



HAL
open science

Reconstructing the dynamics of past coral endosymbiotic algae communities using coral ancient DNA (cora DNA)

Olivier Rey, Delphine Dissard, Eve Toulza, Thomas Guinebert, Mathilde Saccas, Jean-François Allienne, John Butsher, Mourad Bensalah Zoubir, G. Iwankow, Christelle Tougard, et al.

► To cite this version:

Olivier Rey, Delphine Dissard, Eve Toulza, Thomas Guinebert, Mathilde Saccas, et al.. Reconstructing the dynamics of past coral endosymbiotic algae communities using coral ancient DNA (cora DNA). 2024. hal-04650192

HAL Id: hal-04650192

<https://hal.science/hal-04650192>

Preprint submitted on 16 Jul 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

1 Reconstructing the dynamics of past coral
2 endosymbiotic algae communities using
3 coral ancient DNA (*coraDNA*)
4

5 Olivier Rey ¹, Delphine Dissard ², Eve Toulza ¹, Thomas Guinebert ³, Mathilde Saccas ³, Jean-
6 François Allienne ¹, John Butsher², Mourad BenSalah Zoubir ⁴, Iwankow G. ⁵, Christelle
7 Tougard ⁶, Jérémie Vidal-Dupiol ³

8
9 ¹ IHPE, Univ Montpellier, CNRS, IFREMER, Univ Perpignan Via Domitia, Perpignan, France

10 ² IRD/UMR LOCEAN (IRD-CNRS-MNHN-Sorbonne Université), Centre IRD de Nouméa,
11 101 Promenade Roger Laroque, Nouméa 98848, New Caledonia.

12 ³ IHPE, Univ. Montpellier, CNRS, IFREMER, Univ. Perpignan Via Domitia, Montpellier
13 France

14 ⁴ Radiology Department, Centre Hospitalier de Perpignan, Perpignan, France

15 ⁵ PSL Research University: EPHE - UPVD - CNRS, USR 3278 CRIOBE, 66860, Perpignan,
16 France

17 ⁶ ISEM, Université de Montpellier, CNRS, IRD, EPHE, Montpellier, France.

18

Abstract

19

20

Most scleractinian corals are drastically threatened due to global changes but some colonies are intriguingly resistant to heat stress. Coral thermal tolerance partly relies on genomic determinism among the cnidarian compartment but also on the physiology of their associated symbiotic algae (Symbiodiniaceae). In fact, some corals can shift and/or shuffle their associated Symbiodiniaceae communities to temporally cope with heat stress. So far coral adjustments of their endosymbiotic algae were mainly observed at short-term evolutionary time scales and we lack a general vision of coral holobiont evolution at broader timescales. We here combined the use of ancient DNA from a coral core and a metabarcoding approach, to retrace past Symbiodiniaceae communities associated with a living colony of *Porites lobata* from New Caledonia over the last century. We were able to extract ancient DNA along the coral core at 19 time points dating back to the 1870's. Overall, we detected 13 OTUs, nine of which were affiliated to the Symbiodiniaceae *Cladocopium* clade, one to *Azadinium spinosum* (Dinophyceae); one to the host *P. lobata*, the two other OTUs remained unidentified. One OTU was largely predominant and was ubiquitous over all samples. The number of OTUs was marginally correlated to the total number of sequences per sample but not to the age of the *coraDNA* sample. We found a generally stable core microbiota associated with *P. lobata*, although drastic change in community composition was observed in *coraDNA* samples corresponding to an extreme hot winter temperature event. More generally, this study paves the way for further investigations on the evolutionary dynamics of coral holobionts at the colony level over large temporal scales.

40

41

Keywords

42

Coral; Symbiodiniaceae; Ancient DNA; metabarcoding, *ITS2*

43

44 Introduction

45

46 Scleractinian corals and the associated reef ecosystems are among the most threatened
47 systems worldwide due to global changes. Almost half of all living corals have already been
48 destroyed in the last 150 years ¹. Such massive loss has accelerated over the last three decades
49 under the influence of extreme climatic events, in particular heat waves, the frequency of which
50 is steadily increasing ¹. Despite this alarming situation, coral colonies particularly resistant to
51 heat stress have been identified ²⁻⁴. These observations provide some hope for the maintenance
52 and/ or the restoration of corals and ecosystems they support. They also call for an urging need
53 to unravel the molecular mechanisms by which some coral colonies survive through time
54 despite recurrent events of environmental stresses and help adjust conservation plans. This task
55 is all but trivial in particular because corals are complex holobionts composed of cnidarians
56 associated with microbial communities including – among others – endosymbiotic algae
57 (Symbiodiniaceae), protista and bacteria, each of these partners potentially influencing the
58 thermotolerance of the colonies ^{5,6}.

59 Variation in coral thermal tolerance across latitude, at least partly relies on genomic
60 variation among the cnidarian compartment of coral colonies ⁷. In this respect, it has been
61 suggested that resistant genotypes could emerge through intrinsic rapid genomic changes such
62 as somatic mutations ⁸, the activation of transposable elements ⁹ and/ or some modifications in
63 the proportions of genotypes coexisting within the same colony ^{10,11}. Additionally to genomic
64 modifications, changes in DNA methylation patterns in cnidarians may also induce – at least
65 temporarily – adaptive phenotypic adjustments in coral colonies exposed to recurrent heat stress
66 ^{12,13}. Besides changes within the cnidarian compartments, coral thermal tolerance also depends
67 on the physiology of their associated symbiotic algae (Symbiodiniaceae), with which they form
68 a phototrophic mutualistic symbiosis ^{14,15}. Symbiodiniaceae constitute a highly diversified
69 taxonomic group among which the identified species and even strains among species display
70 huge variation in thermal tolerance ^{16,17}. Recently, a laboratory experiment has shown that
71 experimentally adapted strains of the Symbiodiniaceae *Cladocopium goreau* to high
72 temperature, provide a better protection to heat stress in *Acropora tenuis* colonies after
73 reimplantation ¹⁸. This suggests that thermal tolerance may be acquired rapidly by natural coral
74 colonies *via* the acquisition of acclimatized or adapted Symbiodiniaceae from the surrounding
75 environment in response to heat stress. In fact, symbiont switching – the acquisition of new
76 (thermally resistant) species/strain from the environment – and symbiont shuffling – the
77 modification of the relative abundance of the inner Symbiodiniaceae strains within host –

78 constitute two alternative rapid responses for corals to temporarily cope with heat waves^{19,20}.
79 Finally, while other partners involved within the coral holobiont such as bacteria, fungi, viruses
80 and protists, certainly display higher adaptive capacity than corals in particular due to their short
81 generation time, their role in fostering adaptive response to heat stress at the holobiont scale
82 still remain to be demonstrated^{5,13,21}.

83 Most of our knowledge on the mechanisms underlying the adaptive response of coral
84 colonies to global changes relies on empirical studies based on controlled experiments
85 conducted either in laboratory or in the field, over extremely short-term evolutionary time
86 scales. These approaches are crucial to dissect the relative importance of specific molecular
87 mechanisms in action to foster coral responses. They have dramatically changed our vision on
88 the short-term adaptive capacity of corals^{12,13}. However, and complementary to these
89 approaches, we need a more general vision of coral holobiont evolution at broader timescales
90 to assess their evolutionary dynamics in response to the recent fast evolving environmental
91 changes. In this respect, ancient DNA (aDNA) based approaches are promising²². These
92 approaches generally rely on DNA extracted from archaeological or paleontological remains or
93 from museum samples. For instance, museum samples of 8 octocoral species originally
94 collected from successive epochs revealed that mutualism between several coral species and
95 their associated Symbiodiniaceae remained stable overtime with no major changes in the last
96 two centuries despite major anthropogenic global change²³. In a more general context of
97 biodiversity, aDNA was also applied to reconstruct the community assemblages of reef
98 ecosystems from sediment cores^{24,25}. Surprisingly however, no attempts were made to extract
99 aDNA directly from cores excavated from a living massive coral colony that chronicles decades
100 and up to centuries, of its lifetime. Such an approach is particularly promising because it could
101 allow accessing the DNA material from individual holobiontic colonies over time and thus
102 reconstructing their intrinsic eco-evolutionary history.

103 We here provide the first proof of concept of the use of aDNA from a coral core,
104 hereafter called *coraDNA* (referring to the recent *sedaDNA* approach developed to study DNA
105 from sedimentary cores), to reconstruct past Symbiodiniaceae communities associated with a
106 living colony of *Porites lobata* over the last century. We discuss the benefit of such approach
107 to unravel the eco-evolutionary dynamics of coral holobiont and the current technical
108 limitations that will need to be bypassed to have access to DNA from the cnidarian compartment
109 and hence reconstruct the full eco-evolutionary trajectories of coral holobionts over time.

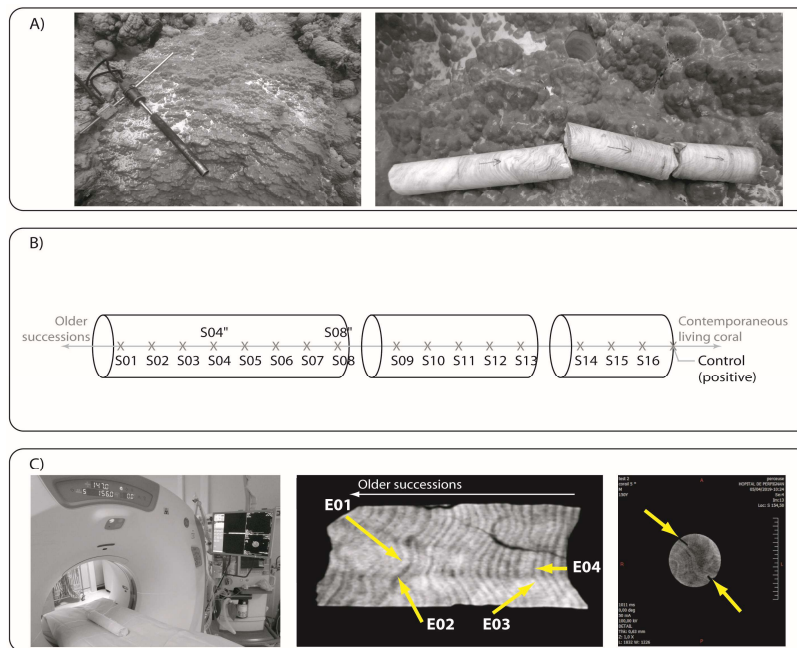
110

111 **Material and methods**

112

113 ***Core sampling***

114 *Porites lobata* is a massive reef-building scleractinian coral ubiquitous over the Tropical Pacific
115 Ocean. Colonies can be extremely long-lived (up to several centuries) and their growth strongly
116 depend on the environmental conditions in which they grow, especially seawater temperature
117 ²⁶. These characteristics make this species particularly suitable in the context of this study since
118 it makes it possible to obtain long cores and the marked seasonal successions of growth allow
119 the collection of core matrix at the year scale from which DNA can be extracted. A coral-matrix
120 core was collected from a 2.5-m high colony of *Porites lobata* at 10-m depth within the
121 Southern Lagoon of New Caledonia (22°17,146 et 166°11,004) the 17th of December 2018
122 (Figure 1.A.). The excavated 8-cm diameter and ~ 80-cm long core was immediately stored in
123 dry ice and transferred under freezing conditions to the Institute de Recherche pour le
124 Developpement (IRD) in Nouméa, prior being sent in dry ice to the IHPE laboratory in
125 Perpignan where it was stored at -80°C until subsequent analyses. Thus, the core has been kept
126 at -80°C from its initial excavation until the sampling of *coraDNA*.



127

128 **Figure 1:** Details on the coral core of the studied *Porites lobata* colony. Pictures of its excavation in
129 December 2018 from the living colony in New Caledonia are provided in (A). In (B), the *coraDNA*
130 samples that were extracted along the core are represented from the older sample (S01) to the
131 contemporaneous living coral (control). In (C) Pictures of the interventional sampling using a CT scan
132 of the four *coraDNA* samples corresponding to successions before (E01) and after (E02) the 1997-1998
133 ENSO event; and before (E03) and after (E04) the anormal hot winter in 2010. Yellow arrows in the
134 last panel in (C) point toward the hole left by the drilling bit after the sampling of the E04 *coraDNA*
135 sample.

136 ***Dating successions and sampling ancient DNA from the coral core***

137 The aging of the coral core was determined based on the counting of density bands as described
138 in Wu *et al.* ²⁷. Annual skeletal density bands were observed using a CT scan at the imagery
139 service of the public Hospital of Perpignan (France). The observed density bands result from
140 variation in colony growth rate during the winter (slow) and during the summer (rapid) that lead
141 to a more or less dense aragonite skeleton along the year ²⁶. According to this pattern, one year
142 was reconstructed by summing a clear (summer) and dark (winter) density bands ²⁷. Based on
143 the reconstructed chronology of the sampled coral colony, a total of 23 samples were collected
144 along the coral core (Figure 1.B and C). Briefly, each sampling location along the core was first
145 rapidly washed using a 10% NaClO solution and ~ 3 mm of the external layer was removed
146 from the core surface using a sterile disposable scalpel to avoid possible DNA contamination
147 with contemporaneous genomic material. Once the surface of the core was decontaminated, an
148 electric drill with an individualized sterile 2-mm diameter drill bit was used to extract core
149 powder along a ~ 1.5 – 2 cm depth drilling hole perpendicular to the surface of the core. The
150 bits containing the powder was immediately transferred and rinsed in a 2 ml Eppendorf
151 (DNA/RNA and DNase/RNase free tube) containing 1 ml of Tissue Lysis buffer ATL from the
152 QIAamp DNA Micro Kit (Qiagen) and stored at 4°C until the DNA extraction process (i.e. at
153 most 24 h later).

154 Sampling along the core was achieved following two strategies. The first strategy
155 consisted in systematically sampling every 5 cm along the core without accurate dating.
156 According to the retraced chronology and to the thickness of the observed density bands, such
157 strategy roughly corresponded to a sample collected every 8 to 10 years back in time over the
158 colony history from December 2018 (collection date) until the 1870's. A total of 17 *coraDNA*
159 samples were extracted following this design including one sample from the top of the coral
160 core (as positive control) which corresponds to the living colony at the time of the core sampling
161 (Sample S01 to S16 and control in Figure 1.B.). This strategy was used to specifically test our
162 ability to detect and obtain processable *coraDNA* samples over large timescales. Moreover,
163 two duplicates were sampled for two random samples (S04 and S08; Figure 1.B.). These
164 duplicates consisted in independent *coraDNA* samples obtained from the same section along
165 the core and using two independent sterile drill bits.

166 The second strategy aimed at studying the dynamics of the algae endosymbiotic
167 communities associated with coral colonies during well documented past extreme climatic
168 events. We targeted two well-known climatic anomalies that were easily observable along the
169 core in 2010 (abnormally hot winter) and in 1997-1998 which corresponded to a severe ENSO

170 event²⁷. Two samples were collected, one prior and the other after each of these two climatic
171 events (N = 4; Figure 1.C.). For this purpose, and to accurately sample the targeted coral
172 successions, the drilling procedure was achieved under interventional CT 3D scan at the
173 imagery services from the public Hospital of Perpignan. The coordinates of the targeted
174 successions were first retrieved, and the drilling sampling was achieved under interventional
175 scan to ensure that the same succession was sampled within the core during the sampling
176 process (Figure 1.C.). The precautions previously described were taken to avoid contamination
177 (treatment with bleached plus abrasion of the ~3 mm of the external layer of the core and a
178 unique sterile drill bit per sample).

179 Additionally to the overall 23 samples collected along the core, a negative control was
180 prepared at the time of the sampling collection to check for possible contaminations over the
181 whole process from DNA sampling to library preparation. This negative control was obtained
182 following the same protocol as described above except that the drill bit did not touch the core
183 prior to the rinsing step into the Tissue Lysis buffer ATL.

184

185 ***DNA extraction***

186 The overall DNA extraction process and DNA amplification steps were performed at the
187 degraded DNA platform (Institut des Sciences de l'Evolution de Montpellier, France;
188 <http://club.quomodo.com/plateforme-adn-degrade>) offering facilities dedicated to the study of
189 ancient DNA. DNA extractions were performed using the QIAamp DNA Micro Kit (Qiagen)
190 following the “*Purification of genomic DNA from bones*” protocol. Briefly, 25 µl of Qiagen
191 Proteinase K were added to each sample. Samples were then incubated at 56°C with shaking at
192 1200 rpm overnight. The day after, 1 ml of AL buffer was added and samples were incubated
193 at 70°C during 10 minutes to inactivate enzymes. After a centrifugation step at full speed during
194 one minute, the supernatant was transferred to a QIAamp MinElute column. Once the DNA
195 attached on the column membrane (centrifugation step at 8000 rpm for 1 minute), the membrane
196 was successively washed using 600 µl of the AW1 and the AW2 buffer. After these washing
197 steps, the membrane was dried by centrifugation during 3 minutes at full speed. The DNA was
198 eluted using 30 µL of sterile water. The eluted DNA samples were then stored at -20°C until
199 subsequent molecular processes. The quality of DNA extracts was assessed on a Bioanalyzer
200 High Sensitivity DNA kit (Agilent, USA) and DNA was quantified using a Qubit fluorometric
201 quantification with the ds DNA High Sensitivity assay kit (Thermo Fisher Scientific, USA).

202

203 **Library preparation and sequencing**

204 Each DNA sample was used as initial template for amplifying a portion of the *ITS2* gene using
205 a set of 4 primers derived from the literature ^{28,29} with Illumina adapters and spacers (Table 1).

206

ITS2-MiSeqNN-F: TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGNNGTGAATTGCAGAACTCCGTG
ITS2-MiSeqNN-R: GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGNNCCTCCGCTTACTTATATGCTT
ITS2-MiSeqNNN-F: TCGTCGGCAGCGTCAGATGTGTATAAGAGACAGNNGTGAATTGCAGAACTCCGTG
ITS2-MiSeqNNN-R: GTCTCGTGGGCTCGGAGATGTGTATAAGAGACAGNNCCTCCGCTTACTTATATGCTT

207 **Table 1:** Sequence of the 4 primers (including adapters and spacers) used to amplify a ~ 350
208 bp fragment of the *ITS2* gene

209

210 Concomitantly, the extraction negative control and a PCR negative control (consisting in
211 distilled water) were used in the same PCR reaction to control for potential contamination
212 during the overall process. PCRs were performed in 50 μ L containing 5 μ L of Buffer 10X PCR
213 Gold (1X), 5 μ L of MgCl₂ (25 mM), 1 μ L of each dNTPs (200 μ M), 1.35 μ L of primer mix
214 (0.25 μ M), 0.25 μ L of Taq Polymerase (1.25 units), 4 μ L of DNA template and 35.4 μ L of
215 distilled sterile water. Amplification was performed using the following PCR conditions: an
216 initial denaturation step at 95°C during 7 minutes followed by 35 cycles each of which
217 constituted of a denaturation step at 95°C during 15 sec, an annealing step at 57°C during 30
218 sec and an elongation step at 72°C during 30 sec. After these 35 cycles, a final elongation step
219 at 72°C during 7 minutes was applied. The amplification was checked by migrating 5 μ L of
220 each PCR reaction on a 2% agarose gel stained with ethidium bromide and visualized under
221 UVs. Expected size of the amplicon is around 350 bp.

222 Indexed libraries were generated using the standard Illumina two-step PCR protocol using Q5
223 high fidelity DNA polymerase (New England Biolabs). Paired-end sequencing with a 2x250 bp
224 read length was performed at the Bio-Environment platform (University of Perpignan Via
225 Domitia Perpignan, France) on a MiSeq system (Illumina) using v2 chemistry according to the
226 manufacturer's protocol. Sequencing data are available for download on SRA under the
227 bioproject number ###

228

229 **Data processing**

230 The sequence datasets were uploaded to the Galaxy web platform ³⁰ and processed using the
231 Finding Rapidly OTUs with Galaxy Solution (FROGS) pipeline at the GenoToul platform
232 (Toulouse, France) ³¹. The first pre-processing step of this pipeline consisted in demultiplexing,

233 dereplicating and cleaning all reads. Given the theoretical expected amplicon size (i.e., ~ 350
234 bp) and after a quick overview of the overall amplicon lengths, we kept all sequences which
235 sizes ranged from 150 to 490 pb. These filtered sequences were then clustered using the
236 SWARM algorithm using an aggregation distance set at 1. This iterative clustering approach
237 uses amplicons' homology, structure and abundance hence limiting potential biases generated
238 by other approaches such as *de novo* clustering methods (i.e., input order dependencies and
239 arbitrary clustering) (Mahe et al., 2014). Clusters were then cleaned to remove potential
240 chimeras, singletons and under-represented clusters (i.e. <50 sequences) using VSEARCH
241 (Rognes et al., 2016).

242 Each OTU was identified based on a nucleotide megablast using the online standard
243 database (nt/nr) available from NCBI. To more precisely identify OTUs that were affiliated to
244 the Symbiodiniaceae genus *Cladocopium* (clade C) based on the results from Blast, we next
245 computed pairwise genetic distance between each OTU seed sequence and a subset of
246 sequences from different *Cladocopium* strains available from LaJeunesse *et al.*³². Pairwise
247 genetic distances were computed using the 'K80' evolutionary model as implemented in the
248 ape package V5.0 in R³³.

249

250 [Results](#)

251

252 ***Dating back coral successions along the core***

253 The obtained coral-skeleton core followed the colony's growth axis on more than 2/3 of its
254 length (see Figure 1.C.; middle panel for illustration). We were hence capable to accurately date
255 back the growth successions over the last seven decades, i.e., back to 1950. Density bands along
256 the oldest part of the coral core partly deviated from the central vertical axis preventing our
257 capability to date back accurately the oldest successions. Annual growth bands were
258 approximately 5-6 mm thick and generally homogenous along the core. According to this
259 measure, we estimated that the oldest *coraDNA* sample collected from the core (S01; Figure
260 1.B.) roughly correspond to coral holobiont that lived in the 1870's.

261

262 ***Amplicon sequencing from coraDNA samples, sequence affiliation and identification of*** 263 ***endosymbiotic algae communities***

264 Because of low DNA concentrations, DNA quality and quantity could not be assessed from all
265 samples except the positive control. PCR amplicons of expected size for ITS2 Symbiodiniaceae
266 marker were however obtained from all samples. After sequencing and filtration steps,

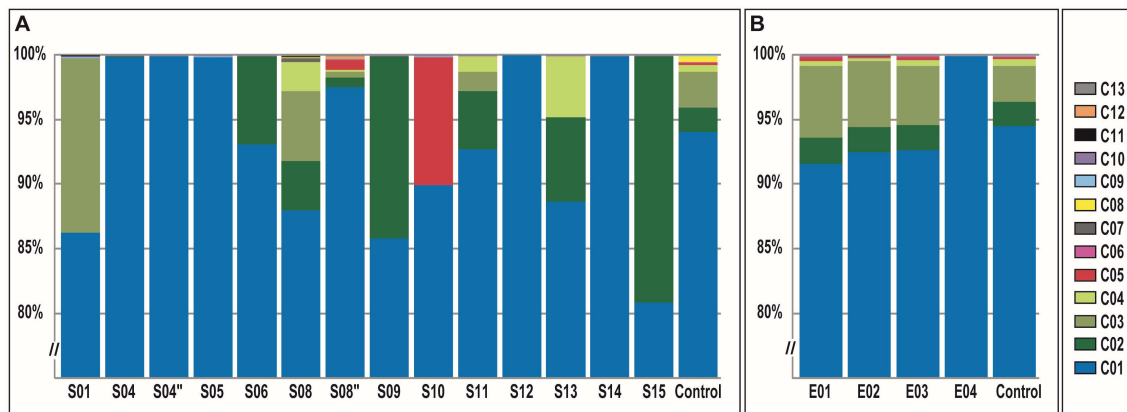
267 sequences were validated from 19 out of the 23 initial *coraDNA* samples including the positive
 268 control (Table 2). The final number of filtered sequences obtained from these 19 *coraDNA*
 269 samples ranged from 1476 (sample S12) to 76403 (sample S13) (Table 2). Four *coraDNA*
 270 samples displayed negligible numbers of sequences (from 9 to 33) and were then excluded for
 271 further analyses. Similarly, extraction and PCR negative controls exhibited negligible numbers
 272 of sequences (8 and 17, respectively) with an expected size of 300 bp (190 – 450 bp; Table 1),
 273 which indicates negligible cross-contaminations during all the process from sampling,
 274 extraction to sequencing.
 275

Sample	% kept	Paired-end assembled (%)	With 5' primer (%)	With 3' primer (%)	With expected length (%)	Without Ns (%)	Nseq OTU > 50 seq
<u>Samples kept in the analyses</u>							
E01	97.29	77.44	77.38	76.15	75.34	75.34	73241
E02	97.12	57.91	57.87	56.68	56.24	56.24	54571
E03	96.37	73.18	73.13	71.18	70.52	70.52	68484
E04	91.60	48.53	48.52	47.35	44.46	44.46	43454
S01	87.58	75.61	75.58	74.20	66.21	66.21	64448
S04	75.10	59.92	59.90	59.09	45.00	45.00	44203
S04"	85.18	15.65	15.62	15.30	13.33	13.33	12993
S05	4.44	89.98	89.96	89.83	3.99	3.99	3928
S06	67.49	65.52	65.50	63.76	44.22	44.22	42583
S08	96.01	77.93	77.90	75.11	74.82	74.82	71366
S08"	97.56	46.68	46.63	45.66	45.54	45.54	44501
S09	63.04	70.01	69.98	68.80	44.13	44.13	43147
S10	8.32	48.20	48.19	48.09	4.012	4.012	3884
S11	85.80	54.13	54.11	53.04	46.44	46.44	45236
S12	6.98	21.95	21.94	21.90	1.53	1.53	1476
S13	96.83	80.93	80.90	78.79	78.36	78.36	76403
S14	93.24	74.74	74.69	73.05	69.69	69.69	68031
S15	56.67	88.20	88.18	86.22	49.98	49.98	48388
Control	28.60	8.73	8.73	8.66	2.50	2.50	2454
<u>Samples removed from the analyses</u>							
S02	0.02	152.242	152.221	152.075	33	33	0
S03	0.02	58.41	58.406	58.344	9	9	0
S07	0.02	76.544	76.531	76.462	15	15	0
S16	0.02	52.119	52.104	52.046	11	11	0
<u>Negative controls</u>							
Extraction	0.02	45.646	45.644	45.597	8	8	0
PCR	0.15	11.01	11.007	10.998	17	17	0

276

277 **Table 2:** Details on the obtained and conserved sequences from each *coraDNA* sample.

278 The sequences clustered into 13 OTUs. Nine of these OTUS were affiliated to
 279 Symbiodiniaceae and all of which were assigned to the *Cladocopium* clade. Based on the
 280 genetic distances computed between each of these 9 clusters and *ITS2* sequences from
 281 LaJeunesse *et al.*³², all OTUs were more specifically affiliated to the *ITS2*-C15 type (computed
 282 distances ranged from 0 to 0.044; Table S1). Among the 4 other non-specific OTUs, one was
 283 affiliated to *Azadinium spinosum* (Dinophyceae; OTU_7; Query cover = 100%, E-Value = 6e-
 284 156; Per. Ident. = 98.1%); one to *P. lobata* (the coral host species; OTU_11; Query cover =
 285 100%, E-Value = 8e-175; Per. Ident. = 100%), and the two others were not successfully affiliated
 286 with any identified sequence available from the NCBI nr database (OTU_12 and OTU_13).
 287 Sequences of *Azadinium spinosum* (OTU_7) were amplified only in the S08 and its duplicate
 288 S08'' *coraDNA* samples. Amplified sequences of *P. lobata* (OTU_11) were found in the S01,
 289 S08, E02 and E03 *coraDNA* samples although at low abundance (Figure 2; Table S2). Finally,
 290 OTUs that were not affiliated with any organism documented in the NCBI database (OTU_12
 291 and OTU_13) were present in samples S08 and/or S08'' again with low read numbers (Figure
 292 2).
 293



294
 295 **Figure 2:** Proportion of sequences attributed to each of the 13 clusters among the 19 positive *coraDNA*
 296 samples A. obtained from the systematic sampling (i.e. every 5 cm along the coral core) and B. collected
 297 under CT SCAN corresponding to successions before (E01) and after (E02) the 1997-1998 ENSO event;
 298 and before (E03) and after (E04) the anormal hot winter in 2010.

299

300 *Distribution of Symbiodinium OTUs over the coraDNA samples*

301 The total number of OTUs obtained from each *coraDNA* sample varied from 1 to 10. Among
 302 the 9 Symbiodiniaceae OTUs identified, 1 OTU (OTU_1, Figure 2) was clearly predominant
 303 representing 92% of the generated sequences overall samples (from 80.88 % in S15 to 100 %
 304 in S12). Only OTU_1 is ubiquitous among all *coraDNA* samples. OTU_9 and OTU_10 could

305 also be reasonably considered as ubiquitous since they have been detected in all except the S12
306 and the positive control *coraDNA* samples. However, these two samples were the one harboring
307 the lowest sequence coverage which may explain this absence (Table 1).

308 The number of OTUs per sample is marginally correlated to the total number of
309 sequences obtained per sample (Spearman correlation, $\rho = 0.53$; p-value = 0.04) but is not
310 correlated to the age of the *coraDNA* sample (using the position order at which the *coraDNA*
311 was sampled along the core as a proxy; $\rho = 0.148$; p-value = 0.60).

312

313 [Discussion](#)

314

315 *Unlocking the access to past coral communities*

316 According to our results, ancient DNA from a coral core (*coraDNA*) excavated from living
317 *Porites lobata* colonies can be obtained and used for metabarcoding approaches to reconstruct
318 the Symbiodiniaceae endosymbiotic communities that have been successively associated to the
319 colonies over a century. This paves the way for unprecedented time-series studies to document
320 the eco-evolutionary dynamics of the coral/Symbiodiniaceae mutualistic interaction to most
321 massive coral species.

322 Nine of the 13 OTUs detected in this study belong to the Symbiodiniaceae and all were
323 affiliated to the *ITS2*-C15 type. Since pairwise genetic distances computed between each of
324 these OTUs were relatively low, it is likely that the observed diversity among these strains result
325 from intragenomic variation at the *ITS2* marker as previously highlighted^{34,35}. Importantly
326 however, the possible resulting overestimation of the diversity in the Symbiodiniaceae
327 community documented here cannot be related to possible post-mortem DNA modifications
328 commonly observed in ancient DNA samples³⁶. Indeed, all but one OTU were detected in the
329 living part of the coral core (positive control) which means that the nature and state of the
330 *coraDNA* samples does not seem to artificially inflate diversity of the Symbiodiniaceae
331 community.

332 Moreover, among the 13 identified OTUs, 1 was attributed to *P. lobata*. This *P. lobata*
333 OTU was detected, although at low abundance, in 4 *coraDNA* samples that do not have obvious
334 commonalities (e.g. spatial location along the core) but a high number of sequences. The
335 detection of the coral host species using the present *ITS2* metabarcoding confirms that host
336 DNA may also be extracted and amplified to some extent. This result makes it possible to
337 consider the exploitation of *coraDNA* samples to trace the eco-evolutionary dynamics of the
338 genome and/or epigenome of the host coral species *P. lobata* at the colony scale.

339 Among the OTUs not affiliated to Symbiodiniaceae or to the cnidarian, we unexpectedly
340 detected *A. spinosum* among two *coraDNA* duplicates collected from the same location along
341 the core. These duplicates correspond to coral holobionts that lived in the 1940's – 1950's.
342 *Azadinium spinosum* is a photosynthetic dinoflagellate that was first described in the late 2000's
343 and since then, has been reported on the coasts of Northern Europe ³⁷, South and Central
344 America ^{38,39} and very recently in Asian Pacific ⁴⁰. While we found no direct evidence of its
345 occurrence in New Caledonia or the Southern Pacific exists in the literature, *Azadinium spp.*
346 was recently observed in French Polynesia under a scanning electron microscope (Mirielle
347 Chanin; pers. comm). Importantly *A. spinosum* is one of the primary producer of azaspiracid
348 toxins causing important health issues to several animals, mainly vertebrates including humans,
349 through toxin bioaccumulation ⁴¹. In this context, azaspiracid-2 (AZA2) toxins were recently
350 detected in New Caledonia based on a SPATT (Solid Phase Adsorption Toxin Tracking)
351 approach, hence indirectly indicating that *Azadinium spp.* can be present locally at least
352 temporary ⁴². So far, no interactions were described between *P. lobata* or any other coral species
353 and *A. spinosum*. We here hypothesize that *A. spinosum* could have been accidentally captured
354 by coral hosts during feeding. Accordingly, the detection of *A. spinosum* at only one time period
355 (although detected in two *coraDNA* duplicate samples from this time period) could coincide
356 with a *A. spinosum* bloom episode as previously described at some localities ³⁸. Thus,
357 additionally to DNA from Symbiodiniaceae and their coral hosts, our results suggest that we
358 can also detect the punctual presence back in time of other organisms (most likely present in
359 high abundance) in the environment and that may have been captured by corals. However,
360 (short) specific molecular markers tailored to the targeted organisms would be necessary, as the
361 marker used in this study was not initially designed for such purposes.

362 From a technical point of view, it is important to note that the number of OTUs detected
363 in the *coraDNA* samples was associated to sequencing output but not to the age of the *coraDNA*
364 samples (estimated from the position of the *coraDNA* samples along the core). This suggests
365 that a low number of sequences but probably not the age of the *coraDNA* could lead to an under
366 represented vision of the studied past Symbiodiniaceae communities (see also rarefaction
367 curves in Supplementary Figure SF1). This is clearly illustrated by the S12 *coraDNA* fairly
368 recent sample, for which we obtained the smallest number of sequences and that harbors only
369 one OTU (OTU_1; Figure 2) which is also predominant in all *coraDNA* samples (representing
370 80.9 % to 100 % percent of the overall filtered sequences). Conversely, we detected up to 5
371 different clusters in the oldest *coraDNA* sample (S01) including 4 OTUs affiliated to
372 *Cladocopium* and one affiliated to *P. lobata*. We thus advise to sequence libraries from

373 *cora*DNA samples with a high coverage to avoid possible false negatives or to use a rarefaction
374 approach to characterize the optimal sequencing depth.

375

376 ***Dynamics of Symbiodiniaceae at large temporal scale***

377 In addition to breaking down a technical barrier, this study also traces back the dynamics of the
378 Symbiodiniaceae community associated with *P. lobata* over time at the colony scale. More
379 particularly, the Symbiodiniaceae community associated with this *P. lobata* colony is composed
380 of 1 OTU (OTU1) assigned to the *ITS2*-C15-type. This occurrence is largely predominant since
381 the earliest part of the coral core; that was estimated to date back to the 1870's approximately.
382 Two other Symbiodiniaceae OTUs were found to be (nearly) ubiquitous although at very low
383 proportion even in the contemporaneous living coral (OTU9 and OTU10). These three OTUs
384 are thus likely to be in tight association with the coral host and probably part of the core
385 Symbiodiniaceae community of the *P. lobata* colony. This is in line with previous studies that
386 have documented a similar pattern in the symbiotic community associated with natural colonies
387 of *P. lobata* where the Symbiodiniaceae C15 strain was highly predominant⁴³. No other clear
388 pattern was observed in terms of community changes over time except for the most abundant
389 non-ubiquitous OTUs such as OTU2, OTU4 and OTU5 which are generally absent in the oldest
390 *cora*DNA samples and appear sporadically only from the S06 – S08 samples (i.e. since the
391 1920's) and upward along the core. Two hypotheses could explain this temporal fluctuation of
392 these OTUs. First, the abundance of these OTUs in the environment display important temporal
393 fluctuations and the studied *P. lobata* colony adjusted its associated Symbiodiniaceae
394 community according to the most prevalent OTU present in the environment. Alternatively, the
395 abundance of the different Symbiodiniaceae strains in the environment is relatively stable in
396 time and the *P. lobata* colony adjusted its Symbiodiniaceae community according to its
397 interaction' preference, physiological state and/or to the prevailing environment⁴⁴. Importantly
398 however, and considering that each OTU is a singular genetic entity, we lack information
399 regarding the functional and physiological consequence of the association between these
400 different *Cladocopium* strains and *P. lobata* to support one of these hypotheses. The use of
401 more resolutive genetic markers could make it possible to better distinguish between different
402 strains from the C15 clade potentially associated with *P. lobata* colonies(ref). Importantly
403 however, and because ancient DNA is more prone to degradation, we could be constrained by
404 the amplicon size. We would thus be more in favor of combining multiple small barcodes rather
405 than using a larger marker.

406

407 ***Dynamics of Symbiodiniaceae associated with extreme climatic events***

408 No major changes in the Symbiodiniaceae community were observed after the targeted
409 severe ENSO event that occurred in 1997-1998 and which led to a decrease in growth visible
410 on the core, compared to that observed in the *coraDNA* sampled before this event. Two
411 hypotheses might explain this result. First, the targeted ENSO event did not stress the colony
412 enough (e.g. no thermal bleaching occurred) to temporally modify the associated
413 Symbiodiniaceae community. In this regard, and although not comparable to a bleaching event,
414 stability of the Symbiodiniaceae community associated with *P. lobata* during extreme storm
415 events was previously reported on Kiritimati Island in the central equatorial Pacific Ocean ³⁴.
416 More generally, the association between *P. lobata* and their symbionts are generally
417 acknowledged to be stable over time even when facing environmental stress ^{34,43}. Alternatively,
418 and despite all precautions, we might have missed the succession corresponding to the past
419 coral colony recovering from the ENSO event during the *coraDNA* sampling. Clearly, more
420 *coraDNA* replicates could have allowed teasing apart these two hypotheses. However, because
421 of the difficulty of sampling only a single succession of coral growth band, and the limited
422 amount of material that can be obtained, replicating *coraDNA* samples is particularly tedious.
423 One solution could be to use a drill to excavate larger-diameter cores from natural colonies.
424 The most important pattern observed in this study however, concerns the apparent loss of the
425 Symbiodiniaceae community diversity observed post 2010 abnormal warm winter period ²⁷. In
426 fact, the E04 *coraDNA* sample harbor a very different symbiotic community compared to the
427 3 others recent *coraDNA* samples and to the control. Only 3 Symbiodiniaceae OTUs were
428 detected in this *coraDNA* sample while 8 to 10 were found in the other 3 recent samples and in
429 the contemporaneous control sample. Such low diversity found in E04 cannot be explained by
430 a lower sequencing coverage (Supplementary Figure SF1). One hypothesis could be that this
431 pattern reflects a temporary and partial loss of Symbiodiniaceae diversity by the coral colony
432 during this abnormally warm and stable period over the year. This is in line with a pattern of
433 decreased in symbiotic algae diversity observed in less variable environments in several coral
434 species ⁴⁵. Moreover, the remaining 3 OTUs detected in E04 do not correspond to the most
435 abundant ones, which suggest that this loss in *Symbiodinium* OTUs is likely to be non-random.
436 These 3 OTUs are those that are ubiquitous to all *coraDNA* samples. This result hence supports
437 the hypothesis that these 3 OTUs are part of the core Symbiodiniaceae community of the *P.*
438 *lobata* colony irrespective to their (sometimes low) relative abundance among the colony ¹⁵.
439

440 **Conclusion and perspectives**

441

442 Together our results highlight the fact that ancient DNA can be extracted from cores excavated
443 from stony corals, the so-called *cora*DNA, dating back to at least one century. Moreover, among
444 the DNA material extracted from the core, we detected DNA from the coral host species, the
445 dinoflagellate symbionts and a free-living environmental dinoflagellate. This result paves the
446 way for studying the temporal evolutionary dynamics of coral holobionts at the colony scale.
447 Combined with some geochemical analyses on the same samples collected along the coral core,
448 this approach could provide new insights on the mechanisms underlying the adaptive responses
449 of corals to several past stress events including temperature changes, pH and/or chemicals such
450 as heavy metals.

451

452

453 [Supplementary material](#)

454 Supplementary table S1: Pairwise genetic distances computed between each pair of the
 455 sequences from the OTUs obtained in this study or from previously identified *Symbiodinium*
 456 strains available from LaJeunesse *et al.* (2003).

	OTU_1	OTU_2	OTU_3	OTU_4	OTU_5	OTU_6	OTU_8	OTU_9	OTU_10
OTU_1	0	0,014	0	0,007	0,007	0	0,044	0,022	0,022
OTU_2	0,014	0	0,014	0,022	0,022	0,014	0,059	0,036	0,036
OTU_3	0	0,014	0	0,007	0,007	0	0,044	0,022	0,022
OTU_4	0,007	0,022	0,007	0	0,014	0,007	0,051	0,029	0,029
OTU_5	0,007	0,022	0,007	0,014	0	0,007	0,051	0,029	0,029
OTU_6	0	0,014	0	0,007	0,007	0	0,044	0,022	0,022
OTU_8	0,044	0,059	0,044	0,051	0,051	0,044	0	0,067	0,067
OTU_9	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0	0,029
OTU_10	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,029	0
AY239363.1_Symb_C1b	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY239364.1_Symb_C1c	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY239365.1_Symb_C3h	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY239366.1_Symb_C3j	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY239367.1_Symb_C8	0,037	0,052	0,037	0,044	0,044	0,037	0,083	0,059	0,059
AY239368.1_Symb_C8a	0,044	0,059	0,044	0,052	0,052	0,044	0,091	0,067	0,067
AY239369.1_Symb_C15	0	0,014	0	0,007	0,007	0	0,044	0,022	0,022
AY239370.1_Symb_C17	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY239372.1_Symb_C21	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY239378.1_Symb_C26	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY258488.1_Symb_C1d	0,036	0,051	0,036	0,044	0,044	0,036	0,082	0,059	0,059
AY258496.1_Symb_C31	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY258501.1_Symb_C35a	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AY765398.1_Symb_C1m	0,037	0,052	0,037	0,044	0,044	0,037	0,083	0,059	0,059
AY765400.2_Symb_C33	0,044	0,059	0,044	0,052	0,052	0,044	0,091	0,067	0,067
AY765401.1_Symb_C35	0,036	0,051	0,036	0,044	0,044	0,036	0,082	0,059	0,059
AY765402.1_Symb_C42	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY765413.1_Symb_C78	0,036	0,051	0,036	0,044	0,044	0,036	0,082	0,059	0,059
AY765414.2_Symb_C79	0,044	0,059	0,044	0,052	0,052	0,044	0,091	0,067	0,067
AF333518.1_Symb_C4	0,014	0,029	0,014	0,022	0,022	0,014	0,059	0,036	0,036
AY589730.1_Symb_C1g	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY589734.1_Symb_C3f	0,029	0,044	0,029	0,036	0,036	0,029	0,075	0,051	0,051
AY589746.1_Symb_C31a	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY589752.1_Symb_C47	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY589771.1_Symb_C66	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY258473.1_Symb_C1h	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AY258475.1_Symb_C8b	0,037	0,052	0,037	0,044	0,044	0,037	0,083	0,059	0,059
AY258481.1_Symb_C37	0,052	0,067	0,052	0,06	0,06	0,052	0,099	0,075	0,075
AY258485.1_Symb_C40	0,036	0,051	0,036	0,044	0,044	0,036	0,082	0,059	0,059
AY258487.1_Symb_C42	0,036	0,051	0,036	0,044	0,044	0,036	0,082	0,059	0,059
AF499789.1_Symb_C3	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AF499794.1_Symb_C4	0,029	0,044	0,029	0,037	0,037	0,029	0,075	0,051	0,051
AF499797.1_Symb_C7	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
AF499801.1_Symb_C12	0,022	0,036	0,022	0,029	0,029	0,022	0,067	0,044	0,044
JQ003816.1_Symb_D	0,827	0,82	0,827	0,856	0,827	0,827	0,856	0,82	0,861

457

458

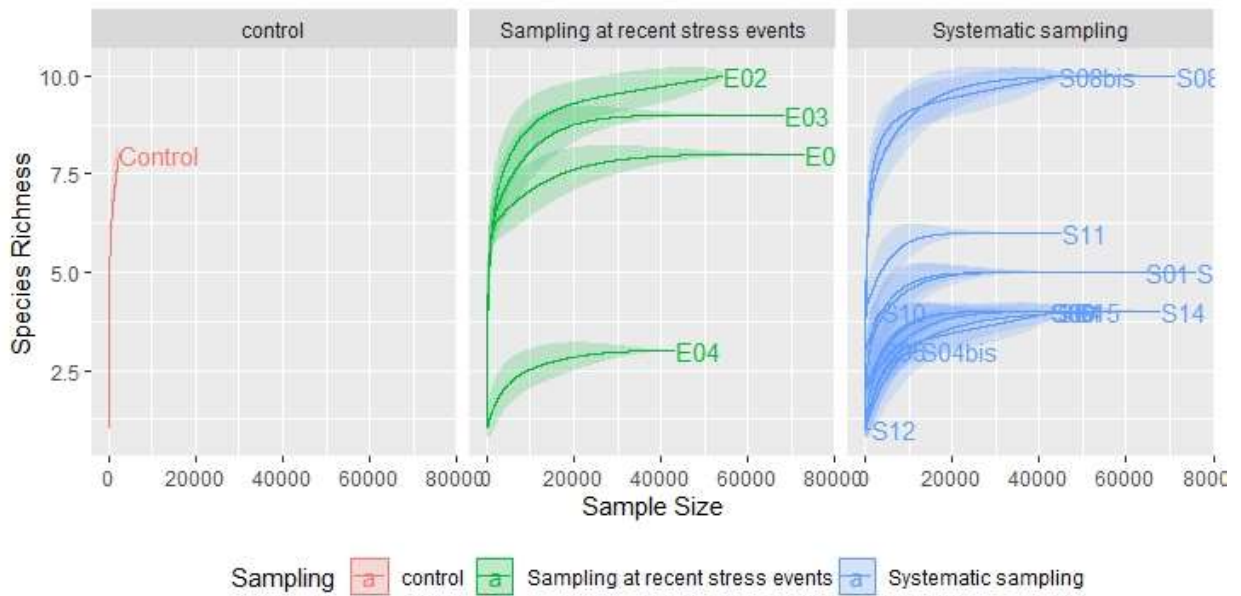
459 Supplementary table S2: Raw data of the sequence abundance of each OTU identified in this
 460 study over all *cora*DNA samples.

OTU_ id	Nseq total	S01	S04	S04"	S05	S06	S08	S08"	S09	S10	S11	S12	S13	S14	S15	E01
OTU_1	748108	55576	44178	12986	3924	39658	62753	43406	37033	3493	41942	1476	67729	68005	39137	67107
OTU_2	32296	0	1	0	0	2912	2786	340	6099	0	2030	0	4994	3	9241	1460
OTU_3	23547	8773	0	0	0	0	3858	172	0	0	694	0	0	0	0	4078
OTU_4	6503	0	0	0	0	0	1574	84	0	0	553	0	3653	0	0	237
OTU_5	1193	0	0	0	0	0	0	333	0	386	0	0	0	0	0	225
OTU_6	264	0	0	0	0	0	0	0	0	0	0	0	0	0	0	123
OTU_7	230	0	0	0	0	0	211	19	0	0	0	0	0	0	0	0
OTU_8	141	0	0	0	0	0	113	0	0	0	0	0	0	0	0	0
OTU_9	139	8	11	5	1	6	10	1	9	2	9	0	15	15	6	7
OTU_10	114	10	13	2	3	7	8	8	6	3	8	0	12	8	4	4
OTU_11	92	81	0	0	0	0	4	0	0	0	0	0	0	0	0	0
OTU_12	94	0	0	0	0	0	0	94	0	0	0	0	0	0	0	0
OTU_13	93	0	0	0	0	0	49	44	0	0	0	0	0	0	0	0

461

462

463 SF1: Rarefaction curves obtained for each of the 19 samples.



465 **Declarations**

466 ***Availability of data and materials***

467 Raw sequences from the metabarcoding approach are available on GenBank under the SRA
468 project id. PRJNA1086717.

469 ***Competing interests***

470 The authors declare that they have no competing interests.

471 ***Funding***

472 This study was fully funded by an internal grant from the IHPE laboratory in the context of
473 the challenge ‘Holobiont Dynamics and Fitness’. The drilling of the coral was funded through
474 the South West Pacific ‘chantier’ of the UMR LOCEAN, while sea access, core drilling,
475 preservation and transport, was allowed through the personal and facilities of the IRD
476 Research Centre of New Caledonia.

477 ***Authors' contributions***

478 O.R and J.V.D equally contributed to the conception and design of the work. The coral core
479 was sampled and sent to the IHPE laboratory by D.D and J.B with the help of G.I for
480 administrative aspects. D.D. and T.G. dated the coral core successions. T.G, M.S, O.R, M.B.Z
481 and J.V.D acquired the ancient DNA extracts with the help of C.T at the degraded DNA
482 platform (Montpellier). O.R, J.F, M.S and J.V.D processed the DNA extracts. O.R., T.G and
483 E.T. analyzed the metabarcoding datasets. O.R., T.G. and J.V.D interpreted the results. O.R
484 have drafted the manuscript and J.V.D, D.D and E.T. substantively revised it. All authors
485 approved the submitted version.

486 ***Acknowledgments***

487 O.R and J.V.D would like to thank Diane Merceron for her kind help in getting the coral core
488 travelling from New Caledonia to Perpignan. We thank the personal (divers, boat pilot, etc,..)
489 of the IRD centre of New Caledonia who allowed for coral core extraction and transportation.
490 We thank the Bio-Environment platform (University of Perpignan Via Domitia) for the
491 sequencing process, Dr. Cristian Chaparro and the IHPE bioinformatics service and the
492 GenoToul bioinformatics platform, Toulouse Occitanie (Bioinfo Genotoul, doi:
493 10.15454/1.5572369328961167E12) for providing computing resources (Galaxy instance;
494 <http://sigenae-workbench.toulouse.inra.fr>). Finally, we would like to warmly thanks all staff
495 from the imagery service at the public Hospital of Perpignan for their kind welcome and help
496 during CT scan including Stephane Belfio, Marine Maurel and Cécilia Colomer. This study is
497 set within the framework of the “Laboratoire d’Excellence (LabEx)” TULIP (ANR-10-LABX-
498 41) and with the technical support of the LabEx CeMEB (ANR-10-LABX-04-01).

499 [References](#)

500

501 1. Díaz, S., Settele, J., Brondízio, E., Ngo, H.T., Guèze, M., Agard, J., Arneth, A.,
502 Balvanera, P., Brauman, K., Watson, R.T., et al. (2019). Résumé à l'intention des décideurs
503 du rapport sur l'évaluation mondiale de la biodiversité et des services écosystémiques de la
504 Plateforme intergouvernementale scientifique et politique sur la biodiversité et les services
505 écosystémiques. 53.

506 2. DeCarlo, T.M., Harrison, H.B., Gajdzik, L., Alaguarda, D., Rodolfo-Metalpa, R.,
507 D'Olivo, J., Liu, G., Patalwala, D., and McCulloch, M.T. (2019). Acclimatization of massive
508 reef-building corals to consecutive heatwaves. *Proc. R. Soc. B* 286, 20190235.
509 10.1098/rspb.2019.0235.

510 3. Maggioni, F., Pujo-Pay, M., Aucan, J., Cerrano, C., Calcinai, B., Payri, C., Benzoni,
511 F., Letourneur, Y., and Rodolfo-Metalpa, R. (2021). The Bouraké semi-enclosed lagoon (New
512 Caledonia) – a natural laboratory to study the lifelong adaptation of a coral reef ecosystem to
513 extreme environmental conditions. *Biogeosciences* 18, 5117–5140. 10.5194/bg-18-5117-
514 2021.

515 4. Palumbi, S.R., Barshis, D.J., Traylor-Knowles, N., and Bay, R.A. (2014). Mechanisms
516 of reef coral resistance to future climate change. *Science* 344, 895–898.
517 10.1126/science.1251336.

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

521 6. Webster, N.S., and Reusch, T.B.H. (2017). Microbial contributions to the persistence
522 of coral reefs. *ISME J* 11, 2167–2174. 10.1038/ismej.2017.66.

523 7. Dixon, G.B., Davies, S.W., Aglyamova, G.V., Meyer, E., Bay, L.K., and Matz, M.V.
524 (2015). Genomic determinants of coral heat tolerance across latitudes. *Science* 348, 1460–
525 1462. 10.1126/science.1261224.

526 8. Van Oppen, M.J.H., Souter, P., Howells, E.J., Heyward, A., and Berkelmans, R.
527 (2011). Novel Genetic Diversity Through Somatic Mutations: Fuel for Adaptation of Reef
528 Corals? *Diversity* 3, 405–423. 10.3390/d3030405.

529 9. Rey, O., Danchin, E., Mirouze, M., Loot, C., and Blanchet, S. (2016). Adaptation to
530 Global Change: A Transposable Element–Epigenetics Perspective. *Trends in Ecology &*
531 *Evolution* 31, 514–526. 10.1016/j.tree.2016.03.013.

532 10. Rinkevich, B. (2019). Coral chimerism as an evolutionary rescue mechanism to
533 mitigate global climate change impacts. *Glob Change Biol* 25, 1198–1206.
534 10.1111/gcb.14576.

535 11. Vidal-Dupiol, J., Harscouet, E., Shefy, D., Toulza, E., Rey, O., Allienne, J.-F., Mitta,
536 G., and Rinkevich, B. (2022). Frontloading of stress response genes enhances robustness to
537 environmental change in chimeric corals. *BMC Biol* 20, 167. 10.1186/s12915-022-01371-7.

- 538 12. Liew, Y.J., Howells, E.J., Wang, X., Michell, C.T., Burt, J.A., Idaghdour, Y., and
539 Aranda, M. (2020). Intergenerational epigenetic inheritance in reef-building corals. *Nat. Clim.*
540 *Chang.* 10, 254–259. 10.1038/s41558-019-0687-2.
- 541 13. Torda, G., Donelson, J.M., Aranda, M., Barshis, D.J., Bay, L., Berumen, M.L.,
542 Bourne, D.G., Cantin, N., Foret, S., Matz, M., et al. (2017). Rapid adaptive responses to
543 climate change in corals. *Nature Climate Change* 7, 627–636. 10.1038/nclimate3374.
- 544 14. Berkelmans, R., and van Oppen, M.J.H. (2006). The role of zooxanthellae in the
545 thermal tolerance of corals: a ‘nugget of hope’ for coral reefs in an era of climate change.
546 *Proc. R. Soc. B* 273, 2305–2312. 10.1098/rspb.2006.3567.
- 547 15. Brener-Raffalli, K., Clerissi, C., Vidal-Dupiol, J., Adjeroud, M., Bonhomme, F.,
548 Pratlong, M., Aurelle, D., Mitta, G., and Toulza, E. (2018). Thermal regime and host clade,
549 rather than geography, drive Symbiodinium and bacterial assemblages in the scleractinian
550 coral *Pocillopora damicornis sensu lato*. *Microbiome* 6, 39. 10.1186/s40168-018-0423-6.
- 551 16. LaJeunesse, T.C., Parkinson, J.E., Gabrielson, P.W., Jeong, H.J., Reimer, J.D.,
552 Voolstra, C.R., and Santos, S.R. (2018). Systematic Revision of Symbiodiniaceae Highlights
553 the Antiquity and Diversity of Coral Endosymbionts. *Current Biology* 28, 2570-2580.e6.
554 10.1016/j.cub.2018.07.008.
- 555 17. Swain, T.D., Chandler, J., Backman, V., and Marcelino, L. (2017). Consensus
556 thermotolerance ranking for 110 *Symbiodinium* phylotypes: an exemplar utilization of a novel
557 iterative partial-rank aggregation tool with broad application potential. *Funct Ecol* 31, 172–
558 183. 10.1111/1365-2435.12694.
- 559 18. Buerger, P., Alvarez-Roa, C., Coppin, C.W., Pearce, S.L., Chakravarti, L.J.,
560 Oakeshott, J.G., Edwards, O.R., and van Oppen, M.J.H. (2020). Heat-evolved microalgal
561 symbionts increase coral bleaching tolerance. *Sci. Adv.* 6, eaba2498. 10.1126/sciadv.aba2498.
- 562 19. Cunning, R., Silverstein, R.N., and Baker, A.C. (2015). Investigating the causes and
563 consequences of symbiont shuffling in a multi-partner reef coral symbiosis under
564 environmental change. *Proc. R. Soc. B.* 282, 20141725. 10.1098/rspb.2014.1725.
- 565 20. Matthews, J.L., Oakley, C.A., Lutz, A., Hillyer, K.E., Roessner, U., Grossman, A.R.,
566 Weis, V.M., and Davy, S.K. (2018). Partner switching and metabolic flux in a model
567 cnidarian–dinoflagellate symbiosis. *Proc. R. Soc. B.* 285, 20182336. 10.1098/rspb.2018.2336.
- 568 21. Voolstra, C.R., and Ziegler, M. (2020). Adapting with Microbial Help: Microbiome
569 Flexibility Facilitates Rapid Responses to Environmental Change. *BioEssays* 42, 2000004.
570 10.1002/bies.202000004.
- 571 22. Hofreiter, M., Paijmans, J.L.A., Goodchild, H., Speller, C.F., Barlow, A., Fortes, G.G.,
572 Thomas, J.A., Ludwig, A., and Collins, M.J. (2015). The future of ancient DNA: Technical
573 advances and conceptual shifts: Prospects & Overviews. *BioEssays* 37, 284–293.
574 10.1002/bies.201400160.
- 575 23. Baker, D.M., Weigt, L., Fogel, M., and Knowlton, N. (2013). Ancient DNA from
576 Coral-Hosted Symbiodinium Reveal a Static Mutualism over the Last 172 Years. *PLoS ONE*
577 8, e55057. 10.1371/journal.pone.0055057.

- 578 24. DiBattista, J.D., Reimer, J.D., Stat, M., Masucci, G.D., Biondi, P., De Brauwer, M.,
579 and Bunce, M. (2019). Digging for DNA at depth: rapid universal metabarcoding surveys
580 (RUMS) as a tool to detect coral reef biodiversity across a depth gradient. *PeerJ* 7, e6379.
581 [10.7717/peerj.6379](https://doi.org/10.7717/peerj.6379).
- 582 25. Gomez Cabrera, M., Young, J.M., Roff, G., Staples, T., Ortiz, J.C., Pandolfi, J.M., and
583 Cooper, A. (2019). Broadening the taxonomic scope of coral reef palaeoecological studies
584 using ancient DNA. *Mol Ecol* 28, 2636–2652. [10.1111/mec.15038](https://doi.org/10.1111/mec.15038).
- 585 26. Smith, L.W., Barshis, D., and Birkeland, C. (2007). Phenotypic plasticity for skeletal
586 growth, density and calcification of *Porites lobata* in response to habitat type. *Coral Reefs* 26,
587 559–567. [10.1007/s00338-007-0216-z](https://doi.org/10.1007/s00338-007-0216-z).
- 588 27. Wu, H.C., Dissard, D., Douville, E., Blamart, D., Bordier, L., Tribollet, A., Le Cornec,
589 F., Pons-Branchu, E., Dapoigny, A., and Lazareth, C.E. (2018). Surface ocean pH variations
590 since 1689 CE and recent ocean acidification in the tropical South Pacific. *Nat Commun* 9,
591 2543. [10.1038/s41467-018-04922-1](https://doi.org/10.1038/s41467-018-04922-1).
- 592 28. Quigley, K.M., Davies, S.W., Kenkel, C.D., Willis, B.L., Matz, M.V., and Bay, L.K.
593 (2014). Deep-Sequencing Method for Quantifying Background Abundances of Symbiodinium
594 Types: Exploring the Rare Symbiodinium Biosphere in Reef-Building Corals. *PLoS ONE* 9,
595 e94297. [10.1371/journal.pone.0094297](https://doi.org/10.1371/journal.pone.0094297).
- 596 29. Lajeunesse, T., and Trench, R. (2000). Biogeography of two species of Symbiodinium
597 (Freudenthal) inhabiting the intertidal sea anemone *Anthopleura elegantissima* (Brandt). *The*
598 *Biological Bulletin* 199, 126–134. [10.2307/1542872](https://doi.org/10.2307/1542872).
- 599 30. Afgan, E., Baker, D., Batut, B., Van Den Beek, M., Bouvier, D., Čech, M., Chilton, J.,
600 Clements, D., Coraor, N., and Grüning, B.A. (2018). The Galaxy platform for accessible,
601 reproducible and collaborative biomedical analyses: 2018 update. *Nucleic acids research* 46,
602 W537–W544.
- 603 31. Escudié, F., Auer, L., Bernard, M., Mariadassou, M., Cauquil, L., Vidal, K., Maman,
604 S., Hernandez-Raquet, G., Combes, S., and Pascal, G. (2018). FROGS: Find, Rapidly, OTUs
605 with Galaxy Solution. *Bioinformatics* 34, 1287–1294. [10.1093/bioinformatics/btx791](https://doi.org/10.1093/bioinformatics/btx791).
- 606 32. LaJeunesse, T.C., Loh, W.K.W., van Woesik, R., Hoegh-Guldberg, O., Schmidt,
607 G.W., and Fitt, W.K. (2003). Low symbiont diversity in southern Great Barrier Reef corals,
608 relative to those of the Caribbean. *Limnol. Oceanogr.* 48, 2046–2054.
609 [10.4319/lo.2003.48.5.2046](https://doi.org/10.4319/lo.2003.48.5.2046).
- 610 33. Paradis, E., and Schliep, K. (2019). ape 5.0: an environment for modern phylogenetics
611 and evolutionary analyses in R. *Bioinformatics* 35, 526–528.
- 612 34. Claar, D.C., Tietjen, K.L., Cox, K.D., Gates, R.D., and Baum, J.K. (2020). Chronic
613 disturbance modulates symbiont (Symbiodiniaceae) beta diversity on a coral reef. *Sci Rep* 10,
614 4492. [10.1038/s41598-020-60929-z](https://doi.org/10.1038/s41598-020-60929-z).
- 615 35. Thornhill, D.J., Lajeunesse, T.C., and Santos, S.R. (2007). Measuring rDNA diversity
616 in eukaryotic microbial systems: how intragenomic variation, pseudogenes, and PCR artifacts
617 confound biodiversity estimates. *Molecular Ecology* 16, 5326–5340. [10.1111/j.1365-294X.2007.03576.x](https://doi.org/10.1111/j.1365-294X.2007.03576.x).

- 619 36. Dabney, J., Meyer, M., and Pääbo, S. (2013). Ancient DNA damage. Cold Spring
620 Harbor perspectives in biology 5, a012567.
- 621 37. Salas, R., Tillmann, U., John, U., Kilcoyne, J., Burson, A., Cantwell, C., Hess, P.,
622 Jauffrais, T., and Silke, J. (2011). The role of *Azadinium spinosum* (Dinophyceae) in the
623 production of azaspiracid shellfish poisoning in mussels. Harmful Algae 10, 774–783.
- 624 38. Akselman, R., and Negri, R.M. (2012). Blooms of *Azadinium cf. spinosum* Elbrächter
625 et Tillmann (Dinophyceae) in northern shelf waters of Argentina, Southwestern Atlantic.
626 Harmful Algae 19, 30–38. 10.1016/j.hal.2012.05.004.
- 627 39. Hernández-Becerril, D.U., Barón-Campis, S.A., and Escobar-Morales, S. (2012). A
628 new record of *Azadinium spinosum* (Dinoflagellata) from the tropical Mexican Pacific.
629 Revista de Biología Marina y Oceanografía 47, 553–557.
- 630 40. Fu, Z., Piumsomboon, A., Punnarak, P., Uttayarnmanee, P., Leaw, C.P., Lim, P.T.,
631 Wang, A., and Gu, H. (2021). Diversity and distribution of harmful microalgae in the Gulf of
632 Thailand assessed by DNA metabarcoding. Harmful Algae 106, 102063.
- 633 41. Tillmann, U., Elbrächter, M., Krock, B., John, U., and Cembella, A. (2009).
634 *Azadinium spinosum* gen. et sp. nov. (Dinophyceae) identified as a primary producer of
635 azaspiracid toxins. European Journal of Phycology 44, 63–79.
- 636 42. Sibat, M., Mai, T., Tanniou, S., Biegala, I., Hess, P., and Jauffrais, T. (2023). Seasonal
637 Single-Site Sampling Reveals Large Diversity of Marine Algal Toxins in Coastal Waters and
638 Shellfish of New Caledonia (Southwestern Pacific). Toxins 15, 642. 10.3390/toxins15110642.
- 639 43. Stat, M., Pochon, X., Franklin, E.C., Bruno, J.F., Casey, K.S., Selig, E.R., and Gates,
640 R.D. (2013). The distribution of the thermally tolerant symbiont lineage (*Symbiodinium* clade
641 D) in corals from Hawaii: correlations with host and the history of ocean thermal stress. Ecol
642 Evol 3, 1317–1329. 10.1002/ece3.556.
- 643 44. Baker, A.C. (2003). Flexibility and Specificity in Coral-Algal Symbiosis: Diversity,
644 Ecology, and Biogeography of *Symbiodinium*. Annu. Rev. Ecol. Evol. Syst. 34, 661–689.
645 10.1146/annurev.ecolsys.34.011802.132417.
- 646 45. Thornhill, D.J., LaJeunesse, T.C., Kemp, D.W., Fitt, W.K., and Schmidt, G.W. (2006).
647 Multi-year, seasonal genotypic surveys of coral-algal symbioses reveal prevalent stability or
648 post-bleaching reversion. Marine Biology 148, 711–722. 10.1007/s00227-005-0114-2.
- 649