proportions relative to protist sequences. Such an approach was already effective in the study of fish and krill gut contents (Vestheim and Jarman, 2008; Leray et al., 2013), and in the removal of metazoa sequences from seawater community samples (Tan and Liu, 2018). To the best of our knowledge, this is the first time that this strategy has been used on coral samples. These blocking primers targeted regions similar to the reverse primer for each of the two primer sets used to amplify variable loops of the 18S rRNA gene (V1V2 and V4) (Wuyts et al., 2000, 2002; Stoeck et al., 2010).

Both blocking primers were used to explore protist diversity within colonies of *P. damicornis sensu lato* that were sampled from two geographic regions with contrasting thermal regimes: Djibouti and New Caledonia (Figure 1 and Supplementary Table 1). A previous study on these samples showed different *Symbiodinium* clades between these regions using ITS2 (internal transcribed spacer 2) (Brener-Raffalli et al., 2018). These authors also highlighted that colonies from Djibouti and New Caledonia

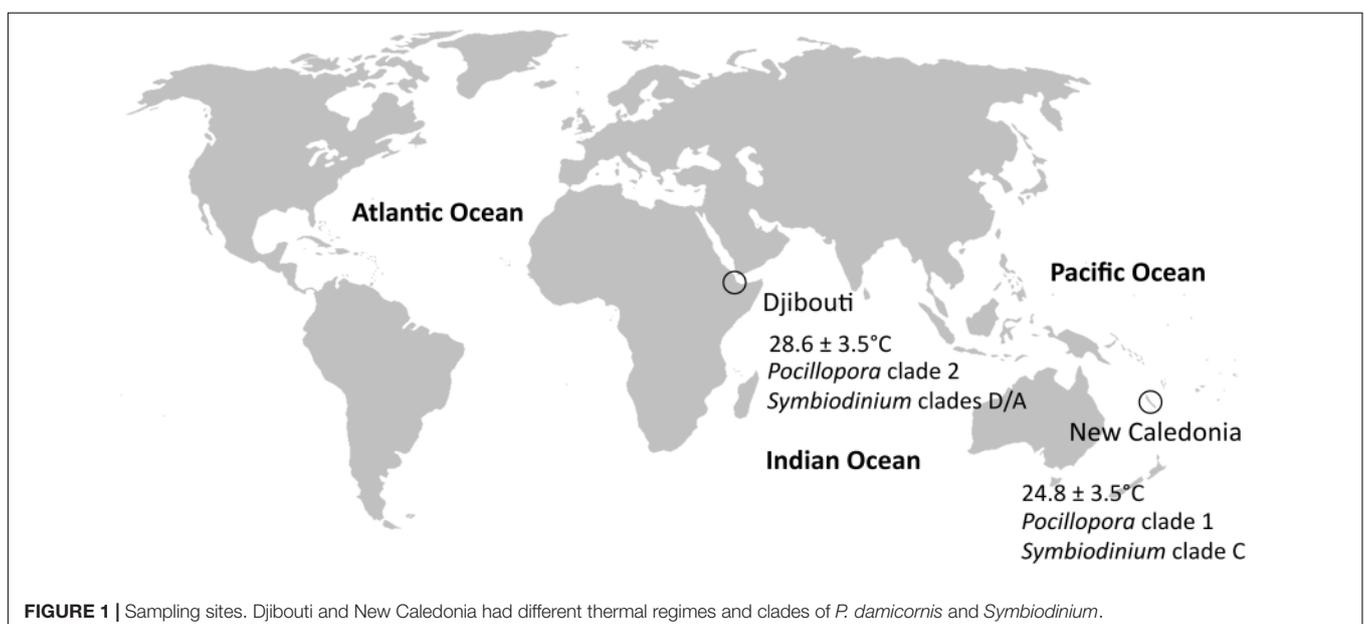


FIGURE 1 | Sampling sites. Djibouti and New Caledonia had different thermal regimes and clades of *P. damicornis* and *Symbiodinium*.

corresponded to two different clades of *P. damicornis*. As a consequence, geography, genetics and environmental conditions divided the two *P. damicornis* populations, and allowed for the comparison of different holobionts.

MATERIALS AND METHODS

Sampling Sites

Colonies of *P. damicornis sensu lato* growing between one to five meters depth were sampled by snorkeling within two regions (Djibouti and New Caledonia) in six localities (**Figure 1** and **Supplementary Table 1**). A total of 16 colonies were sampled during this survey. The tip (1–2 cm) from one healthy branch of each colony was cut and placed individually in a plastic bag. Each bag was filled with seawater surrounding the colony to hold samples during the sampling cruise. Samples were subsequently transferred into modified CHAOS buffer (4 M guanidium thiocyanate, 0.5% N-lauryl sarcosine sodium 25 mM Tris-HCl pH 8, 0.1 M β -Mercaptoethanol) as previously described (Adjeroud et al., 2014).

Design of Blocking Primers for Scleractinia

A preliminary sequencing test was performed to study eukaryote diversity within a sample of *P. damicornis* using two primer sets targeting two different regions of the 18S rRNA gene, 18SV1V2 and 18SV4 (**Table 1**). While primers for 18SV4 were designed previously to amplify all eukaryotic-specific 18S rDNA (Stoeck et al., 2010), primers for 18SV1V2 were designed using the Protist Ribosomal Reference database (PR²) (Guillou et al., 2012) in order to prevent amplification of metazoan 18S rRNA genes especially from *Crassostrea gigas* oysters. Both sequencing tests showed an excess of amplicons from *P. damicornis*, since they represented ~99% of sequences (for a total of 3383 and 2460 cleaned sequences using 18SV1V2 and 18SV4, respectively; data not shown).

Thus we designed blocking primers for both primer sets in order to reduce the proportion of *P. damicornis* amplicons. First, we downloaded the non-redundant (99%) Silva SSU database (release 128, September 2016) (Quast et al., 2013; Yilmaz et al., 2014). Then we only kept sequences that matched with either the primer set for 18SV1V2 or 18SV4. Based on annotations, metazoa were removed to produce a metazoa-free database and sequences of Scleractinia were used to create a host database. In order to design blocking primers that overlap the reverse primer and the 3'-region of Scleractinia amplicons, we aligned the last 40 nucleotides (corresponding to the 3'-region of

amplicon and the reverse primer) of Scleractinia with metazoa-free database using MUSCLE v3.8.31 (Edgar, 2004). Then, we analyzed the nucleotide polymorphism at each position of the alignment for Scleractinia and metazoa-free sequences using entropy decomposition (R package {otu2ot}, CalcEntropy.seq) (Ramette and Buttigieg, 2014). According to previous studies and entropy values (**Supplementary Figure 1**), we designed blocking primers <30 bp with 10 bp overlapping the reverse primer, and having a T_m similar to the targeted primer set (Vestheim and Jarman, 2008; Leray et al., 2013). The best candidate for each primer set (targeting either 18SV1V2 or 18SV4 region) was identified using specificity tests against the Scleractinia and metazoa-free databases. Lastly, these primers were synthesized and modified at the 3'-end with a Spacer C3 CPG (3 hydrocarbons).

DNA Extraction, PCR, and Sequencing

DNA extractions were performed using CTAB (Cetyl TrimethylAmmonium Bromide)-based extraction method (Winnepenninckx et al., 1993). Briefly, coral tips were lysed 2 h in 600 μ L CTAB buffer (2% CTAB, 0.2% β -Mercaptoethanol, 1.4 M NaCl, 20 mM EDTA pH 8, 100 mM Tris-HCl pH 8, 100 μ g/mL proteinase K) at 60°C. Thus protists of the whole coral tissues were analyzed in this study. An equal volume of chloroform:isoamyl-alcohol (24:1) was then added. After centrifugation for 10 min at 14,000 g, the aqueous phase was transferred to a new tube and DNA was precipitated by adding 400 μ L of ice-cold isopropanol and incubating 1 h at -20°C. After centrifugation for 15 min at 14,000 g, the supernatant was discarded and the pellet washed with 70% ethanol. The pellet was air-dried for 5 min and resuspended in water. DNA concentration and quality were checked with Epoch microplate spectrophotometer (BioTek Instruments, Inc.).

Then, the 18S rRNA gene of eukaryotic communities was amplified and sequenced using the variable V1V2 and V4 loops (**Table 1**; Wuyts et al., 2002; Stoeck et al., 2010). PCR reactions were carried in a 25 μ l volume with final concentrations of 0.4 μ M of each PCR primers, 0.02 U of the Qiagen HotStar Taq DNA Polymerase, 0.2 mM of the dNTP mix and 1 \times Taq buffer. In order to reduce amplification of *P. damicornis* amplicons, blocking primers were added to the PCR mix at a final concentration of 1.2 μ M (**Table 1**). PCR cycling included an initial incubation of 15 min at 96°C followed by 35 cycles of 96°C for 30 s, 52°C for 30 s, and 72°C for 1 min, with a final 10 min incubation at 72°C. Paired-end sequencing (250 bp read length) was performed at the McGill University (Génome Québec Innovation Centre, Montréal, QC, Canada) on the MiSeq system (Illumina) using the v2 chemistry according to the manufacturer's

TABLE 1 | Primers and blocking primers used in this study.

Marker region	18SV1V2	18SV4
Forward (5'→3')	ACCTGGTTGATCCTGCCA	CCAGCASCYGC GGTAATTCC
Reverse (5'→3')	GTARKCCWMTAYMYTACC	ACTTTCGTTCTTGATYRA
Blocking primer (5'→3')	CTACCTTACCATCGACAGTTGATAG	TCTTGATTAATGAAAACATTCTTGGC
Expected amplicon size (bp)	~340	~430

protocol. Raw sequence data are available in the Sequence Read Archive repository under accession ID PRJNA393088 (to be released upon publication).

Sequence Analyses

The FROGS pipeline (Find Rapidly OTU with Galaxy Solution) implemented into a galaxy instance was used to define Operational Taxonomic Units (OTU), and compute taxonomic annotations (Escudie et al., 2017). Briefly, paired reads were merged using FLASH (Magoc and Salzberg, 2011). After denoising and primer/adapters removal with cutadapt (Martin, 2011), *de novo* clustering was done using SWARM that uses a local clustering threshold, with aggregation distance $d = 3$ (Mahé et al., 2015). Chimera was removed using VSEARCH (Rognes et al., 2016). We filtered the dataset for singletons and performed affiliation using Blast+ against the Protist Ribosomal Reference database (PR²) (Guillou et al., 2012) to produce an OTU and affiliation table in standard BIOM format. Because we were interested in studying low frequency OTUs, we used additional steps to remove most PCR and sequencing errors. First, we removed OTUs having an annotation with a blast coverage <90%. Secondly, we computed a phylogenetic tree of the whole OTUs using MAFFT (Katoh et al., 2002) and FastTree (GTR model) (Price et al., 2010). OTUs were removed from the dataset if they corresponded to very long branches on the phylogenetic tree (according to minimal branch length values). Lastly, OTUs were considered present in each sample if they had at least three sequences.

Rarefaction curves of protist species richness were produced using the {phyloseq} R package, and the rarefy_even_depth and ggrare functions (McMurdie and Holmes, 2013). We also used phyloseq to obtain abundances at the genus taxonomic rank (tax_glom function). Pielou's measure of evenness was computed using affiliated genera and the {vegan} R package.

Annotation of *Symbiodinium* OTUs

In order to characterize the environmental diversity of *Symbiodinium*, reference sequences of *Symbiodinium* (clades A, B, C, D, and G) were obtained for each 18S rRNA regions from the National Center for Biotechnology Information (NCBI) (Supplementary Table 2). In addition, we selected two outgroups: *Polarella glacialis* and *Pelagodinium beii*. The reference were aligned with the environmental sequences of *Symbiodinium* using MUSCLE v3.8.31 (Edgar, 2004), alignments were trimmed at each extremity, and sequences were clustered at different nucleotide similarities (from 90 to 99%) using Mothur (Schloss et al., 2009). The environmental sequences were annotated for a similarity of 95 and 97% for 18SV1V2 and 18SV4, respectively, *i.e.*, when all the reference sequences of *Symbiodinium* clade A, B, C, D, and G clustered into five different groups.

Alignment and Phylogenetic Analyses

In one hand, phylogenetic reconstructions of *Symbiodinium* reference isolates were carried out to compare phylogenetic signals of both 18SV1V2 and 18SV4 markers with ITS2. We selected two reference sequences of *Symbiodinium* clade A,

three reference sequences of clade B, two reference sequences of clade C, one reference sequences of clade D and clade G (Supplementary Table 3). Except the strain of clade G, sequences of the three markers were available for each reference isolate of *Symbiodinium*. For each marker, sequences were aligned using MUSCLE v3.8.31 (Edgar, 2004).

On the other hand, phylogenetic reconstructions were computed to describe either environmental *Symbiodinium* diversity, the whole protist genera or coccidians associated with *P. damicornis* samples. First, *Symbiodinium* diversity was studied according to the annotation step of *Symbiodinium* OTUs. In particular, we used the output alignment of Mothur obtained at 95 and 97% similarity cutoffs for 18SV1V2 and 18SV4, respectively. These alignments contained representative OTUs of environmental *Symbiodinium*, the two outgroups (*P. glacialis* and *P. beii*), and the reference sequences of *Symbiodinium* clades. Secondly, sequences of protist genera, *Symbiodinium* clades, and *P. damicornis* (accession number: LT631138.1 for both 18SV1V2 and 18SV4) were aligned using MUSCLE v3.8.31 (Edgar, 2004). Thirdly, we described the diversity of coral-associated coccidians using reference sequences of Apicomplexa (Schrével et al., 2016), and best BLASTn hits of coccidian sequences of this study against the National Center for Biotechnology Information (NCBI).

Finally, all alignments were trimmed at each extremity and maximum likelihood (ML) trees were computed with IQ-TREE v1.3.8 using the best model (selected with the Bayesian information criterion) (Nguyen et al., 2015), and validated via a ultrafast bootstrap procedure with 1000 replicates (Minh et al., 2013).

Statistical Analyses

All statistical analyses were done using R v3.3.1 (R Core Team, 2008).

First, phylogenetic signals were compared between ITS2, 18SV1V2 and 18SV4 using *Symbiodinium* reference isolates. Patristic distances were obtained from phylogenetic trees (R package {stats}, cophenetic), and compared using Mantel test (R package {vegan}, mantel) (Mantel, 1967).

Secondly, Fisher's exact tests (R package {stats}, fisher.test) were computed to estimate the association between protist genera and *Symbiodinium* clades with both geographic regions, *i.e.*, Djibouti and New Caledonia.

P-values were adjusted for multiple comparisons using the Bonferroni correction ({stats}, p.adjust). The threshold of significance level was set at 0.05.

RESULTS

Specificity of Blocking Primers

In order to describe protist diversity associated with *P. damicornis* colonies from Djibouti and New Caledonia, we performed a preliminary sequencing test using one sample and two primer sets targeting different variable loops of the 18S rRNA gene (V1V2 and V4). Since most sequences corresponded to *P. damicornis*, we designed blocking primers using the Silva SSU database (see

TABLE 2 | *In silico* specificity of blocking primers.

Removed taxa	18SV1V2 (%)	18SV4 (%)
Scleractinia	100	93.8
Rhizaria	1.6	0
Nucleotmycea	0.4	<0.1
Alveolata	0.1	0.6
Cryptomonadales	0	0.5
Chloroplastida	0	0.3

Methods for more details). These blocking primers targeted 10 bp of reverse primers and ~15 bp of the amplicon 3'-end of Scleractinia (Table 1 and Supplementary Figure 1). Because their 3'-end had a spacer C3 CPG, elongation is expected to abort, whereas annealing properties are not modified (Vestheim and Jarman, 2008). To estimate the specificity of these blocking primers, we identified sequences of the Silva database that matched with primer sets and blocking primers. We found a very high *in silico* specificity, since 100 and 93.8% of Scleractinia were removed by the 18SV1V2 and 18SV4 blocking primers, respectively (Table 2). In addition, they removed very low fractions of protists found in the Silva database.

As a consequence, we used both primer sets and their blocking primers to study protists associated with the colonies of *P. damicornis* from Djibouti and New Caledonia. Because DNA extraction was done directly on coral tips, we expected to be able to describe the entire protist community (*i.e.*, microbes that were part of the holobiont, and possibly environmental microbes). On average, each sample had ~29,566 *Pocillopora* sequences and ~18,724 protist sequences representing ~26 OTUs (Table 3 and Supplementary Table 4). While *in silico*

analyses showed very high specificity of both blocking primers, PCR and MiSeq sequencing displayed higher host contamination (Figure 2A). Indeed, *Pocillopora* sequences still represented 71 and 48% of amplicons for 18SV1V2 and 18SV4, respectively. In particular, *Pocillopora* proportion was lower for 18SV4 than for 18SV1V2.

Symbiodinium Diversity

Rarefaction curves for protists tended to level off for both marker regions, suggesting that most diversity was sequenced in each sample (Supplementary Figure 2).

Not surprisingly, *Symbiodinium* accounted for most protist diversity within *P. damicornis* tissues for both primer sets (Figure 2B). In order to describe *Symbiodinium* diversity, we first estimated phylogenetic signals of both 18SV1V2 and 18SV4 compared to ITS2. ITS2 is the most common marker used to study *Symbiodinium* diversity (LaJeunesse et al., 2010; Wicks et al., 2010; Silverstein et al., 2011; Putnam et al., 2012; Tonk et al., 2013), since it has high polymorphism. The strength of correlation between the three markers was estimated using Mantel tests (Table 4). The three phylogenetic trees were significantly congruent (Supplementary Figure 3) ($p = 0.003$), but congruency with ITS2 was higher for 18SV1V2 ($r = 0.88$) than for 18SV4 ($r = 0.72$) (Table 4). We then annotated environmental *Symbiodinium* OTUs using a clustering approach and reference sequences of *Symbiodinium* clade A, B, C, D, and G (Supplementary Table 4). We also computed phylogenetic reconstruction with *P. glacialis* and *P. beii* as outgroups (Figure 3). While *Symbiodinium* clades A, C and D were common for both marker genes, strains from clade G were not identified with 18SV1V2 nor with 18SV4. Moreover, *Symbiodinium* clade B was found with 18SV4 but not with 18SV1V2, and we were not able to assign all environmental

TABLE 3 | Number of sequences and OTUs.

Sample	Total number of raw sequences	Total number of cleaned sequences	Total number of OTUs	Number of <i>Pocillopora</i> sequences	Number of protist sequences
DJMI5	53724/42120	44953/31038	24/20	29269/11462	15465/19576
DJMI6	90752/30981	74660/16993	29/14	30128/1213	44513/15780
DJMI7	63586/11187	51314/6835	26/11	15387/704	35609/6124
DJRK1	46195/20867	37723/12100	23/11	24296/2204	13408/9896
DJRK3	62498/34901	52163/24230	19/13	38052/8707	14111/15523
DJRK4	63927/51803	54167/40238	18/34	35607/7719	18556/32519
DJRK5	95369/24355	76347/14707	34/17	42900/2156	33419/12551
DJRK7	41294/59287	35298/42366	17/47	25045/6777	10238/35589
DJSB6	102976/68110	88376/48495	25/51	79796/26472	8568/22023
NCBM1	63399/63417	53813/47370	13/45	46548/30929	7256/16340
NCBM3	64930/72320	55578/55268	14/29	44263/34066	11307/21182
NCBM4	65261/75658	54262/57280	8/31	42120/32709	12134/24563
NCBS3	82706/84640	71188/61287	10/151	65493/25015	5688/36272
NCGR1	41951/72332	35359/53978	11/21	27956/34244	7403/19731
NCGR4	69287/85822	57476/62195	20/21	46548/41107	10919/21088
NCGR6	75101/82547	64603/64542	15/20	46797/40431	17798/24016

Values correspond to 18SV1V2/18SV4.

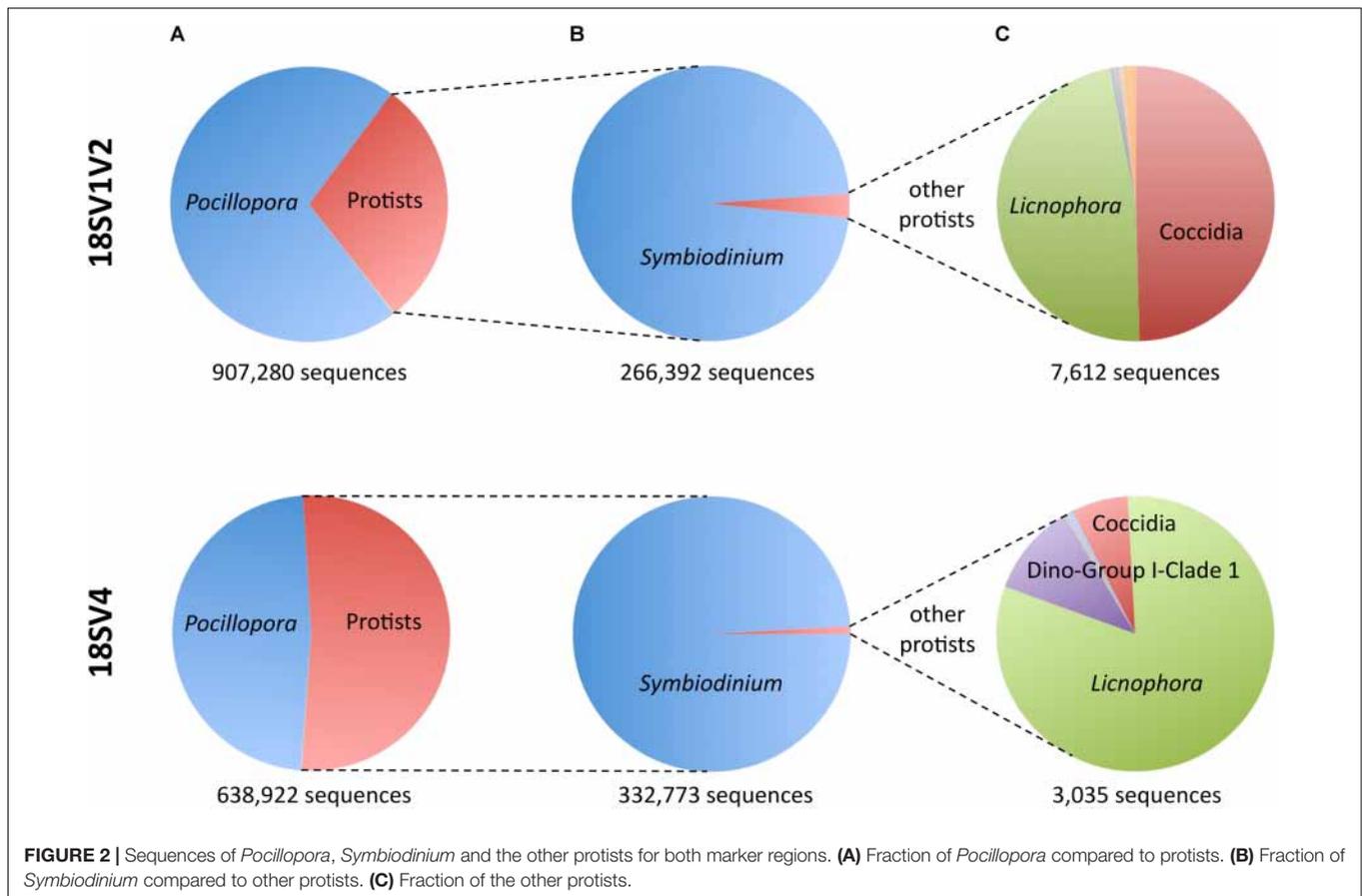


TABLE 4 | Phylogenetic congruences between ITS2, 18SV1V2, and 18SV4 markers for *Symbiodinium*.

Marker 1	Marker 2	Correlation coefficient (r)	p-value
ITS2	18SV1V2	0.88	0.003
ITS2	18SV4	0.72	0.003
18SV1V2	18SV4	0.83	0.003

Values correspond to correlation coefficients between patristic distances obtained using reference sequences of *Symbiodinium* and the Mantel test.

Symbiodinium to a known clade for 18SV4 in comparison to 18SV1V2 (Supplementary Table 4).

Diversity of the Other Dominant Genera

Although protist proportion was lower for 18SV1V2 (Figure 2A), the proportion of protists other than *Symbiodinium* was lower for 18SV4 (0.9% compared to 2.9% for 18SV1V2) (Figure 2B). The *Symbiodinium* genus was removed from the dataset to study the other protist genera of *P. damicornis* (Figure 2C and Supplementary Table 5). *Licnophora*, unidentified coccidians and Dino-Group I-Clade 1 (Syndiniales) were the main taxa found in *P. damicornis* samples among the 17 genera found with both primer sets. Among them, *Licnophora* represented a high fraction for 18SV1V2 and 18SV4, whereas coccidians showed different proportions between these markers. In particular,

18SV1V2 showed a more even protist diversity at the genus level than 18SV4 ($0.05 > 0.03$, Pielou's measure of evenness). A BLASTn search against NCBI nucleotide collection suggested that for both markers, *Licnophora* sequences were related to *Licnophora* strains, and that Dino-Group I-Clade 1 (Syndiniales) were similar to uncultured eukaryotes (Table 5). Interestingly, coccidian sequences were similar to protists already described in healthy coral colonies of *Agaricia agaricita*, *A. tenuifolia*, *Favia fragum*, *Montastraea annularis*, *M. faveolata*, *Mycetophyllia ferox*, *Porites astreoides*, and *Siderastrea siderea* (Toller et al., 2002; Kirk et al., 2013; Šlapeta and Linares, 2013). As a consequence, we computed a phylogenetic reconstruction of coral-associated coccidians with other Apicomplexa genera to describe their diversity. We found that all coral-associated coccidians formed a robust monophyletic clade (Figure 4). In addition, a phylogenetic tree using the longest available sequences of these symbionts highlighted their relationships with other marine Apicomplexa (Supplementary Figure 4), and confirmed that they corresponded to coccidians (Schréval et al., 2016).

Distribution of *P. damicornis*-Associated Protists

Because 18SV4 had (i) a low number of sequences related to protists other than *Symbiodinium*, (ii) low evenness for protist

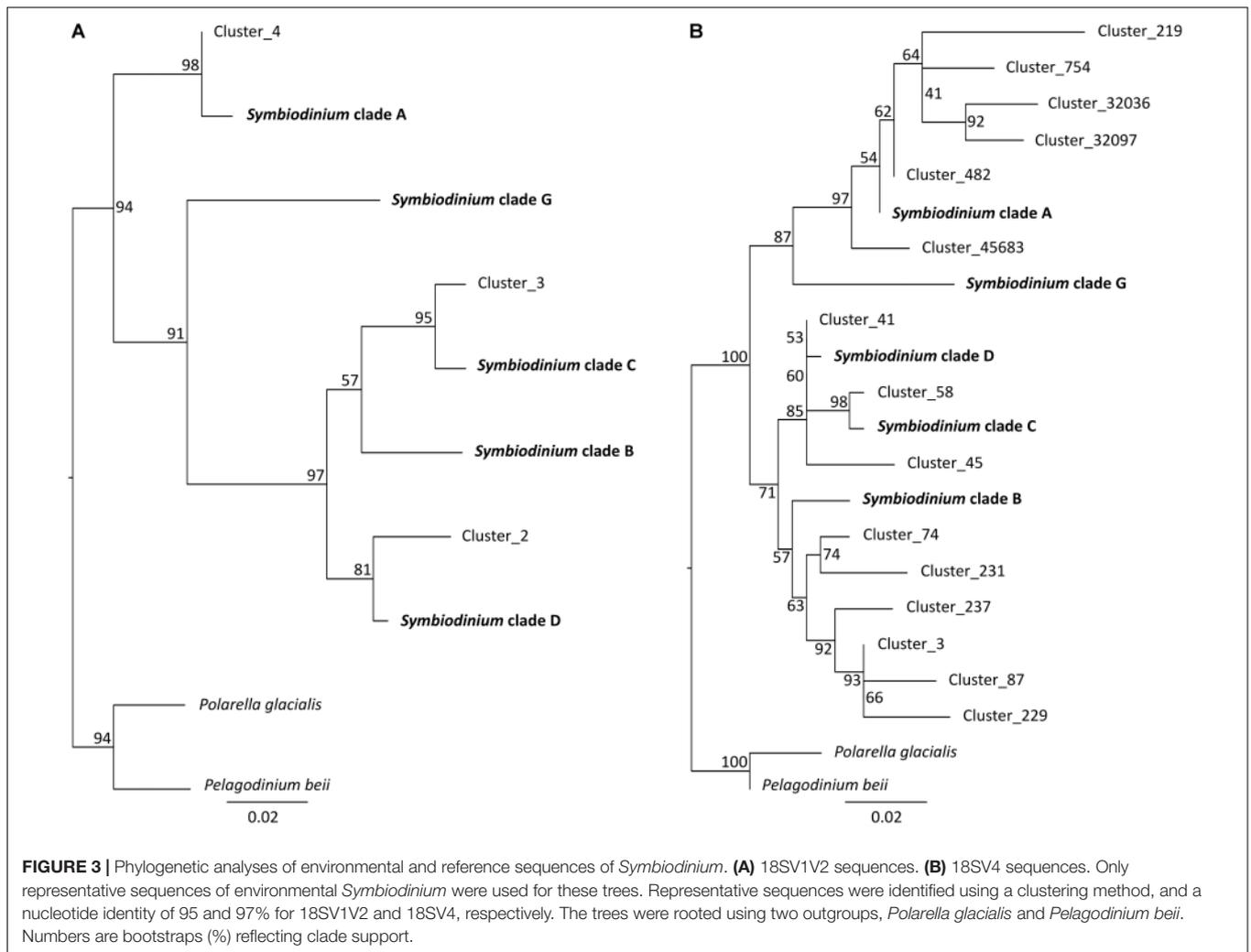


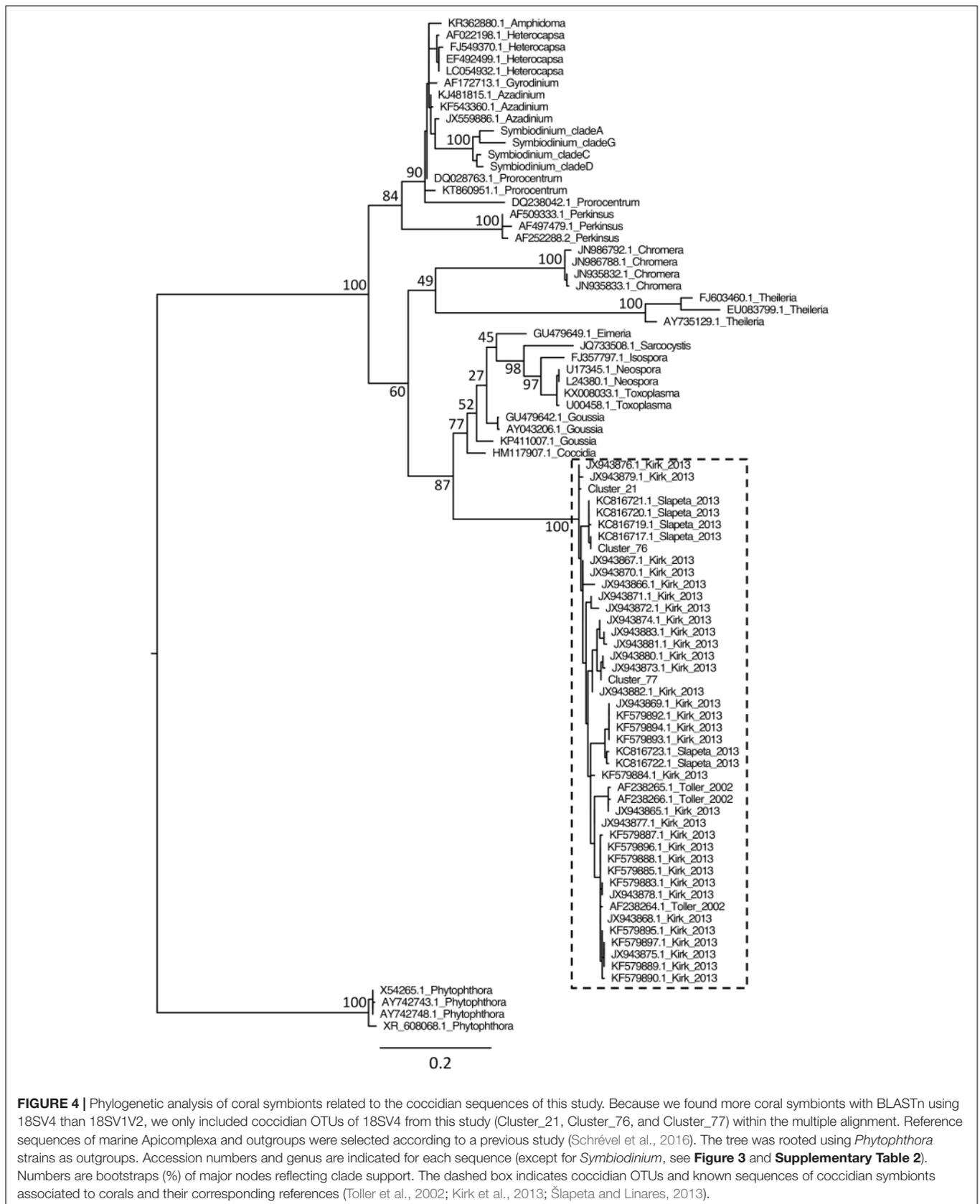
TABLE 5 | BLASTn search of coccidians, *Licnophora*, and Dino-Group I-Clade 1 (Syndiniales) against NCBI.

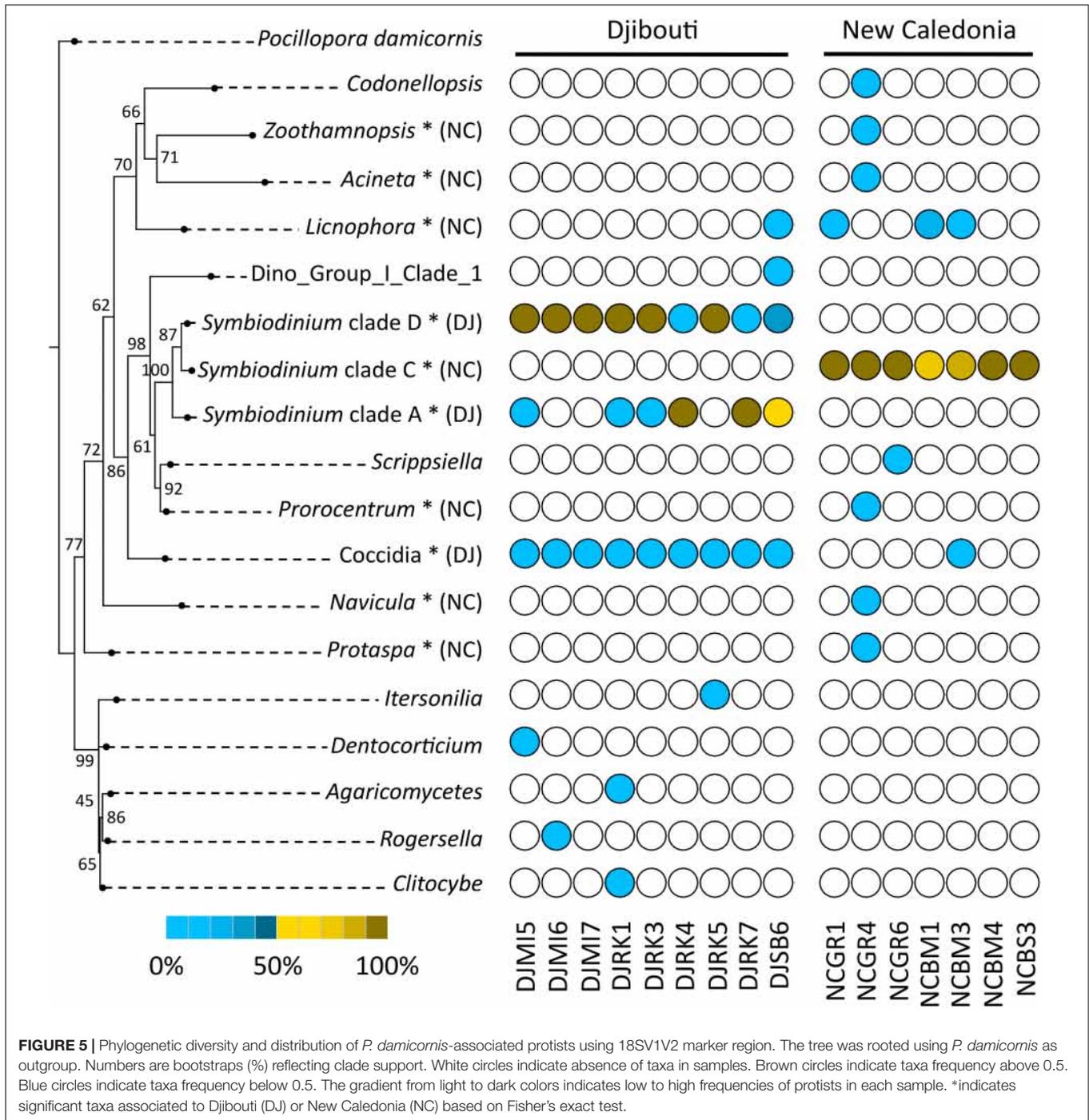
Marker region	Genus	Description	Identity (%)	Coverage (%)	E-value	Accession number
18SV1V2	Unidentified coccidia	Unidentified symbiont Type N clone N:0-1	96	100	1e-135	AF238264.1
	<i>Licnophora</i>	<i>Licnophora macfarlandi</i>	98	92	1e-128	AF527758.1
	Dino-Group I-Clade 1	Uncultured eukaryote clone SGP555	100	100	6e-152	KJ763756.1
18SV4	Unidentified coccidia	Coral symbiont from <i>Montastraea faveolata</i> haplotype 12	99	100	0.0	JX943876.1
	<i>Licnophora</i>	<i>Licnophora macfarlandi</i>	96	100	2e-165	AF527758.1
	Dino-Group I-Clade 1	Uncultured eukaryote clone ST5900.009	100	100	0.0	KF129971.1

genera, and (iii) low phylogenetic signals (low congruency with ITS2 tree and low efficiency of annotations with reference *Symbiodinium* clades), we used 18SV1V2 amplicons to study protist distribution within the samples from Djibouti and New Caledonia.

A phylogenetic reconstruction of identified *Symbiodinium* clades and protist genera was carried out using maximum

likelihood, and corresponding frequencies in samples were plotted in front of taxa (Figure 5). Two colors were used for frequencies to discriminate the high proportions of *Symbiodinium*, and lower values of other protists. Most protist genera were found in only one sample (e.g., *Codonellopsis*, *Zoothamnopsis*, *Acineta*, etc.). However, the different *Symbiodinium* clades, *Licnophora* and coccidians





were present in several *P. damicornis* colonies. In particular, we observed different distribution between Djibouti and New Caledonia.

In order to statistically test differences between both geographic regions, we computed Fisher's exact test for each protist genus and *Symbiodinium* clade (Figure 5). We found that coccidians and *Symbiodinium* clade D and A were linked to Djibouti, whereas *Licnophora* and *Symbiodinium* clade C were mostly associated with New Caledonia.

DISCUSSION

Efficiency of Blocking Primers

First, a very high specificity was obtained *in silico* for both blocking primers. In accordance with sequence entropy values (Supplementary Figure 1), all Scleractinia from the Silva database were expected to be blocked for 18SV1V2, and we found that ~94% of them were targeted by the blocking primers of 18SV4. Although both blocking primers matched with

Pocillopora sequences, we observed various efficiencies for the different samples from Djibouti and New Caledonia. On average *Pocillopora* still represented 70% (from 30 to 92%) and 39% (from 7 to 66%) of sequences for 18SV1V2 and 18SV4, respectively. Such variations were also described for artificial rDNA mixtures of algae and krill (between 26 and 42% of krill sequences were not blocked by blocking primers) (Vestheim and Jarman, 2008), and for gut content of fish (between 14 and 45% of sequences were not blocked by blocking primers) (Leray et al., 2013). These variations might be related to (i) the ratio between host and total sequences (Vestheim and Jarman, 2008), (ii) the ratio between blocking primers and targeted primer set concentrations (Vestheim and Jarman, 2008), and (iii) the complexity of samples for sequence composition, *i.e.*, taxa diversity.

For environmental samples, the description of protist diversity might be improved by increasing the sequencing depth. In this exploratory study, we limited the number of sequences to an average of 60,000 per sample before the cleaning steps. One might also design blocking primers for *Symbiodinium* to increase the proportion of others protists. However, such an approach might fail if blocking primers for *Symbiodinium* and Scleractinia form primer dimers, and further if blocking primers for *Symbiodinium* target other closely related Suessiales or even alveolates. Indeed, other alveolates were previously identified in coral tissues (Moore et al., 2008).

18SV1V2 Is a More Suitable Marker Than 18SV4 to Explore Protist Diversity Within Corals

Protist diversity was mostly described using 18S rRNA and ITS2 markers in marine environments. While the 18S rRNA gene was effective to study the diversity of a wide phylogenetic range of taxa within a sample (Viprey et al., 2008; Bik et al., 2012; de Vargas et al., 2015; Tragin et al., 2016), ITS were more appropriate for closely related taxa (Arif et al., 2014; Su et al., 2017). Because ITS polymorphism is high, it offers a higher resolution than the 18S rRNA gene.

To date, ITS2 has been one of the most common markers used to describe *Symbiodinium* diversity (LaJeunesse et al., 2010; Wicks et al., 2010; Silverstein et al., 2011; Putnam et al., 2012; Tonk et al., 2013), because it provides enough resolution to describe *Symbiodinium* diversity within clades (LaJeunesse, 2002; Thornhill et al., 2017). In this study, we used two 18S rRNA markers to describe phylogenetically distant taxa, but the comparison of phylogenetic signals for *Symbiodinium* showed that 18SV1V2 was more congruent with ITS2 than 18SV4. This difference might explain why we easily annotated all environmental *Symbiodinium* for 18SV1V2 compared to 18SV4. In addition, the diversity of protist genera was more even for 18SV1V2 than for 18SV4, as *Symbiodinium* and *Licnophora* represented a lower proportion of protists using 18SV1V2.

Overall, in comparison to 18SV4, blocking primers and the primer set for 18SV1V2 showed a better phylogenetic signal for *Symbiodinium*, and a more even representation of protist diversity. Based on our findings, we recommend the use of 18SV1V2 to study protists associated with coral colonies.

Different Distributions Between *Symbiodinium* Clade C and A/D

Because of the advantages of 18SV1V2 and because we obtained sequences for protists other than *Symbiodinium*, we focused our analyses on this marker to study the distribution of protist genera and *Symbiodinium* clades within the different samples.

In order to describe *Symbiodinium* diversity, we looked for reference sequences of the different clades that matched with 18SV1V2 and 18SV4. However, since ITS2 was the most common marker used so far, only representative sequences of clades A, B, C, D, and G were found. Unfortunately, although clade F was sometimes identified in Scleractinia (LaJeunesse, 2001; Rodriguez-Lanetty et al., 2003; Pochon et al., 2006), we were not able to use this clade to annotate environmental sequences. Clade G was described in other Anthozoa (Van Oppen et al., 2005; Bo et al., 2011), but not in scleractinian corals so far, thus it was not surprising that sequences of this clade were absent from our dataset. In contrast, clades A, C, D were the most common. In particular, clade C was dominant in New Caledonia, whereas clades D and A were mainly found in Djibouti. This result was similar to the analysis of the same samples using ITS2 (Brenner-Raffalli et al., 2018). Thus, 18SV1V2 not only had a similar phylogenetic signal to ITS2, but also offered similar community composition for *Symbiodinium*.

Coccidians and *Licnophora* Were the Two Other Main Taxa Within *P. damicornis*

Although eukaryotic microborers were common in coral colonies (Tribollet, 2008b; Pica et al., 2016), we did not find any of them in our samples. However, even though boring microflora inhabited live and dead corals, they were more abundant in the latter ones (Le Campion-Alsumard et al., 1995; Tribollet and Payri, 2001; Tribollet, 2008a). Moreover, in this study we did not crush coral skeleton (*i.e.*, where microborers inhabited), but instead, we extracted DNA from coral tissue. Similar to previous studies, we identified many Stramenopiles (Kramarsky-Winter et al., 2006; Harel et al., 2008; Siboni et al., 2010), and in particular different Bacillariophyta. Among them, the genus *Navicula* was present in one sample and was already isolated from the soft coral *Dendronephthya* (Hutagalung et al., 2014). We also found many fungi from the family Agaricomycetes (class Basidiomycota). Despite being a terrestrial mushroom-forming fungi (Hibbett, 2007), this family was already identified in many marine samples, from deep-sea sediments to oxygen-deficient environments, as well as within *Acropora hyacinthus* coral colonies (Amend et al., 2012). Many studies highlighted the presence of fungi in coral tissues: they were very diverse, and might be parasites, commensalists, and possibly mutualists that participated in nitrogen recycling (Wegley et al., 2007; Amend et al., 2012).

Furthermore, our samples contained many alveolates from divisions Dinophyta, Apicomplexa and Ciliophora. In particular, *Licnophora* (ciliates) and unidentified coccidia genera were the most common genera after *Symbiodinium* in *P. damicornis* colonies. Both ciliates and coccidians were already observed

in coral samples using low-throughput methods, such as microscopy and culture, and they were mainly associated with coral diseases (Upton and Peters, 1986; Sweet and Bythell, 2012; Sweet et al., 2013; Sweet and Séré, 2016). However, the presence of *Licnophora* together with disease were possibly indirect, *i.e.*, resulting from a microbiota dysbiosis, since they are known to feed others protozoa (Sweet and Séré, 2016). Moreover, coccidians were also found within healthy coral colonies of *A. agaricita*, *A. tenuifolia*, *F. fragum*, *M. annularis*, *M. faveolata*, *M. ferox*, *P. astreoides*, and *S. siderea* (Toller et al., 2002; Kirk et al., 2013; Šlapeta and Linares, 2013). In this study, corals did not show any outward signs of pathology, suggesting that these genera might be commensalists or mutualists. Interestingly, coccidian sequences of this study were very similar to the other coral-associated coccidians, and these sequences formed a robust monophyletic clade within Apicomplexa. This observation suggested that a speciation event of coccidians was linked to interactions with corals. Future studies should test the role of coccidians in coral holobionts. For example, it would be interesting to know whether these coccidians have retained a relict or a functional plastid like the coral-associated chromerids (Janouškovec et al., 2012).

Finally, *Licnophora* and coccidians had different distributions within our samples from Djibouti and New Caledonia. Similarly to *Symbiodinium* clades, geographic locations, *Pocillopora* clades and thermal regimes might influence their distribution. However, because of our sampling strategy, it was not possible to identify the factors responsible for this pattern.

To conclude, we designed two blocking primers to characterize protist diversity using high-throughput amplicon sequencing for the first time within coral colonies. We were able to characterize the diversity of *Symbiodinium* and of other less known genera associated with *P. damicornis sensu lato*. Among them, *Licnophora* and unidentified coccidia genera were common in coral samples from Djibouti and New Caledonia. In particular, coccidian sequences were phylogenetically related to coccidians described in other scleractinian coral species. Furthermore, different distributions were highlighted between *Licnophora* and coccidians, and between *Symbiodinium* clades C and A/D. Because the dataset was limited to two geographic regions, we did not know the respective influence of geography, *P. damicornis* clades or thermal regimes on protist assemblages. Moreover, we could not confirm that *Licnophora* and coccidians were part of the coral holobiont, and not simply just a part of

the larger environmental microbial community. Notably, future studies should decipher if they serve a specific function within the holobiont. However, we believe that these blocking primers are promising tools to bring new knowledge and understanding of the diversity and distribution of protists within *P. damicornis* colonies, as well as for other species of corals, as they were designed to target most Scleractinia.

AUTHOR CONTRIBUTIONS

CC, J-ME, and ET conceived the project. SB and PL designed the experimental protocol to test blocking primers. JV-D and MA were involved in the collection of samples and data acquisition. CC, LG, and ET performed the analyses. CC drafted the manuscript. All authors contributed to critical revisions and approved the final manuscript.

FUNDING

CC benefited of post-doctoral fellowships from CNRS and IFREMER. This work was supported by the French National Research Agency ANR, project ANR-14-CE19-0023 DECIPHER (coordinator G. Mitta), Campus France PHC Hubert Curien program Maïmonide-Israel, and by the DHOF program of the UMR5244/IHPE (<http://ihpe.univ-perp.fr/en/ihpe-transversal-holobiont/>).

ACKNOWLEDGMENTS

We thank Lorenzo Bramanti for help in collecting corals from Djibouti, and IHPE members for stimulating discussions. We are grateful to the genotoul bioinformatics platform Toulouse Midi-Pyrenees and Sigenae group for providing help and computing resources thanks to Galaxy instance <http://sigenae-workbench.toulouse.inra.fr>.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmicb.2018.02043/full#supplementary-material>

REFERENCES

- Adjeroud, M., Guérécheau, A., Vidal-Dupiol, J., Flot, J.-F., Arnaud-Haond, S., and Bonhomme, F. (2014). Genetic diversity, clonality and connectivity in the scleractinian coral *Pocillopora damicornis*: a multi-scale analysis in an insular, fragmented reef system. *Mar. Biol.* 161, 531–541. doi: 10.1007/s00227-013-2355-9
- Ainsworth, T. D., Fordyce, A. J., and Camp, E. F. (2017). The other microeukaryotes of the coral reef microbiome. *Trends Microbiol.* 25, 980–991. doi: 10.1016/j.tim.2017.06.007
- Ainsworth, T. D., Krause, L., Bridge, T., Torda, G., Raina, J.-B., Zakrzewski, M., et al. (2015). The coral core microbiome identifies rare bacterial taxa as ubiquitous endosymbionts. *ISME J.* 9, 2261–2274. doi: 10.1038/ismej.2015.39
- Amend, A. S., Barshis, D. J., and Oliver, T. A. (2012). Coral-associated marine fungi form novel lineages and heterogeneous assemblages. *ISME J.* 6, 1291–1301. doi: 10.1038/ismej.2011.193
- Arif, C., Daniels, C., Bayer, T., Banguera-Hinestroza, E., Barbrook, A., Howe, C. J., et al. (2014). Assessing *Symbiodinium* diversity in scleractinian corals via next-generation sequencing-based genotyping of the ITS2 rDNA region. *Mol. Ecol.* 23, 4418–4433. doi: 10.1111/mec.12869
- Bayer, T., Neave, M. J., Alsheikh-Hussain, A., Aranda, M., Yum, L. K., Mincer, T., et al. (2013). The microbiome of the Red Sea coral *Stylophora pistillata* is dominated by tissue-associated Endozoicomonas bacteria. *Appl. Environ. Microbiol.* 79, 4759–4762. doi: 10.1128/AEM.00695-13
- Bik, H. M., Sung, W., De Ley, P., Baldwin, J. G., Sharma, J., Rocha-Olivares, A., et al. (2012). Metagenetic community analysis of microbial eukaryotes illuminates

- biogeographic patterns in deep-sea and shallow water sediments. *Mol. Ecol.* 21, 1048–1059. doi: 10.1111/j.1365-294X.2011.05297.x
- Bo, M., Baker, A., Gaino, E., Wirshing, H., Scoccia, F., and Bavestrello, G. (2011). First description of algal mutualistic endosymbiosis in a black coral (Anthozoa: Antipatharia). *Mar. Ecol. Prog. Ser.* 435, 1–11. doi: 10.3354/meps09228
- Brener-Raffalli, K., Clerissi, C., Vidal-Dupiol, J., Adjeroud, M., Bonhomme, F., Pralong, M., et al. (2018). Thermal regime and host clade, rather than geography, drive *Symbiodinium* and bacterial assemblages in the scleractinian coral *Pocillopora damicornis* sensu lato. *Microbiome* 6:39. doi: 10.1186/s40168-018-0423-6
- Coffroth, M. A., and Santos, S. R. (2005). Genetic diversity of symbiotic dinoflagellates in the genus *Symbiodinium*. *Protist* 156, 19–34. doi: 10.1016/j.protis.2005.02.004
- de Vargas, C., Audic, S., Henry, N., Decelle, J., Mahé, F., Logares, R., et al. (2015). Eukaryotic plankton diversity in the sunlit ocean. *Science* 348:1261605. doi: 10.1126/science.1261605
- Edgar, R. C. (2004). MUSCLE: multiple sequence alignment with high accuracy and high throughput. *Nucleic Acids Res.* 32, 1792–1797. doi: 10.1093/nar/gkh340
- Escudé, F., Auer, L., Bernard, M., Mariadassou, M., Cauquil, L., Vidal, K., et al. (2017). FROGS: find, rapidly, OTUs with galaxy solution. *Bioinformatics* 34, 1287–1294. doi: 10.1093/bioinformatics/btx791
- Guillou, L., Bachar, D., Audic, S., Bass, D., Berney, C., Bittner, L., et al. (2012). The protist ribosomal reference database (PR2): a catalog of unicellular eukaryote Small Sub-Unit rRNA sequences with curated taxonomy. *Nucleic Acids Res.* 41, D597–D604. doi: 10.1093/nar/gks1160
- Harel, M., Ben-Dov, E., Rasoulouniriana, D., Siboni, N., Kramarsky-Winter, E., Loya, Y., et al. (2008). A new Thraustochytrid, strain Fng1, isolated from the surface mucus of the hermatypic coral *Fungia granulosa*. *FEMS Microbiol. Ecol.* 64, 378–387. doi: 10.1111/j.1574-6941.2008.00464.x
- Hibbett, D. S. (2007). After the gold rush, or before the flood? Evolutionary morphology of mushroom-forming fungi (Agaricomycetes) in the early 21st century. *Mycol. Res.* 111, 1001–1018. doi: 10.1016/j.mycres.2007.01.012
- Hutagalung, R. A., Sukoco, A. E., Soedharma, D., Goreti, L. M., Andean, I., Elshaddai, B., et al. (2014). Isolation, identification and growth optimization of microalgae derived from soft coral *Dendronephthya* sp. *APCBEE Proc.* 10, 305–310. doi: 10.1016/j.apcbee.2014.10.057
- Janoušková, J., Horák, A., Barott, K. L., Rohwer, F. L., and Keeling, P. J. (2012). Global analysis of plastid diversity reveals apicomplexan-related lineages in coral reefs. *Curr. Biol.* 22, R518–R519. doi: 10.1016/j.cub.2012.04.047
- Katoh, K., Misawa, K., Kuma, K., and Miyata, T. (2002). MAFFT: a novel method for rapid multiple sequence alignment based on fast Fourier transform. *Nucleic Acids Res.* 30, 3059–3066. doi: 10.1093/nar/gkf436
- Kirk, N. L., Thornhill, D. J., Kemp, D. W., Fitt, W. K., and Santos, S. R. (2013). Ubiquitous associations and a peak fall prevalence between apicomplexan symbionts and reef corals in Florida and the Bahamas. *Coral Reefs* 32, 847–858. doi: 10.1007/s00338-013-1038-9
- Kramarsky-Winter, E., Harel, M., Siboni, N., Dov, E. B., Brickner, I., Loya, Y., et al. (2006). Identification of a protist-coral association and its possible ecological role. *Mar. Ecol. Prog. Ser.* 317, 67–73. doi: 10.3354/meps317067
- Lajeunesse, T. C. (2001). Investigating the biodiversity, ecology, and phylogeny of endosymbiotic dinoflagellates in the genus *Symbiodinium* using the ITS region: in search of a “species” level marker. *J. Phycol.* 37, 866–880. doi: 10.1046/j.1529-8817.2001.01031.x
- Lajeunesse, T. C. (2002). Diversity and community structure of symbiotic dinoflagellates from Caribbean coral reefs. *Mar. Biol.* 141, 387–400. doi: 10.1007/s00227-002-0829-2
- Lajeunesse, T. C., Pettay, D. T., Sampayo, E. M., Phongsuwan, N., Brown, B., Obura, D. O., et al. (2010). Long-standing environmental conditions, geographic isolation and host-symbiont specificity influence the relative ecological dominance and genetic diversification of coral endosymbionts in the genus *Symbiodinium*. *J. Biogeogr.* 37, 785–800. doi: 10.1111/j.1365-2699.2010.02273.x
- Le Campion-Alsumard, T., Golubic, S., and Hutchings, P. (1995). Microbial endoliths in skeletons of live and dead corals: *Porites lobata* (Moorea, French Polynesia). *Mar. Ecol. Prog. Ser.* 117, 149–157. doi: 10.3354/meps117149
- Leray, M., Agudelo, N., Mills, S. C., and Meyer, C. P. (2013). Effectiveness of annealing blocking primers versus restriction enzymes for characterization of generalist diets: unexpected prey revealed in the gut contents of two coral reef fish species. *PLoS One* 8:e58076. doi: 10.1371/journal.pone.0058076
- Magoc, T., and Salzberg, S. L. (2011). FLASH: fast length adjustment of short reads to improve genome assemblies. *Bioinformatics* 27, 2957–2963. doi: 10.1093/bioinformatics/btr507
- Mahé, F., Rognes, T., Quince, C., de Vargas, C., and Dunthorn, M. (2015). Swarm v2: highly-scalable and high-resolution amplicon clustering. *PeerJ* 3:e1420. doi: 10.7717/peerj.1420
- Mantel, N. (1967). The detection of disease clustering and a generalized regression approach. *Cancer Res.* 27, 209.
- Martin, M. (2011). Cutadapt removes adapter sequences from high-throughput sequencing reads. *EMBnet J.* 17:10. doi: 10.14806/ej.17.1.200
- McDevitt-Irwin, J. M., Baum, J. K., Garren, M., and Vega Thurber, R. L. (2017). Responses of coral-associated bacterial communities to local and global stressors. *Front. Mar. Sci.* 4:262. doi: 10.3389/fmars.2017.00262
- McMurdie, P. J., and Holmes, S. (2013). phyloseq: an R package for reproducible interactive analysis and graphics of microbiome census data. *PLoS One* 8:e61217. doi: 10.1371/journal.pone.0061217
- Minh, B. Q., Nguyen, M. A. T., and von Haeseler, A. (2013). Ultrafast approximation for phylogenetic bootstrap. *Mol. Biol. Evol.* 30, 1188–1195. doi: 10.1093/molbev/mst024
- Mohamed, A. R., Cumbo, V. R., Harii, S., Shinzato, C., Chan, C. X., Ragan, M. A., et al. (2018). Deciphering the nature of the coral–Chromera association. *ISME J.* 12, 776–790. doi: 10.1038/s41396-017-0005-9
- Moore, R. B., Oborník, M., Janoušková, J., Chrudimský, T., Vancová, M., Green, D. H., et al. (2008). A photosynthetic alveolate closely related to apicomplexan parasites. *Nature* 451, 959–963. doi: 10.1038/nature06635
- Neave, M. J., Apprill, A., Ferrier-Pagès, C., and Voolstra, C. R. (2016). Diversity and function of prevalent symbiotic marine bacteria in the genus *Endozoicomonas*. *Appl. Microbiol. Biotechnol.* 100, 8315–8324. doi: 10.1007/s00253-016-7777-0
- Neave, M. J., Rachmawati, R., Xun, L., Michell, C. T., Bourne, D. G., Apprill, A., et al. (2017). Differential specificity between closely related corals and abundant *Endozoicomonas* endosymbionts across global scales. *ISME J.* 11, 186–200. doi: 10.1038/ismej.2016.95
- Nguyen, L.-T., Schmidt, H. A., von Haeseler, A., and Minh, B. Q. (2015). IQ-TREE: a fast and effective stochastic algorithm for estimating maximum-likelihood phylogenies. *Mol. Biol. Evol.* 32, 268–274. doi: 10.1093/molbev/msu300
- Peixoto, R. S., Rosado, P. M., Leite, D. C., Rosado, A. S., and Bourne, D. G. (2017). Beneficial microorganisms for corals (BMC): proposed mechanisms for coral health and resilience. *Front. Microbiol.* 8:341. doi: 10.3389/fmicb.2017.00341
- Pica, D., Tribollet, A., Golubic, S., Bo, M., Di Camillo, C. G., Bavestrello, G., et al. (2016). Microboring organisms in living stylasterid corals (Cnidaria, Hydrozoa). *Mar. Biol. Res.* 12, 573–582. doi: 10.1080/17451000.2016.1169298
- Pochon, X., Montoya-Burgos, J. I., Stadelmann, B., and Pawlowski, J. (2006). Molecular phylogeny, evolutionary rates, and divergence timing of the symbiotic dinoflagellate genus *Symbiodinium*. *Mol. Phylogenet. Evol.* 38, 20–30. doi: 10.1016/j.ympev.2005.04.028
- Price, M. N., Dehal, P. S., and Arkin, A. P. (2010). FastTree 2—approximately maximum-likelihood trees for large alignments. *PLoS One* 5:e9490. doi: 10.1371/journal.pone.0009490
- Putnam, H. M., Stat, M., Pochon, X., and Gates, R. D. (2012). Endosymbiotic flexibility associates with environmental sensitivity in scleractinian corals. *Proc. R. Soc. B Biol. Sci.* 279, 4352–4361. doi: 10.1098/rspb.2012.1454
- Quast, C., Pruesse, E., Yilmaz, P., Gerken, J., Schweer, T., Yarza, P., et al. (2013). The SILVA ribosomal RNA gene database project: improved data processing and web-based tools. *Nucleic Acids Res.* 41, D590–D596. doi: 10.1093/nar/gks1219
- Quigley, K. M., Davies, S. W., Kenkel, C. D., Willis, B. L., Matz, M. V., and Bay, L. K. (2014). Deep-sequencing method for quantifying background abundances of *Symbiodinium* types: exploring the rare *Symbiodinium* biosphere in reef-building corals. *PLoS One* 9:e94297. doi: 10.1371/journal.pone.0094297
- R Core Team (2018). *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing. available at: <http://www.R-project.org>
- Ramette, A., and Buttigieg, P. L. (2014). The R package otu2ot for implementing the entropy decomposition of nucleotide variation in sequence data. *Front. Microbiol.* 5:601. doi: 10.3389/fmicb.2014.00601

- Ritchie, K. B. (2006). Regulation of microbial populations by coral surface mucus and mucus-associated bacteria. *Mar. Ecol. Prog. Ser.* 322, 1–14. doi: 10.3354/meps322001
- Rodriguez-Lanetty, M., Chang, S.-J., and Song, J.-I. (2003). Specificity of two temperate dinoflagellate-anthozoan associations from the north-western Pacific Ocean. *Mar. Biol.* 143, 1193–1199. doi: 10.1007/s00227-003-1165-x
- Rognes, T., Flouri, T., Nichols, B., Quince, C., and Mahé, F. (2016). VSEARCH: a versatile open source tool for metagenomics. *PeerJ* 4:e2584. doi: 10.7717/peerj.2584
- Rohwer, F., Seguritan, V., Azam, F., and Knowlton, N. (2002). Diversity and distribution of coral-associated bacteria. *Mar. Ecol. Prog. Ser.* 243, 1–10. doi: 10.3354/meps243001
- Schloss, P. D., Westcott, S. L., Ryabin, T., Hall, J. R., Hartmann, M., Hollister, E. B., et al. (2009). Introducing mothur: open-source, platform-independent, community-supported software for describing and comparing microbial communities. *Appl. Environ. Microbiol.* 75, 7537–7541. doi: 10.1128/AEM.01541-09
- Schrével, J., Valigurová, A., Prensier, G., Chambouvet, A., Florent, I., and Guillou, L. (2016). Ultrastructure of *Selenidium pendula*, the type species of archigregarines, and phylogenetic relations to other marine Apicomplexa. *Protist* 167, 339–368. doi: 10.1016/j.protis.2016.06.001
- Shnit-Orland, M., and Kushmaro, A. (2009). Coral mucus-associated bacteria: a possible first line of defense. *FEMS Microbiol. Ecol.* 67, 371–380. doi: 10.1111/j.1574-6941.2008.00644.x
- Siboni, N., Rasoulouniriana, D., Ben-Dov, E., Kramarsky-Winter, E., Sivan, A., Loya, Y., et al. (2010). Stramenopile microorganisms associated with the massive coral *Favia* sp. *J. Eukaryot. Microbiol.* 57, 236–244. doi: 10.1111/j.1550-7408.2010.00469.x
- Silverstein, R., Correa, A., LaJeunesse, T., and Baker, A. (2011). Novel algal symbiont (*Symbiodinium* spp.) diversity in reef corals of Western Australia. *Mar. Ecol. Prog. Ser.* 422, 63–75. doi: 10.3354/meps08934
- Šlapeta, J., and Linares, M. C. (2013). Combined amplicon pyrosequencing assays reveal presence of the Apicomplexan “type-N” (cf. *Gemmocystis cylindrus*) and *Chromera velia* on the Great Barrier Reef, Australia. *PLoS One* 8:e76095. doi: 10.1371/journal.pone.0076095
- Stoeck, T., Bass, D., Nebel, M., Christen, R., Jones, M. D., Breiner, H. W., et al. (2010). Multiple marker parallel tag environmental DNA sequencing reveals a highly complex eukaryotic community in marine anoxic water. *Mol. Ecol.* 19, 21–31. doi: 10.1111/j.1365-294X.2009.04480.x
- Su, L., Zhang, Q., and Gong, J. (2017). Development and evaluation of specific PCR primers targeting the ribosomal DNA-internal transcribed spacer (ITS) region of peritrich ciliates in environmental samples. *Chin. J. Oceanol. Limnol.* 36, 818–826. doi: 10.1007/s00343-018-6326-3
- Sweet, M., and Bythell, J. (2012). Ciliate and bacterial communities associated with White syndrome and brown band disease in reef-building corals. *Environ. Microbiol.* 14, 2184–2199. doi: 10.1111/j.1462-2920.2012.02746.x
- Sweet, M. J., Craggs, J., Robson, J., and Bythell, J. C. (2013). Assessment of the microbial communities associated with white syndrome and brown jelly syndrome in aquarium corals. *J. Zoo Aquar. Res.* 1, 20–27.
- Sweet, M. J., and Séré, M. G. (2016). Ciliate communities consistently associated with coral diseases. *J. Sea Res.* 113, 119–131. doi: 10.1016/j.seares.2015.06.008
- Tan, S., and Liu, H. (2018). Unravel the hidden protistan diversity: application of blocking primers to suppress PCR amplification of metazoan DNA. *Appl. Microbiol. Biotechnol.* 102, 389–401. doi: 10.1007/s00253-017-8565-1
- Theis, K. R., Dheilly, N. M., Klassen, J. L., Brucker, R. M., Baines, J. F., Bosch, T. C. G., et al. (2016). Getting the hologenome concept right: an eco-evolutionary framework for hosts and their microbiomes. *mSystems* 1:e28-16. doi: 10.1128/mSystems.00028-16
- Thingstad, T. F., Bellerby, R. G. J., Bratbak, G., Børsheim, K. Y., Egge, J. K., Heldal, M., et al. (2008). Counterintuitive carbon-to-nutrient coupling in an Arctic pelagic ecosystem. *Nature* 455, 387–390. doi: 10.1038/nature07235
- Thornhill, D. J., Howells, E. J., Wham, D. C., Steury, T. D., and Santos, S. R. (2017). Population genetics of reef coral endosymbionts (*Symbiodinium*, Dinophyceae). *Mol. Ecol.* 26, 2640–2659. doi: 10.1111/mec.14055
- Thurber, R. V., Payet, J. P., Thurber, A. R., and Correa, A. M. S. (2017). Virus–host interactions and their roles in coral reef health and disease. *Nat. Rev. Microbiol.* 15, 205–2016. doi: 10.1038/nrmicro.2016.176
- Toller, W., Rowan, R., and Knowlton, N. (2002). Genetic evidence for a protozoan (phylum Apicomplexa) associated with corals of the *Montastraea annularis* species complex. *Coral Reefs* 21, 143–146.
- Tonk, L., Bongaerts, P., Sampayo, E. M., and Hoegh-Guldberg, O. (2013). SymbioGBR: a web-based database of *Symbiodinium* associated with cnidarian hosts on the Great Barrier Reef. *BMC Ecol.* 13:7. doi: 10.1186/1472-6785-13-7
- Tragin, M., Lopes, dos Santos, A., Christen, R., and Vaout, D. (2016). Diversity and ecology of green microalgae in marine systems: an overview based on 18S rRNA gene sequences. *Perspect. Phycol.* 3, 141–154. doi: 10.1127/pip/2016/0059
- Tribollet, A. (2008a). Dissolution of dead corals by euendolithic microorganisms across the Northern Great Barrier Reef (Australia). *Microb. Ecol.* 55, 569–580. doi: 10.1007/s00248-007-9302-6
- Tribollet, A. (2008b). “The boring microflora in modern coral reef ecosystems: a review of its roles,” in *Current Developments in Bioerosion Erlangen Earth Conference Series*, eds M. Wisshak and L. Tapanila (Berlin: Springer), 67–94.
- Tribollet, A., and Payri, C. (2001). Bioerosion of the coralline alga hydroolithon onkodes by microborers in the coral reefs of Moorea, French polynesia. *Oceanol. Acta* 24, 329–342. doi: 10.1016/S0399-1784(01)01150-1
- Upton, S. J., and Peters, E. C. (1986). A new and unusual species of coccidium (Apicomplexa: Agamococcidiorida) from Caribbean scleractinian corals. *J. Invertebr. Pathol.* 47, 184–193. doi: 10.1016/0022-2011(86)90045-5
- Van Oppen, M. J. H., Mieog, J. C., Sanchez, C. A., and Fabricius, K. E. (2005). Diversity of algal endosymbionts (zooxanthellae) in octocorals: the roles of geography and host relationships. *Mol. Ecol.* 14, 2403–2417. doi: 10.1111/j.1365-294X.2005.02545.x
- Vestheim, H., and Jarman, S. N. (2008). Blocking primers to enhance PCR amplification of rare sequences in mixed samples – A case study on prey DNA in Antarctic krill stomachs. *Front. Zool.* 5:12. doi: 10.1186/1742-9994-5-12
- Viprey, M., Guillou, L., Ferréol, M., and Vaout, D. (2008). Wide genetic diversity of picoplanktonic green algae (Chloroplastida) in the Mediterranean Sea uncovered by a phylum-biased PCR approach. *Environ. Microbiol.* 10, 1804–1822. doi: 10.1111/j.1462-2920.2008.01602.x
- Wegley, L., Edwards, R., Rodriguez-Brito, B., Liu, H., and Rohwer, F. (2007). Metagenomic analysis of the microbial community associated with the coral *Porites astreoides*. *Environ. Microbiol.* 9, 2707–2719. doi: 10.1111/j.1462-2920.2007.01383.x
- Wegley, L., Yu, Y., Breitbart, M., Casas, V., Kline, D. I., and Rohwer, F. (2004). Coral-associated archaea. *Mar. Ecol. Prog. Ser.* 273, 89–96. doi: 10.3354/meps273089
- Wicks, L. C., Sampayo, E., Gardner, J. P. A., and Davy, S. K. (2010). Local endemicity and high diversity characterise high-latitude coral–*Symbiodinium* partnerships. *Coral Reefs* 29, 989–1003. doi: 10.1007/s00338-010-0649-7
- Winnepenninckx, B., Backeljau, T., and Wachter, R. (1993). Extraction of high molecular weight DNA from molluscs. *Trends Genet.* 9:407. doi: 10.1016/0168-9525(93)90102-N
- Wuyts, J., De Rijk, P., Van de Peer, Y., Pison, G., Rousseeuw, P., and De Wachter, R. (2000). Comparative analysis of more than 3000 sequences reveals the existence of two pseudoknots in area V4 of eukaryotic small subunit ribosomal RNA. *Nucleic Acids Res.* 28, 4698–4708. doi: 10.1093/nar/28.23.4698
- Wuyts, J., Van de Peer, Y., Winkelmans, T., and De Wachter, R. (2002). The European database on small subunit ribosomal RNA. *Nucleic Acids Res.* 30, 183–185. doi: 10.1093/nar/30.1.183
- Yilmaz, P., Parfrey, L. W., Yarza, P., Gerken, J., Pruesse, E., Quast, C., et al. (2014). The SILVA and “All-species Living Tree Project (LTP)” taxonomic frameworks. *Nucleic Acids Res.* 42, D643–D648. doi: 10.1093/nar/gkt1209
- Ziegler, M., Seneca, F. O., Yum, L. K., Palumbi, S. R., and Voolstra, C. R. (2017). Bacterial community dynamics are linked to patterns of coral heat tolerance. *Nat. Commun.* 8:14213. doi: 10.1038/ncomms14213

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright © 2018 Clerissi, Brunet, Vidal-Dupiol, Adjérou, Lepage, Guillou, Escoubas and Toulza. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.