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# Maintaining beneficial alga-associated bacterial communities under heat stress: Insights from controlled co-culture experiments using antibiotic-resistant bacterial strains

Elham Karimi, Simon Dittami

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1 **Maintaining beneficial alga-associated bacterial communities under heat**  
2 **stress: Insights from controlled co-culture experiments using antibiotic-**  
3 **resistant bacterial strains**

4  
5 Elham Karimi<sup>1\*</sup> and Simon M. Dittami<sup>1\*</sup>

6  
7 <sup>1</sup> Sorbonne Université/CNRS, Station Biologique de Roscoff, UMR8227, Integrative Biology  
8 of Marine Models, CS 90074, Roscoff, France.

9  
10 **\*Corresponding authors:** Algal Biology and Interactions with the environment group,  
11 UMR8227, Sorbonne Université-CNRS, Laboratory of Integrative Biology of Marine  
12 Models, Station Biologique de Roscoff, 29688 Roscoff CEDEX, France, Tel: (33) 02 98 29  
13 23 62, Emails: [elham.karimi@sb-roscoff.fr](mailto:elham.karimi@sb-roscoff.fr); [simon.dittami@sb-roscoff.fr](mailto:simon.dittami@sb-roscoff.fr);

14  
15 **Keywords:** Algal-bacterial interactions, metabolic networks, systems biology, holobionts

16  
17 **One sentence summary:** Inoculation with bacterial helper cultures that complement host  
18 metabolism increases the control over host-associated microbiome in the model brown alga  
19 *Ectocarpus*.

## 33 **Abstract**

34

35

36 Brown algae, like many eukaryotes, possess diverse microbial communities. *Ectocarpus* - a  
37 model brown alga- relies on these communities for essential processes, such as growth  
38 development. Controlled laboratory systems are needed for functional studies of these algal-  
39 bacterial interactions. We selected bacterial strains based on their metabolic networks to  
40 provide optimal completion of the algal metabolism, rendered them resistant to two  
41 antibiotics, and inoculate them to establish controlled co-cultures with *Ectocarpus* under  
42 continuous antibiotic treatment. We then monitored the stability of the resulting associations  
43 under control conditions and heat stress using 16S metabarcoding. Antibiotics strongly  
44 reduced bacterial diversity both in terms of taxonomy and predicted metabolic functions. In  
45 the inoculated sample, 63-69% of reads corresponded to the inoculated strains, and the  
46 communities remained stable during temperature stress. They also partially restored the  
47 predicted metabolic functions of the natural community. Overall, the development of  
48 antibiotic-resistant helper cultures offers a promising route to fully controlled laboratory  
49 experiments with algae and microbiota and thus represents an important step towards  
50 generating experimental evidence for specific host-microbe interactions in the systems  
51 studied. Further work will be required to achieve full control and progressively expand our  
52 repertoire of helper strains including those currently “unculturable”.

53

## 54 **Introduction**

55

56 As virtually all eukaryotes, brown algae are colonized by a diverse microbial community,  
57 together forming so-called holobionts (Dittami et al. 2021; Egan et al. 2013). The thallus of  
58 algae is more than a habitat for microbes; there are numerous dynamic inter-species  
59 interactions and metabolic exchanges between both compartments. Technological  
60 advancements in sequencing and metagenomics now permit the generation of valuable  
61 information about the composition of the host microbiome. Furthermore, computational  
62 models of metabolic networks can be used to predict complementarity sets between  
63 microbiome species and hosts (Belcour et al. 2020; Frioux et al. 2018; Levy et al. 2015).

64 Brown algae (Phaeophyceae) are important components of the flora on rocky shores in  
65 temperate and cold marine environments around the world, establishing critical ecosystem  
66 habitats such as kelp forests (Steneck et al. 2002). Many of these kelp forests, especially  
67 along the European coast of the North Sea, Eastern Australia, and California, are declining  
68 (Krumhansl et al. 2016; Smale 2020) - a phenomenon that is commonly attributed to  
69 anthropogenic impacts and global warming, though the precise causes are unknown (Provost  
70 et al. 2017).

71 Among brown algae, *Ectocarpus* (a small filamentous alga) has been established as a genetic  
72 and genomic model (Cock et al. 2010) and it is known to depend on the bacteria for proper  
73 development and for acclimation to low salinities (Dittami et al. 2016; Pedersen 1968; Tapia  
74 et al. 2016). According to a recent study, the co-culture of *Ectocarpus* with selected bacteria  
75 resulted in increased algal growth, and samples treated by different specific bacteria had  
76 diverging metabolite profiles and morphologies (Burgunter-Delamare et al. 2020).

77 Despite advances in our understanding of the diversity of bacterial symbionts and the  
78 prospective use of metabolic complementarity to test host-microbe interactions, there are still  
79 unanswered questions about symbiont acquisition and host-microbe balance in the face of  
80 abiotic stress. Furthermore, it is unresolved if and to what extent imbalances between algae  
81 and their associated microbiomes may play a role in ecologically important things like the  
82 decline of kelp forests. The establishment of controlled laboratory systems for brown algal-  
83 bacterial interaction would constitute a big advance in this field, enabling the mechanistical  
84 study of bacterial algal interactions in a changing environment, and the generation of testable  
85 hypotheses (van der Loos et al. 2019).

86 The aim of this study was to improve our control of the alga-associated microbiome. Given  
87 the strong interdependencies between the algal hosts and their associated microbiome, this  
88 challenge was addressed by providing the alga with a defined set of antibiotic-resistant  
89 ‘helper bacteria’. These bacteria were selected from a collection of host-derived bacteria,  
90 based on their predicted metabolism, to be able to produce the maximum number of  
91 compounds that are missing for the predicted metabolism of the host (Dittami et al. 2014). In  
92 addition, the algae and bacteria were kept under continuous antibiotic treatment to reduce the  
93 proliferation of other non-target strains that might colonize the niche opened up by the  
94 antibiotic treatment. The suitability of this approach was tested in the algal host model  
95 *Ectocarpus*, and the stability of the microbiome was assessed under both control conditions  
96 and under heat stress.

97

## Materials & Methods

### 99 **Beneficial bacterial consortium selection**

100 *In silico* selection of beneficial bacteria was performed in a previous study (Karimi et al.  
101 2021a). Briefly, 81 bacterial genomes isolated from *Ectocarpus* (Karimi et al. 2019) were  
102 annotated using Prokka v 1.13 (Seemann 2014). Subsequently, bacterial metabolic networks  
103 were constructed using Pathway Tools version 23 and the mpwt wrapper implemented in the  
104 AuCoMe pipeline (Belcour et al. 2020). The bacterial metabolic networks and the available  
105 host metabolic network (Dittami et al. 2020) were submitted to MiSCoTo as SMBL files  
106 (Frioux et al. 2018). The latter tool was first used to determine the scope of all algal  
107 compounds that, according to the metabolic models, and without limiting metabolite  
108 exchange, became producible via exchanges between the host and all 81 bacterial genomes  
109 together: a total of 506 compounds listed in Supplementary Table S8 of Karimi et al. (2021a).  
110 The same tool was then used to determine the minimal bacterial consortia that enabled the  
111 production of these compounds. A total of 18 minimal communities was predicted each  
112 comprising 10 bacterial strains (listed in Supplementary Table S1), and the union of all  
113 minimal consortia contained 15 bacteria. All of these 15 bacteria and their taxonomic  
114 affiliations are listed in Supplementary Table S1, and we attempted to generate antibiotic-  
115 resistant strains for each one of them. The host and bacterial networks have also been  
116 deposited in the Zenodo repository (Karimi et al. 2021b).

### 117 **Antibiotic sensitivity testing on algae**

118 Filaments of the brown alga *Ectocarpus subulatus* strain Bft15b were cultured in 10-liter  
119 Nalgene™ Round Polycarbonate flasks with Provasoli-enriched autoclaved seawater for 15  
120 days. Temperature was maintained constant at 16°C, and constant airflow and a light-dark  
121 cycle of 12:12h were applied in controlled culture chambers. The algal filaments were then  
122 placed in 90mm sterilized Petri dishes filled with Provasoli-enriched artificial seawater  
123 containing the following components: NaCl 450mM, MgSO<sub>4</sub>(7H<sub>2</sub>O) 16mM, MgCl<sub>2</sub>(6H<sub>2</sub>O)  
124 30 mM, KCl 10mM, CaCl<sub>2</sub> 9mM adjusted to pH 7.8 with 10mM Tris. Culture conditions  
125 remained identical, except for the absence of bubbling. To obtain axenic algae, the following  
126 antibiotic treatment was selected based on the work of Cottrell and Suttle (1993) and  
127 preliminary experiments in our laboratory: three-day exposure to a combination of  
128 Chloramphenicol (CHL 9.6 µg/ml) and Neomycin (NEO 24.8µg/ml). This treatment

129 efficiently reduced associated bacteria but caused no visible damage (discoloration, rupture)  
130 to the algal cells.

### 131 **Antibiotic sensitivity tests for bacteria and the generation of antibiotic-resistant strains**

132 Disk diffusion tests were carried out to determine the susceptibility of the selected beneficial  
133 bacteria to chloramphenicol (CHL) and neomycin (NEO). Freshly cultured bacterial isolates  
134 were spread evenly on the R2A agar plates prepared with natural seawater, and grown in the  
135 presence of 30 µg CHL and 30 UI NEO antibiotic discs (Bio-Rad, Nanterre, France  
136 (Matuschek et al. 2014) for up to one week at 18°C. Next, we attempted to generate antibiotic  
137 resistance in the selected strains. To this means, bacteria were grown in 25 ml of liquid R2A  
138 medium in Corning® cell culture flasks at 25°C with agitation (50 rpm) supplemented with  
139 0.3 µg/ml of CHL. Once bacterial growth was visible, 1 ml of culture was transferred to a  
140 new flask with a higher concentration and this process continued. Based on the “adaptation  
141 on demand” hypothesis (Johnsen et al. 2021), the increase in antibiotic concentration leads  
142 bacterial population to evolve resistance to the target antibiotic, until growth was observed at  
143 the target concentration of CHL (Supplementary Table S2). At this point, the disk diffusion  
144 test was repeated to check the obtained resistance (Table 1). Then, the same procedure was  
145 carried out starting with 3.93 µg/ml Neomycin (NEO) for the CHL-resistant strains. Finally,  
146 the identity of bacterial strains resistant to both antibiotics was confirmed by sequencing the  
147 16S rRNA gene with the universal primers 27F and 1492R. After reaching the desired  
148 antibiotic resistance, the strains were preserved in 20% (vol/vol) glycerol at -80°C.

### 149 **Co-cultures of algae and bacteria**

150 For our co-culture experiments, we constructed a set that included all seven bacteria for  
151 which resistant strains were obtained. This set corresponds to the predicted minimal  
152 community 11 in Supplementary Table S1, but lacks *Frigoribacterium* sp. 9N, *Bacillus*  
153 sp. 9J, and *Novosphingobium* sp. 9U. These bacteria were grown in liquid R2A media with  
154 both antibiotics at their final target concentration. Once bacterial growth was visible with the  
155 naked eye (approximately 5 days), the optical density (OD) of the cultures was determined  
156 using Genova plus analyzer UV/Vis life science® spectrophotometer at 600 nm. All cultures  
157 were diluted to an OD of 0.1 for the inoculation of the algal cultures. For the co-culture set-  
158 up, algal filaments were dispersed in Petri plates (125 ml cultures), prepared with the two  
159 liquid antibiotics as described above, and inoculated with 500 µl of each resistant cultured

160 bacterium (OD = 0.1). These cultures, along with a set of controls, were then used in the  
161 stress response experiments described below.

## 162 **Temperature stress experiment**

163 The design of the stress response experiments, as well as the controls included are described  
164 in Fig. 1. Briefly, at the start of the experiment ( $t_0$ ), algal-bacterial co-cultures were  
165 inoculated as described above (INOCUL), and in addition, a non-antibiotic treated positive  
166 control (NATUR), and an antibiotic-treated non-inoculated alga as a negative control (ATB)  
167 were included. For all three of these conditions, we prepared 8 replicate Petri dishes with 4  
168 filaments in each (a total of 96 algal filaments). After the acclimation period of 10 days at  
169  $16^\circ\text{C}$  ( $t_{10}$ ) in a culture chamber at  $16^\circ\text{C}$ , 4 of the 8 replicates for each treatment were placed  
170 in a separate but otherwise identical culture chamber and subjected to a temperature increase  
171 of  $2^\circ\text{C}$  every two days for 6 days ( $t_{12}$ ,  $t_{14}$ ,  $t_{16}$ ). The other 4 replicates were maintained at  $16^\circ\text{C}$ .  
172 At each of these time points, algal samples (one filament per Petri dish) were collected in  
173 Eppendorf tubes and immediately frozen in liquid nitrogen, and later at  $-80^\circ\text{C}$  for  
174 downstream analyses. Furthermore, at all steps of the experiment (Fig. 1), the general algal  
175 morphology was observed. Finally, at  $t_{16}$ , aliquots (15 ml) of the culture media were taken,  
176 centrifuged at 10,000 g for 30 min to pellet the bacterial cells present, and the pellets were  
177 stored at  $-80^\circ\text{C}$  for downstream analysis.

## 178 **Metabarcoding profiling of co-culture experiments**

179 A metabarcoding approach was implemented to investigate the composition of the bacterial  
180 community after the co-culture experiments and temperature disturbances. For each culture  
181 condition, frozen algal tissue was freeze-dried and ground (TissueLyserII; Qiagen, Hilden,  
182 Germany;  $2 \times 60$  s, 30 Hz). The powder obtained was then used for DNA extraction (the  
183 Macherey-Nagel NucleoSpin 96 Plant II Kit). The DNA extraction for bacterial pellets  
184 collected from seawater media was performed using the Wizard® Genomic DNA Purification  
185 Kit (Promega, Madison, USA). DNA integrity was verified with gel electrophoresis. Two  
186 blank controls were included as negative controls in addition to the samples. Libraries were  
187 prepared according to the standard Illumina protocol for metabarcoding MiSeq technology  
188 targeting the V3–V4 region (Illumina, 2017). Briefly, the amplicon PCR was performed  
189 using NOCHL primer sets (Thomas et al. 2020). The PCR products were then purified using  
190 AMPure® XP beads (Agencourt Bioscience, Beverly, MA, USA) followed by index PCR in

191 KAPA HiFi HotStart ReadyMix (KAPA Biosystems, Wilmington, MA, USA) to attach dual  
192 indices and Illumina sequencing adapters to each sample using the Nextera XT Index Kit  
193 (Epicentre, Madison, WI, USA). A second PCR clean-up was then carried out as described  
194 above. The resulting libraries were checked using a bioanalyzer (DNS 1000) to verify  
195 fragment size and a Qubit® fluorimeter (Life Technologies, Paisley, UK) for DNA  
196 quantification. An equimolar pool of all libraries was subjected to paired-end ( $2 \times 300$  bp)  
197 sequencing on a single flow cell of an Illumina MiSeq sequencer using the MiSeq v3 kit  
198 (Illumina, San Diego, CA, USA) on Platform GENOMER, FR2424, Roscoff.

### 199 **Sequence analysis**

200 The resulting raw sequences (10,508,975 read pairs) were processed using DADA2 within  
201 the R (v4.0.0) statistical computing environment (Callahan et al. 2016). Reads underwent  
202 quality filtering as error rates were calculated and removed from the dereplicated reads. An  
203 initial Amplicon Sequence Variant (ASV) table was constructed, and later chimeras were  
204 identified using the removeBimeraDenovo function. Finally, taxonomy was assigned using  
205 DADA2's native RDP Bayesian classifier against the Silva database version 138 (McLaren  
206 2020). Non-bacterial sequences as well as all ASVs with less than ten reads or which were  
207 more abundant in the negative control compared to the samples were removed. No  
208 rarefaction was conducted but the 'calc\_obs\_props' function of the 'metacoder' package  
209 version 0.3.4 was used to calculate proportions and the abundance of taxa was computed  
210 using the 'calc\_taxon\_abund' function. For diversity analysis, the 'vegan' package was  
211 employed using the 'diversity' function. PICRUSt2 (v2.4.1) was used to predict functional  
212 traits of bacteria based on their marker gene sequences in each treatment with default settings  
213 (Douglas et al. 2020).

### 214 **Statistical analyses**

215 All statistical analyses and graphs were performed within the computing environment R  
216 (v4.0.0; R Core Development Team, 2005) using the packages phyloseq (McMurdie and  
217 Holmes 2013), phylosmith (Smith 2019), vegan (Oksanen et al. 2020), ggplot2 (Valero-Mora  
218 2010), metacoder (Foster et al. 2017), microbiome (Lahti et al. 2017). Statistical tests were  
219 considered significant at  $\alpha = 0.05$ . Differences in community composition ( $\beta$ -diversity) were  
220 computed using Bray–Curtis dissimilarity matrices and tested via permutational multivariate

221 analysis of variance (PERMANOVA) and the statistical analysis of the predicted pathway  
222 data was performed using STAMP version 2.1.3(Parks et al. 2014).

223

## 224 **Results**

### 225 **Antibiotic resistance and sufficient growth obtained for 7 out of 15 bacteria.**

226 To set up a controlled co-culture experiment, we continuously applied antibiotics. Therefore,  
227 we needed to generate antibiotic-resistant strains of the bacteria we had selected based on  
228 metabolic complementarity. All 15 of the initially bacteria developed resistance to CHL and  
229 subsequently to neomycin (NEO) (Supplementary Table S2). For 10 out of these 15 strains  
230 the resistance to both antibiotics (Supplementary Figure S1) was durable and 7 strains out of  
231 10 exhibited growth rates that were sufficient to prepare co-culture experiments within a  
232 timescale of 5 days (Table1)

### 233 **Metabarcoding survey of algal samples**

234 In total, 71 samples from three algal treatment conditions were considered for the core  
235 analysis of the study: bacterial inoculation with ATB treatment (n = 24, labeled as INOCUL);  
236 no inoculation and no ATB treatment (n = 23, here known as NATUR), and no bacterial  
237 inoculation with ATB treatment (n = 24, labeled as ATB). One sample replicate from the  
238 ATB treatment was removed alongside the negative controls because insufficient reads were  
239 obtained. Of 10 million raw reads were made up 1 005 455 unique sequences belonging to 1  
240 933 different ASVs. The ASVs and taxonomy tables are provided in Supplementary Table  
241 S3.

### 242 **Six inoculated resistant bacteria out of seven persisted in cultures.**

243 Six inoculated bacteria out of seven were detected in metabarcoding data (Fig. 2). Only  
244 *Rhizobium* had no reads although this strain had developed resistance to both antibiotics in a  
245 timely manner. Overall, the inoculated strains were detected specifically in the conditions  
246 they were inoculated in, except for *Maribacter* which was present in all cultures (Fig. 2). In  
247 the samples that underwent the INOCUL treatment, reads corresponding inoculated bacteria,

248 amounted to 66% of total reads (69% in control conditions and 63% in stress conditions,  
249 Supplementary Figure S2).

### 250 **Antibiotic treatments reduce bacterial diversity and modify community structure.**

251 The Shannon diversity indices per sample ranged from 3.33 to 4.77 (Fig. 3, See  
252 Supplementary Table S4 for additional diversity indices). They differed significantly between  
253 ATB-treated, natural, and ATB-treated inoculated samples (two-way ANOVA,  $p < 0.001$ ),  
254 but differences between temperature-stressed and control samples were not significant in the  
255 same analysis ( $p = 0.28$ ; Fig. 3). Generally, the communities from samples inoculated with  
256 the selected bacteria (INOCUL) exhibited lower phylogenetic diversity than control  
257 (NATUR) and higher than the antibiotic treated (ABT).

258 Non-metric Multidimensional Scaling (nMDS) visualization of  $\beta$ -diversity using the  
259 Bray–Curtis dissimilarity index revealed a clear separation of co-culture conditions (Fig. 4;  
260 PERMANOVA, Bray–Curtis method, 999 permutations;  $R^2 = 0.75$ ,  $p < 0.001$ ). However, no  
261 clear differences between stress- and control samples were observed for the overall  
262 community composition. PERMANOVA analyses carried out separately for ATB, INOCL,  
263 and NATUR samples after inculcation ( $t_{10}$ - $t_{16}$ ) also revealed that the community composition  
264 changed slightly but significantly in response to stress for the ATB and INOCL treatments  
265 ( $p=0.013$  and  $p=0.041$ , respectively) but not for the NATUR treatment.

### 266 **Taxonomic composition of bacterial communities**

267 The taxonomic composition of bacterial communities in ATB, INOCUL, and NATUR  
268 cultures is illustrated in Fig. 5A, where only the non-inoculated strains are considered  
269 (inoculated strains are shown in Fig. 2). In the natural samples, we observed a complex  
270 community dominated by sequences corresponding *Flavobacteriales*, *Caulobacterales*,  
271 *Oceanospirellales*, and *Rhodobacterales*. ATB treated samples including the INOCUL  
272 samples (without the inoculated bacteria), were dominated by sequences belonging to  
273 *Flavobacteriales* and more specifically the genus *Winogradskyella*, and only 5-10% of reads  
274 corresponded to other groups.

275 The pairwise comparisons in Fig. 5B display the relative abundance of each observed  
276 taxonomic group in stress versus control samples. Here, nodes represent taxonomic levels,  
277 and each branch represents the phylogenetic relationship between those entities. ASV  
278 richness is represented by node size and the relative abundance of reads corresponding to this

279 node by color. For the natural microbiota, this heat tree shows few taxonomic differences in  
280 the composition in response to stress, notably an increase in the proportion *Cytophagales*  
281 including *Fabibacter*, and a decrease in *Pseudomonadales*. The ATB in INOCL treatment  
282 exhibit a few common responses to stress, such as the increase in the part of *Bacillales* in  
283 response to stress, and a decrease in *Gammaproteobacteria* and *Rhodobacteriaceae*.  
284 Specifically, in the INOCL treatment, we also observed a relative increase in *Micrococcales*  
285 and *Rhizobiaceae* in response to stress.

286  
287

## 288 **Taxonomy-based functional profiling of bacterial communities in control and stressed** 289 **samples**

290 In addition to generating the taxonomic profiles, we used Picrust2 to functional profiles  
291 based on the metabarcoding data. During this process, 15 ASVs with [Nearest Sequenced](#)  
292 [Taxon Index](#) (NSTI) values of more than 2 were eliminated, along with six ASVs with poor  
293 alignment (Barbera et al. 2018; Czech et al. 2020; Louca and Doebeli 2017; Mirarab et al.  
294 2012). The average of NSTI values for our samples (Supplementary Table S5) was  
295  $0.047 \pm 0.007$  (mean + SD), with slightly higher NSTIs ( $0.053 \pm 0.003$ ) for the NATUR  
296 samples than the INOCUL samples ( $0.044 \pm 0.009$ ), [indicating the availability of close](#)  
297 [reference genomes in the PICRUST2 database](#). Principal component analyses of these  
298 profiles revealed that ATB, INOCL, and NATUR samples were clearly associated with  
299 distinct functional profiles (Fig. 6A). Using a Kruskal-Wallis test and a Benjamini Hochberg  
300 correction, we found that 314 out of 349 predicted metabolic pathways differed significantly  
301 ( $p_{adj} < 0.05$  in at least one of these conditions; Supplementary Table S5). Interestingly, from a  
302 functional point of view, INOCL samples were closer to the NATUR samples than the ATB  
303 samples (Fig. 6B). However, none of the predicted metabolic pathways differed significantly  
304 in response to stress when analyzing the ATB, INOCL, and NATUR groups separately.

## 305 **Discussion**

306

### 307 **The effect of antibiotic treatments on algal cultures**

308            Protocols to obtain truly axenic cultures using antibiotic treatments are available for  
309 several microalgal species (e.g., Cirri et al. 2018; von Dassow et al. 2009). For macroalgae  
310 axenic cultures are, to the best of our knowledge, available only for *Ulva mutabilis* (Califano  
311 and Wichard 2018) and even these do not exhibit normal growth and morphology unless  
312 complemented with bacterial morphogens (Spoerner et al. 2012). In most cases, e.g. the  
313 filamentous brown alga *Ectocarpus* (Burgunter-Delamare et al. 2020) but also some  
314 microalgae (Geng et al. 2016) antibiotic treatments reduced bacterial abundance and led to a  
315 shift in bacterial community composition. The example of *Ectoacrpus subulatus* shows that  
316 this reduction may be temporary and that the relative bacterial abundance, as estimated by the  
317 number of bacterial vs. host reads in metatranscriptomic experiments, may even increase after  
318 recovery from strong antibiotic treatments (KleinJan et al. 2023). In our study, the  
319 comparison of the NATUR and the ATB treatments confirms a change in the bacterial  
320 community. In our case, the community shifted from a diverse assembly of Proteobacteria to  
321 a community dominated by Bacteriodetes and notably the genus *Winogradskyella*  
322 (Flavobacteria). This is similar to previous results by Burgunter-Delamare et al. (2020) where  
323 another, yet undescribed genus of Flavobacteria became dominant after antibiotic treatments.  
324 *Winogradskyella* is frequently associated with marine mammals and algae, and uncultivable  
325 strains of the genus have been proposed to have specialized in the utilization of the brown  
326 algal polysaccharide laminarian while reducing other aspects of their metabolism (Alejandre-  
327 Colomo et al. 2021). Our current working hypothesis is that if there is an open niche created  
328 by the antibiotic treatment it will be filled by resistant or previously dormant bacteria that are  
329 well-adapted to live on macroalgae. We may furthermore hypothesize that the newly  
330 established bacteria may, at least in some cases, be less beneficial to the algal host, and in any  
331 case, we have no control over the communities that will establish themselves.

332

### 333 **Inoculation stabilized bacterial communities and partially restores metabolic functions**

334            In this study, we attempted to fill the empty niche created by an antibiotic treatment  
335 by inoculation with a controlled and beneficial bacterial community. At the same time, we  
336 gave this target community a selective advantage by maintaining an antibiotic treatment.  
337 Our data show that this approach worked partially – approximately 63-67% of bacterial reads  
338 obtained corresponded to the inoculated bacteria, and only about 31%-37% to others.  
339 Although this is still a considerable amount of non-target bacteria, in a comparable study

340 without continuous antibiotic treatment, on average only 11% of the final reads corresponded  
341 to the inoculated bacteria (see Burgunter-Delamare et al. (2020), notably Table 4 therein).  
342 Furthermore, our Picrust2 analyses underline that the obtained bacterial communities are  
343 functionally more similar to the “natural” laboratory communities than the communities after  
344 only ATB treatment (Fig. 6). This indicates that the inoculation with selected bacteria was at  
345 least to some extent able to restore the functions naturally present in the microbiome.

### 346 **Bacterial communities had little influence on host temperature stress response or vice** 347 **versa**

348 In *Ectocarpus*, bacterial communities have also been shown to have a significant  
349 impact on the holobiont salinity response and vice versa (Dittami et al. 2016; KleinJan et al.  
350 2023). We, thus, wanted to test if our approach of using antibiotics and antibiotic-resistant  
351 cultures could help stabilize beneficial bacterial communities, and by extension increase  
352 holobiont stress tolerance. Unlike in previous experiments with strong changes in salinity, our  
353 results on temperature stress exhibited only weak changes in the bacterial community in both  
354 the INOCL and in the control (ATB, NATUR), thus making it impossible to conclude on  
355 stabilizing effect. Please note, that the absence of an impact of stress on the bacterial  
356 communities was observed, despite the strong intensity of the temperature stress. Indeed, at  
357 the end of the experiments, we had reached the limit of the thermal tolerance range of our  
358 strains: an additional increase in temperature by two degrees led to rapid algal bleaching and  
359 death regardless of the treatment (ATB, INOCL, NATUR; data not shown).

360 One possible explanation for the discrepancy between the previous salinity tolerance  
361 experiments may be the different effects the stressor had on the host or the microbiome.  
362 *Ectocarpus subulatus* is a euryhaline species frequently found in estuaries. It is, as such, well-  
363 adapted to strong fluctuations in salinity (Peters et al. 2015) . The associated microbiome of  
364 the strain used in Dittami et al (2016), however, might have impoverished and evolved over  
365 the 20 years of cultivation in the laboratory, since its original isolation in 1995 (West and  
366 Kraft 1996) and marine-freshwater transitions in general, are considered rare among microbes  
367 (Logares et al. 2009). Regarding temperature changes, the algal hosts, on the other hand,  
368 generally have narrow temperature tolerance windows, and maximum summer temperatures  
369 are one of the factors limiting their distribution (Lüning 1984) Regarding bacteria, even  
370 bacteria considered psychrophilic usually grow well at 20°C (Morita 1975), and most  
371 (mesophilic) bacteria tolerate up to 45°C (Willey et al. 2008) Although this is presently only

372 a hypothesis, is important to keep in mind the possibility of differences in the stress response  
373 of the host and the different symbiotic partners. Depending on which component is affected  
374 different approaches may be appropriate when attempting to manipulate the system.

### 375 **Bacterial manipulation with antibiotic-resistant bacteria – a promising but low** 376 **throughput strategy**

377 While our experiments show a clear increase in the control over the *Ectocarpus*-  
378 associated bacterial communities, we did not reach complete control over the alga-associated  
379 microbiome, and several aspects of these experiments could be improved. First, as illustrated  
380 by the metabolic distance between the INOCL and the NATUR communities, we are not yet  
381 completely substituting the natural communities in terms of metabolic capacities; This may  
382 be related in part to the fact that we were able to co-culture only six of the initially selected  
383 16 bacterial strains. At the same time, we are also still limited to cultivable isolates.  
384 Increasing our efforts on cultivating the “unculturable” (Zengler et al. 2002) would therefore  
385 also help cover a larger portion of the bacterial metabolism in co-culture experiments. In  
386 parallel, additional effort, and the use of more or different antibiotics may help increase the  
387 control over the remaining alga-associated microbiota. Here, however, a balance needs to be  
388 struck, as antibiotic resistance for the bacteria also comes with a cost, and evolving  
389 resistances may further alter bacterial physiology (Händel et al. 2013) thus potentially  
390 impacting interactions with the host. Another limitation of our approach is the time it takes to  
391 prepare these cultures and co-culture experiments. Experiments with one or two bacterial  
392 strains of interest are easily feasible, but they are difficult to upscale because each bacterium  
393 reacts differently to antibiotics, and sometimes resistances are not stable making repeated  
394 treatments necessary. It will thus be more difficult to envision this approach for medium- or  
395 high-throughput screening of bacteria in a co-culture context, especially if complex  
396 communities are to be tested.

397 Despite these limitations, we believe that the development of a collection of antibiotic-  
398 resistant helper cultures for our algae constitutes one promising avenue towards fully  
399 controlled laboratory experiments with algae for which there are currently no working  
400 axenization protocols. If these cultures can fulfill the metabolic functions of the natural  
401 microbiome, their addition will thus enable increased experimental control over the  
402 microbiome during experiments, enhancing the reproducibility of microbiome-related work.

403 In the long run we could then progressively aim towards replacing the microbes by the  
404 metabolites or metabolic intermediates they provide.

405

## 406 **Data availability**

407 The Illumina sequence data generated in this study (Raw MiSeq data) have been deposited in  
408 the European Nucleotide Archive (ENA) at EMBL-EBI under accession number  
409 PRJEB57188.

## 410 **Acknowledgments**

411 We would like to thank Guillaume Manat for helpful discussions on making bacteria resistant  
412 to antibiotics, Sébastien Colin for help exploring the algal bacterial community by  
413 microscopy, Elodie Rolland for providing facilities for algal culturing, Akira Peters for  
414 providing the *Ectocarpus* culture, Bertille Burgunter-Delamare for useful advice on using  
415 DADA2 scripts, and Gwenn Tanguy and Erwan Legeay from the GENOMER platform  
416 (FR2424, Station Biologique de Roscoff) for access to the sequencing platform and support  
417 during library preparation.

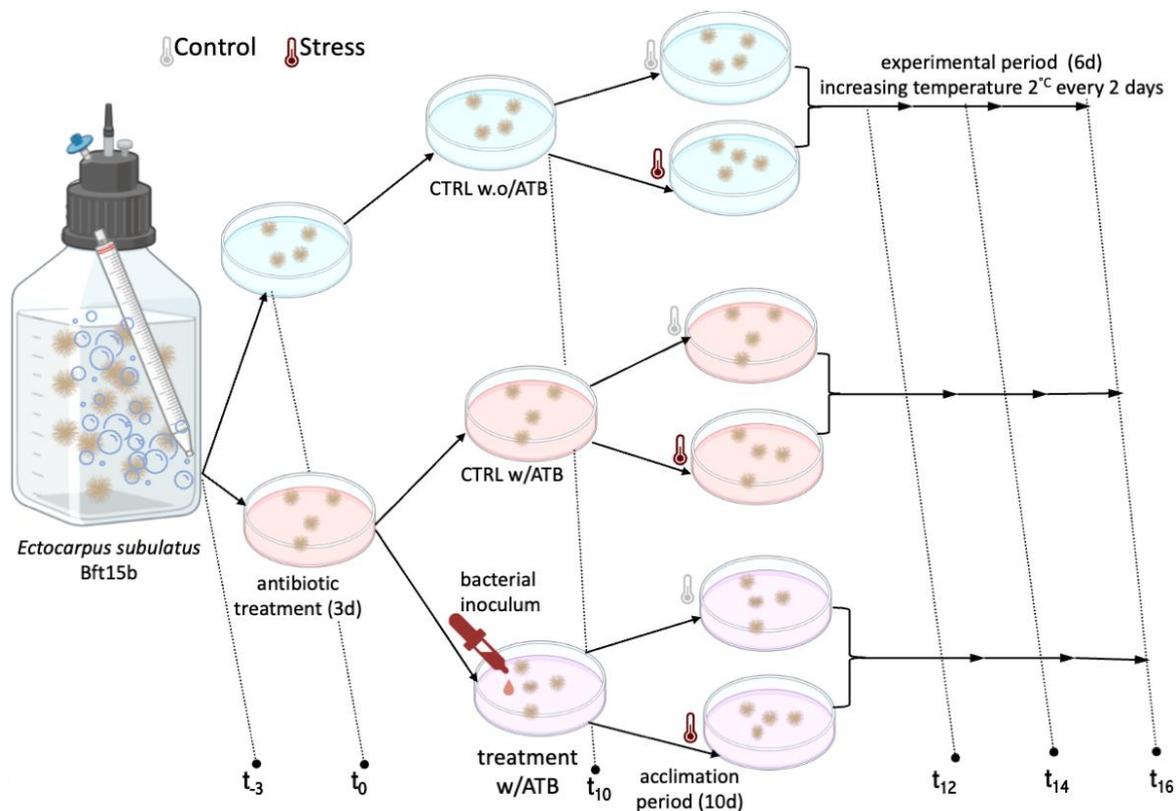
## 418 **Funding**

419 This work was supported by the Centre national de la recherche scientifique (CNRS)  
420 [Momentum call 2017].

421 **Conflict of interest**

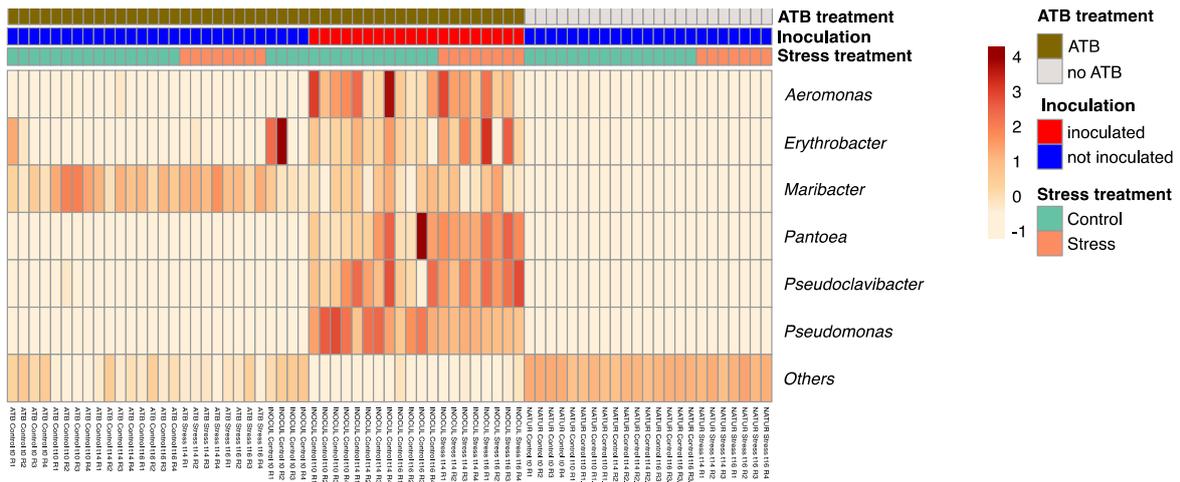
422 The authors declare that they have no conflict of interest.

423 **Figures and Tables**

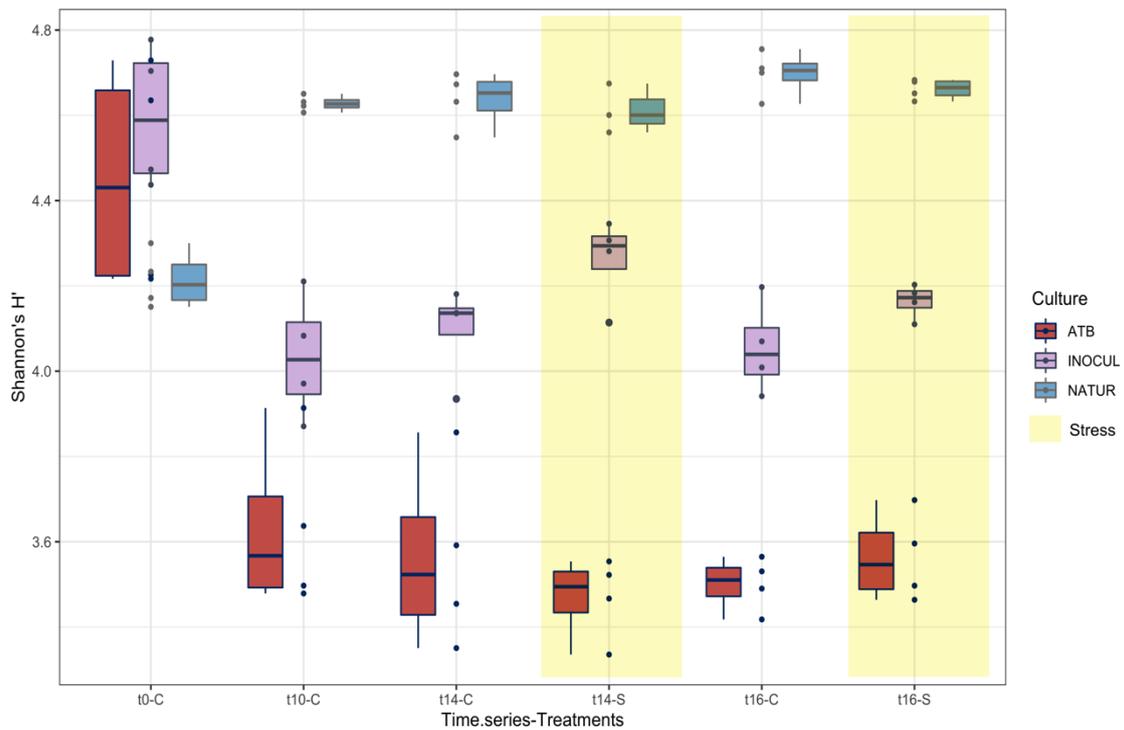


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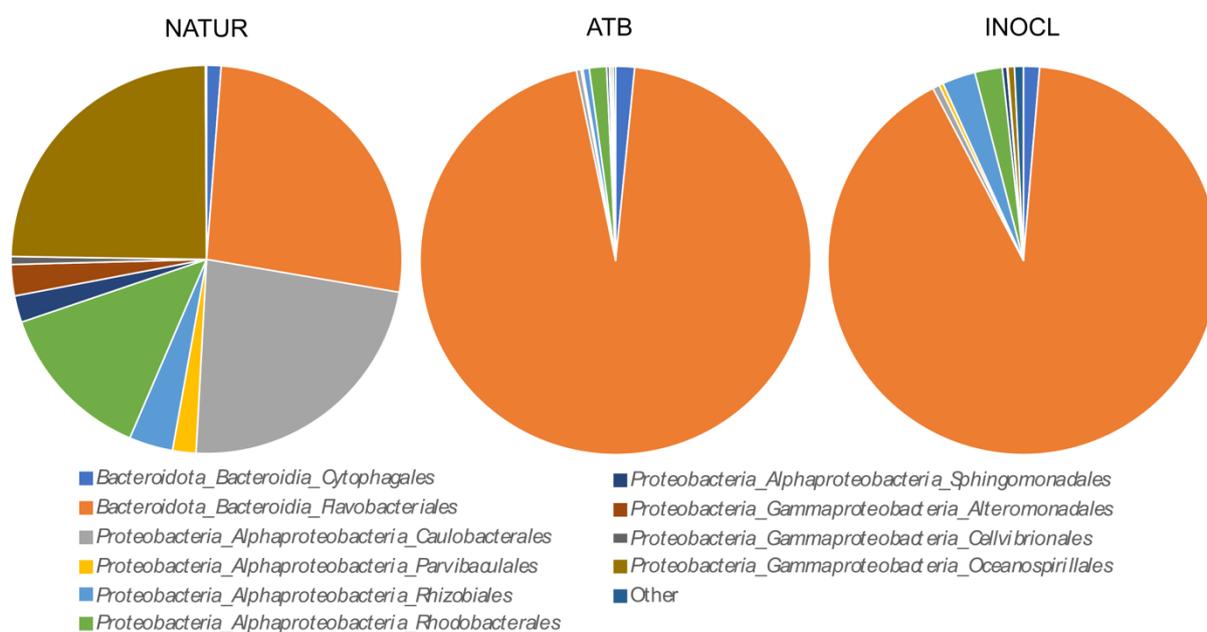
**Fig. 1.** A schematic illustration of the sampling design and experimental procedure. *Ectocarpus subulatus* was cultivated from stock populations of strain Bft15b. In the climate chamber (16°C) algae were grown for 7 weeks and divided into two series in petri dishes. One of the series was treated for three days with a mixture of two antibiotics (CHL & NEO), after which this group were divided into two series and one series received inoculum of 7 different bacteria. All samples stayed at the same temperature for 10 days. Later, replicates of each condition were moved to higher temperatures where the temperature was increased every 2 days in 2°C. Microbiota samples were taken directly after their separation (t-3), before inoculation (t0), after acclimation(t10), and after 4 and 6 days (t14 and t16). Parts of the figure were created with BioRender.com.



437  
 438 **Fig. 2.** Heatmap of relative read abundances corresponding to inoculated bacteria vs. other  
 439 bacteria. Rows are centered; unit variance scaling is applied to rows.  
 440

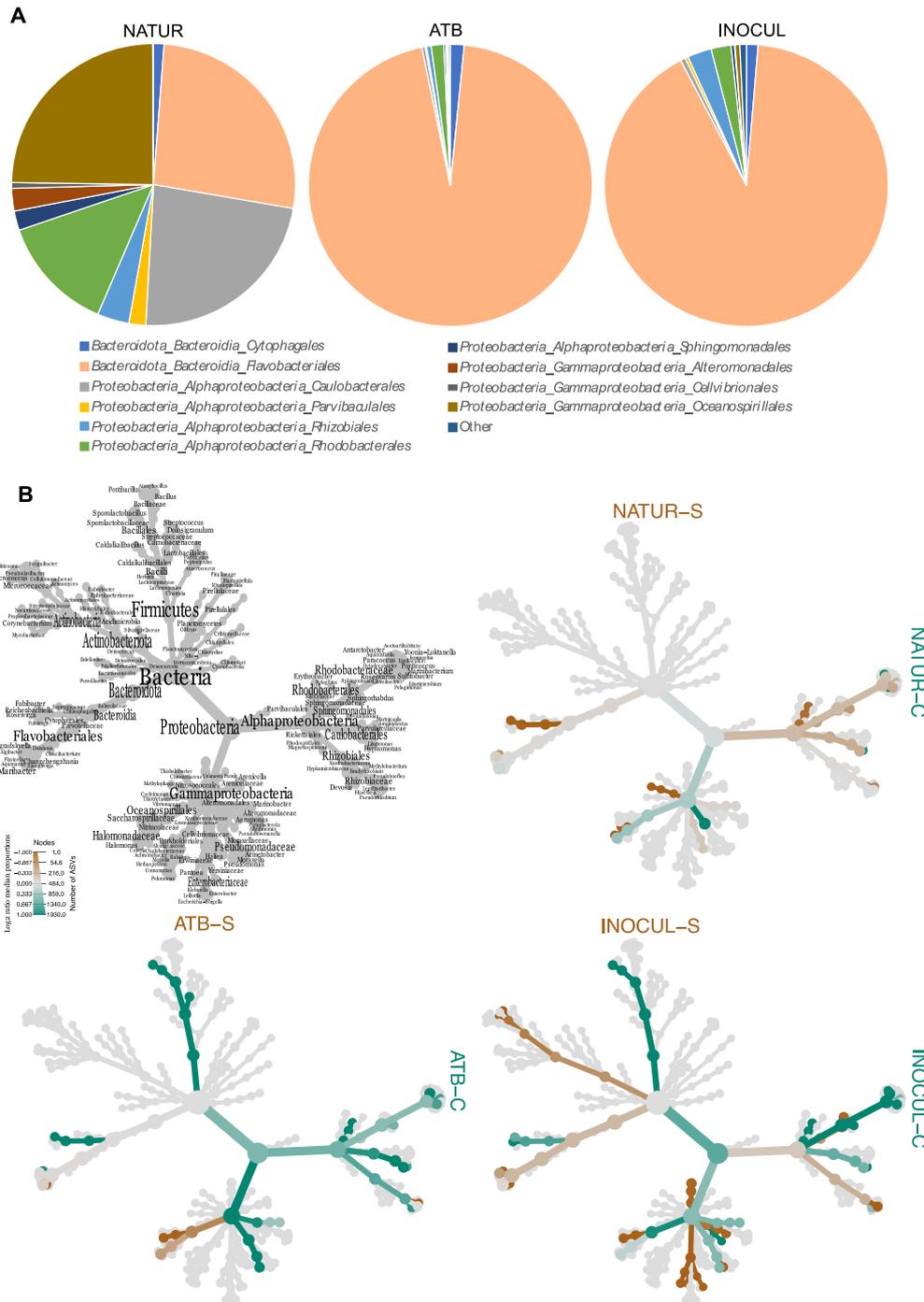


441  
 442 **Fig. 3.** Bacterial Alpha diversity. The dot-plot figures show the Shannon diversity of the  
 443 bacterial communities in the three culture treatment groups, ATB, INOCUL, and NATUR,  
 444 and at different time points in either control (C) or stress conditions (S). Calculations are  
 445 based on the relative abundance of observed ASVs.



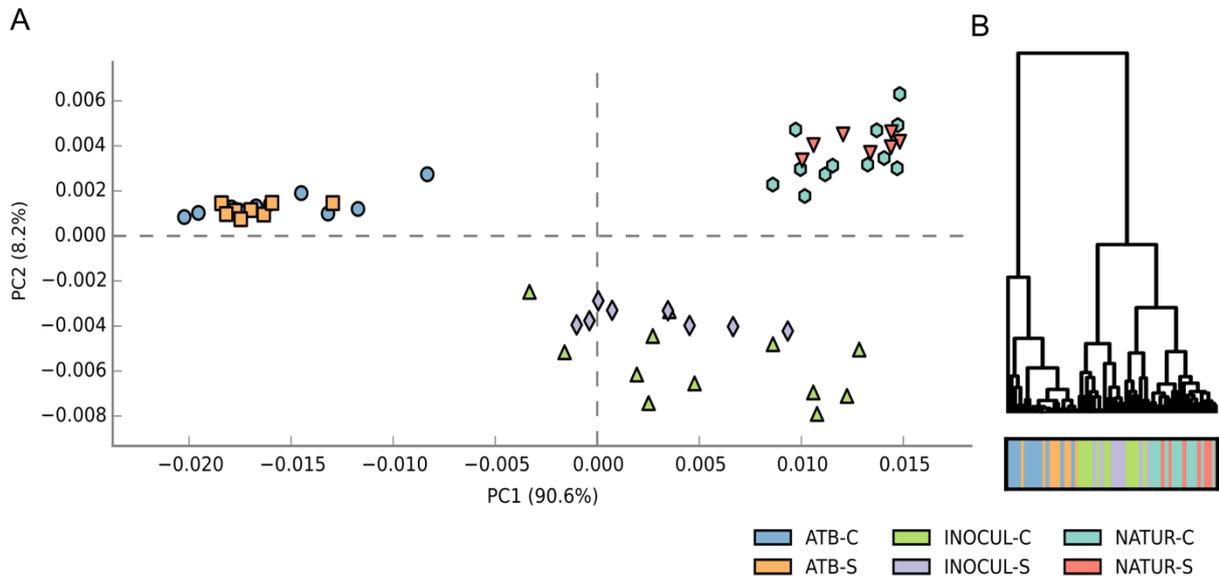
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**Fig. 4.** Bacterial community composition varies based on algae culture conditions. NMDS visualization of beta diversity of the bacterial communities in culture conditions and in time series in stress and control treatments (C for control and S for stressed), based on Bray–Curtis dissimilarity matrices. Each point is an individual replicate. Based on PERMANOVA testing, temperature changes had no significant effects; PERMANOVA results for the comparison of ATB, INOCL, and NATUR are displayed in the figure.



455  
 456 **Fig. 5.** A) Bacterial community in three culture conditions at the order level. Taxon with  
 457 abundances more than 0.1% for all three conditions (the remaining were grouped as  
 458 “others”). Only non-inoculated taxa were considered for this filter (please refer to Figure 2  
 459 for the inoculated taxa), and only samples after T10 (= time of inoculation), to keep the three  
 460 conditions comparable. B) Differential heat tree matrix depicting the change in relative read  
 461 abundance for the different taxa over different conditions and cultures. The number of taxa  
 462 identified at each taxonomic level is represented by the size of the individual nodes in the  
 463 gray cladogram. The smaller cladograms show pairwise comparisons between each culture  
 464 condition: a brown node indicates that the taxon is more abundant in culture condition labeled  
 465 in brown than in the one labeled in green and vice versa (C stands for Control (16 oC) and S  
 466 stands for stressed (20 and 22 oC).

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470 **Fig. 6.** A) Principal Component Analysis of predicted Metacyc pathways (Picrust2). B)  
471 Corresponding average neighbor UPGMA clustering.

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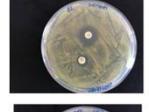
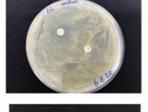
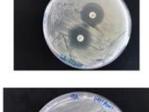
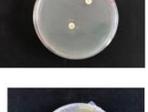
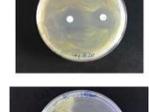
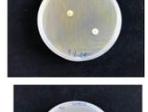
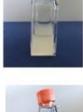
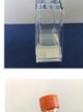
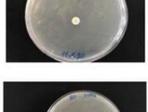
473 **Table 1.** The result of disk diffusion test for susceptibility of selected bacteria to CHL &  
474 NEO antibiotics before and after resistance. Optical density at 600 nm (OD600) was  
475 measured after 5 days of growth in liquid media containing both CHL and NEO antibiotics.

476

Selected bacteria consortia	Zone of inhibition (mm)				Growth in liquid media (OD600 after 5 days)
	Before gaining antibiotic-resistance		After gaining antibiotic-resistance		
	CHL	NEO	CHL	NEO	CHL & NEO
<i>Frigoribacterium</i> sp. 9N	61	16	26	0	0.000
<i>Pseudoclavibacter</i> sp. 8L	18	10	0	0	1.186
<i>Maribacter</i> sp. 151	15	0	0	0	0.184
<i>Bacillus</i> sp. 9J	19	22	0	0	0.000
<i>Aeromonas</i> sp. 9A	43	18	0	0	0.671
<i>Erythrobacter</i> sp. EC-HK427	23	21	0	0	0.128
<i>Novosphingobium</i> sp. 9U	51	18	0	0	0.001
<i>Pantoea</i> sp. 111	33	23	0	0	0.432
<i>Pseudomonas</i> sp. 8O	0	22	0	0	0.301
<i>Rhizobium</i> sp. EC-SD404	56	17	0	0	0.145

477

## Supplementary materials

Selected bacteria consortia	Before ATB resistant	After ATB resistant	Liquid media Inoculation Before ATB resistant	Liquid media Inoculation After ATB resistant
<i>Frigoribacterium</i> sp. 9N				
<i>Pseudoclavibacter</i> sp. 8L				
<i>Maribacter</i> sp. 151				
<i>Bacillus</i> sp. 9J				
<i>Aeromonas</i> sp. 9A				
<i>Erythrobacter</i> sp. EC-HK427				
<i>Novosphingobium</i> sp. 9U				
<i>Pantoea</i> sp. 111				
<i>Pseudomonas</i> sp. 8O				
<i>Rhizobium</i> sp. EC-SD404				

479

480 **Figure S1.** The appearance of normal and antibiotic resistant strains on R2A agar and liquid  
481 R2A medium. The antibiotic discs correspond to Neomycine and Chloraphenicolcol,  
482 respectively. The liquid ABT treatment corresponded to a mixture of Chloramphenicol (9.6  
483 µg/ml) and Neomycin (24.8µg/ml). Photos were taken 5 days after inoculation

484

485 **Table S1.** Overview of minimal bacteria consortia predicted by MiSCoTo and of Antibiotic  
486 resistance survey.

487



495 **Table S3: Sample metadata**

SampleID	Culture	Replicate	Time series	Temperature	Treatment	CUTim	CuT	CuTimTr
T0.C1.1.1	ATB	R1	t0	16OC	Control	t0-C	ATB-C	ATB-t0-C
T0.C1.2.1	ATB	R2	t0	16OC	Control	t0-C	ATB-C	ATB-t0-C
T0.C1.3.1	ATB	R3	t0	16OC	Control	t0-C	ATB-C	ATB-t0-C
T0.C1.4.1	ATB	R4	t0	16OC	Control	t0-C	ATB-C	ATB-t0-C
T0.C2.1.1	NATUR	R1	t0	16OC	Control	t0-C	NATUR-C	NATUR-t0-C
T0.C2.2.1	NATUR	R2	t0	16OC	Control	t0-C	NATUR-C	NATUR-t0-C
T0.C2.3.1	NATUR	R3	t0	16OC	Control	t0-C	NATUR-C	NATUR-t0-C
T0.C2.4.1	NATUR	R4	t0	16OC	Control	t0-C	NATUR-C	NATUR-t0-C
T0.T1.1	INOCUL	R1	t0	16OC	Control	t0-C	INOCUL-C	INOCUL-t0-C
T0.T2.1	INOCUL	R2	t0	16OC	Control	t0-C	INOCUL-C	INOCUL-t0-C
T0.T3.1	INOCUL	R3	t0	16OC	Control	t0-C	INOCUL-C	INOCUL-t0-C
T0.T4.1	INOCUL	R4	t0	16OC	Control	t0-C	INOCUL-C	INOCUL-t0-C
T10.C1.5.1	ATB	R1	t10	16OC	Control	t10-C	ATB-C	ATB-t10-C
T10.C1.6.1	ATB	R1	t10	16OC	Control	t10-C	ATB-C	ATB-t10-C
T10.C1.7.1	ATB	R1	t10	16OC	Control	t10-C	ATB-C	ATB-t10-C
T10.C1.8.1	ATB	R1	t10	16OC	Control	t10-C	ATB-C	ATB-t10-C
T10.C2.5.1	NATUR	R1	t10	16OC	Control	t10-C	NATUR-C	NATUR-t10-C
T10.C2.6.1	NATUR	R1	t10	16OC	Control	t10-C	NATUR-C	NATUR-t10-C
T10.C2.7.1	NATUR	R1	t10	16OC	Control	t10-C	NATUR-C	NATUR-t10-C
T10.C2.8.1	NATUR	R1	t10	16OC	Control	t10-C	NATUR-C	NATUR-t10-C
T10.T5.1	INOCUL	R1	t10	16OC	Control	t10-C	INOCUL-C	INOCUL-t10-C
T10.T6.1	INOCUL	R1	t10	16OC	Control	t10-C	INOCUL-C	INOCUL-t10-C
T10.T7.1	INOCUL	R1	t10	16OC	Control	t10-C	INOCUL-C	INOCUL-t10-C
T10.T8.1	INOCUL	R1	t10	16OC	Control	t10-C	INOCUL-C	INOCUL-t10-C
T10.C1.5.2	ATB	R2	t14	16OC	Control	t14-C	ATB-C	ATB-t14-C
T10.C1.6.2	ATB	R2	t14	16OC	Control	t14-C	ATB-C	ATB-t14-C
T10.C1.7.2	ATB	R2	t14	16OC	Control	t14-C	ATB-C	ATB-t14-C
T10.C1.8.2	ATB	R2	t14	16OC	Control	t14-C	ATB-C	ATB-t14-C
T10.C2.5.2	NATUR	R2	t14	16OC	Control	t14-C	NATUR-C	NATUR-t14-C
T10.C2.6.2	NATUR	R2	t14	16OC	Control	t14-C	NATUR-C	NATUR-t14-C
T10.C2.7.2	NATUR	R2	t14	16OC	Control	t14-C	NATUR-C	NATUR-t14-C
T10.C2.8.2	NATUR	R2	t14	16OC	Control	t14-C	NATUR-C	NATUR-t14-C
T10.T5.2	INOCUL	R2	t14	16OC	Control	t14-C	INOCUL-C	INOCUL-t14-C
T10.T6.2	INOCUL	R2	t14	16OC	Control	t14-C	INOCUL-C	INOCUL-t14-C
T10.T7.2	INOCUL	R2	t14	16OC	Control	t14-C	INOCUL-C	INOCUL-t14-C
T10.T8.2	INOCUL	R2	t14	16OC	Control	t14-C	INOCUL-C	INOCUL-t14-C
T14.C1.1.2	ATB	R1	t14	20OC	Stress	t14-S	ATB-S	ATB-t14-S
T14.C1.2.2	ATB	R2	t14	20OC	Stress	t14-S	ATB-S	ATB-t14-S
T14.C1.3.2	ATB	R3	t14	20OC	Stress	t14-S	ATB-S	ATB-t14-S
T14.C1.4.2	ATB	R4	t14	20OC	Stress	t14-S	ATB-S	ATB-t14-S
T14.C2.1.2	NATUR	R1	t14	20OC	Stress	t14-S	NATUR-S	NATUR-t14-S
T14.C2.2.2	NATUR	R2	t14	20OC	Stress	t14-S	NATUR-S	NATUR-t14-S
T14.C2.3.2	NATUR	R3	t14	20OC	Stress	t14-S	NATUR-S	NATUR-t14-S
T14.T1.2	INOCUL	R1	t14	20OC	Stress	t14-S	INOCUL-S	INOCUL-t14-S
T14.T2.2	INOCUL	R2	t14	20OC	Stress	t14-S	INOCUL-S	INOCUL-t14-S
T14.T3.2	INOCUL	R3	t14	20OC	Stress	t14-S	INOCUL-S	INOCUL-t14-S
T14.T4.2	INOCUL	R4	t14	20OC	Stress	t14-S	INOCUL-S	INOCUL-t14-S
T10.C1.5.3	ATB	R3	t16	16OC	Control	t16-C	ATB-C	ATB-t16-C
T10.C1.6.3	ATB	R3	t16	16OC	Control	t16-C	ATB-C	ATB-t16-C
T10.C1.7.3	ATB	R3	t16	16OC	Control	t16-C	ATB-C	ATB-t16-C
T10.C1.8.3	ATB	R3	t16	16OC	Control	t16-C	ATB-C	ATB-t16-C
T10.C2.5.3	NATUR	R3	t16	16OC	Control	t16-C	NATUR-C	NATUR-t16-C
T10.C2.6.3	NATUR	R3	t16	16OC	Control	t16-C	NATUR-C	NATUR-t16-C
T10.C2.7.3	NATUR	R3	t16	16OC	Control	t16-C	NATUR-C	NATUR-t16-C
T10.C2.8.3	NATUR	R3	t16	16OC	Control	t16-C	NATUR-C	NATUR-t16-C
T10.T5.3	INOCUL	R3	t16	16OC	Control	t16-C	INOCUL-C	INOCUL-t16-C
T10.T6.3	INOCUL	R3	t16	16OC	Control	t16-C	INOCUL-C	INOCUL-t16-C
T10.T7.3	INOCUL	R3	t16	16OC	Control	t16-C	INOCUL-C	INOCUL-t16-C
T10.T8.3	INOCUL	R3	t16	16OC	Control	t16-C	INOCUL-C	INOCUL-t16-C
T16.C1.1.3	ATB	R1	t16	22OC	Stress	t16-S	ATB-S	ATB-t16-S
T16.C1.2.3	ATB	R2	t16	22OC	Stress	t16-S	ATB-S	ATB-t16-S
T16.C1.3.3	ATB	R3	t16	22OC	Stress	t16-S	ATB-S	ATB-t16-S
T16.C1.4.3	ATB	R4	t16	22OC	Stress	t16-S	ATB-S	ATB-t16-S
T16.C2.1.3	NATUR	R1	t16	22OC	Stress	t16-S	NATUR-S	NATUR-t16-S
T16.C2.2.3	NATUR	R2	t16	22OC	Stress	t16-S	NATUR-S	NATUR-t16-S
T16.C2.3.3	NATUR	R3	t16	22OC	Stress	t16-S	NATUR-S	NATUR-t16-S
T16.C2.4.3	NATUR	R4	t16	22OC	Stress	t16-S	NATUR-S	NATUR-t16-S
T16.T1.3	INOCUL	R1	t16	22OC	Stress	t16-S	INOCUL-S	INOCUL-t16-S
T16.T2.3	INOCUL	R2	t16	22OC	Stress	t16-S	INOCUL-S	INOCUL-t16-S
T16.T3.3	INOCUL	R3	t16	22OC	Stress	t16-S	INOCUL-S	INOCUL-t16-S
T16.T4.3	INOCUL	R4	t16	22OC	Stress	t16-S	INOCUL-S	INOCUL-t16-S

497 **Table S4: Alpha diversity indices**

SampleID	observ	diversity_inverse_simpson	diversity_shannon	evenness_pielou	evenness_simpson	dominance_simpson	Samples	Culture	Replicate	Time	serit	Treatment	diversity_
T0.C1.1.1	209	65.78122375	4.635674766	0.867724584	0.314742697	0.015201906	T0.C1.1.1	ATB	R1	10	Control	4.63567	
T0.C1.2.1	255	38.48769115	4.226029821	0.762647325	0.150932122	0.025982333	T0.C1.2.1	ATB	R2	10	Control	4.22603	
T0.C1.3.1	288	41.2517411	4.217438891	0.744741007	0.143235212	0.024241401	T0.C1.3.1	ATB	R3	10	Control	4.21744	
T0.C1.4.1	298	74.5814328	4.728967766	0.830066731	0.250273264	0.013408163	T0.C1.4.1	ATB	R4	10	Control	4.72897	
T0.C2.1.1	225	44.74440875	4.23407198	0.7817156553	0.198864039	0.022349161	T0.C2.1.1	NATUR	R1	10	Control	4.23407	
T0.C2.2.1	238	45.12952927	4.300670806	0.785902427	0.189619871	0.022158441	T0.C2.2.1	NATUR	R2	10	Control	4.30067	
T0.C2.3.1	179	41.24542802	4.172227154	0.804302458	0.230421386	0.024245111	T0.C2.3.1	NATUR	R3	10	Control	4.17223	
T0.C2.4.1	177	41.15570958	4.151394901	0.802023727	0.232518133	0.024297965	T0.C2.4.1	NATUR	R4	10	Control	4.15139	
T0.T1.1	251	69.72233233	4.704260973	0.851380154	0.277778216	0.014342607	T0.T1.1	INOCUL	R1	10	Control	4.70426	
T0.T2.1	266	46.00625713	4.438163262	0.794871711	0.172955854	0.021736174	T0.T2.1	INOCUL	R2	10	Control	4.43816	
T0.T3.1	164	53.64678016	4.473598783	0.877199206	0.327114513	0.018640448	T0.T3.1	INOCUL	R3	10	Control	4.4736	
T0.T4.1	174	90.64201747	4.7773896	0.926020235	0.520931135	0.011032411	T0.T4.1	INOCUL	R4	10	Control	4.77739	
T10.C1.5.1	177	33.74147097	3.914423733	0.756242368	0.19062978	0.029637119	T10.C1.5.1	ATB	R1	110	Control	3.91442	
T10.C1.5.2	98	28.07568219	3.592672977	0.783576545	0.286486553	0.035618013	T10.C1.5.2	ATB	R2	114	Control	3.59267	
T10.C1.5.3	135	27.29934797	3.56516948	0.726803215	0.202217392	0.036630912	T10.C1.5.3	ATB	R3	116	Control	3.56517	
T10.C1.6.1	136	26.24648506	3.637250204	0.740383823	0.192988861	0.03810034	T10.C1.6.1	ATB	R1	110	Control	3.63725	
T10.C1.6.2	157	29.05649781	3.85749491	0.762916808	0.185073234	0.03441571	T10.C1.6.2	ATB	R2	114	Control	3.85749	
T10.C1.6.3	93	22.96305467	3.418635611	0.754232889	0.246914566	0.043548213	T10.C1.6.3	ATB	R3	116	Control	3.41864	
T10.C1.7.1	102	23.85773713	3.499143526	0.75657602	0.233899384	0.041915124	T10.C1.7.1	ATB	R1	110	Control	3.49914	
T10.C1.7.2	79	25.90684317	3.454466107	0.790595568	0.327934724	0.03859984	T10.C1.7.2	ATB	R2	114	Control	3.45447	
T10.C1.7.3	116	26.25661718	3.491088725	0.734410958	0.226350148	0.038085637	T10.C1.7.3	ATB	R3	116	Control	3.49109	
T10.C1.8.1	79	26.21848815	3.481378962	0.796754894	0.331879597	0.038141025	T10.C1.8.1	ATB	R1	110	Control	3.48138	
T10.C1.8.2	43	24.86083096	3.350589429	0.890829875	0.578158859	0.040223917	T10.C1.8.2	ATB	R2	114	Control	3.35059	
T10.C1.8.3	126	26.05771462	3.53113836	0.730134518	0.206807259	0.038376351	T10.C1.8.3	ATB	R3	116	Control	3.53114	
T10.C2.5.1	212	74.28521389	4.632241655	0.864774955	0.350401952	0.013461629	T10.C2.5.1	NATUR	R1	110	Control	4.63224	
T10.C2.5.2	189	83.92979251	4.697185043	0.896110596	0.444072976	0.01191472	T10.C2.5.2	NATUR	R2	114	Control	4.69719	
T10.C2.5.3	225	80.11557242	4.710398875	0.86970302	0.356069211	0.012481968	T10.C2.5.3	NATUR	R3	116	Control	4.7104	
T10.C2.6.1	213	74.69027018	4.606759794	0.859262963	0.350658545	0.013388625	T10.C2.6.1	NATUR	R1	110	Control	4.60676	
T10.C2.6.2	174	66.37871193	4.548269015	0.88160889	0.38148685	0.015065071	T10.C2.6.2	NATUR	R2	114	Control	4.54827	
T10.C2.6.3	249	78.98156023	4.700432287	0.851920691	0.317195021	0.012661183	T10.C2.6.3	NATUR	R3	116	Control	4.70043	
T10.C2.7.1	211	69.2924844	4.650856196	0.869017093	0.3284004	0.01443158	T10.C2.7.1	NATUR	R1	110	Control	4.65086	
T10.C2.7.2	184	80.99832624	4.673556145	0.896186715	0.440208295	0.012345934	T10.C2.7.2	NATUR	R2	114	Control	4.67356	
T10.C2.7.3	218	85.55253821	4.7562912	0.883330961	0.392442836	0.011688724	T10.C2.7.3	NATUR	R3	116	Control	4.75629	
T10.C2.8.1	190	74.89523757	4.62209168	0.880897746	0.394185461	0.013351984	T10.C2.8.1	NATUR	R1	110	Control	4.62209	
T10.C2.8.2	180	80.36303348	4.632489935	0.892071717	0.446461297	0.012443532	T10.C2.8.2	NATUR	R2	114	Control	4.63249	
T10.C2.8.3	137	84.05821921	4.628136766	0.940681851	0.613563644	0.011896515	T10.C2.8.3	NATUR	R3	116	Control	4.62814	
T10.T5.1	219	47.03336789	4.21044067	0.781293009	0.214764237	0.021261501	T10.T5.1	INOCUL	R1	110	Control	4.21044	
T10.T5.2	154	49.00811558	4.181015705	0.830068503	0.318234517	0.020404784	T10.T5.2	INOCUL	R2	114	Control	4.18102	
T10.T5.3	308	40.03152867	4.197199523	0.732482798	0.129972496	0.02498031	T10.T5.3	INOCUL	R3	116	Control	4.1972	
T10.T6.1	186	33.84163918	3.971480712	0.759983398	0.181944297	0.029549396	T10.T6.1	INOCUL	R1	110	Control	3.97148	
T10.T6.2	223	40.64345664	4.136779158	0.765054142	0.182257653	0.024604206	T10.T6.2	INOCUL	R2	114	Control	4.13678	
T10.T6.3	276	37.22721221	4.00881605	0.713261589	0.134881204	0.026862071	T10.T6.3	INOCUL	R3	116	Control	4.00882	
T10.T7.1	185	31.58692654	3.871084439	0.74153651	0.170740143	0.031658667	T10.T7.1	INOCUL	R1	110	Control	3.87108	
T10.T7.2	160	35.14782616	3.936141947	0.77556791	0.219673913	0.028451262	T10.T7.2	INOCUL	R2	114	Control	3.93614	
T10.T7.3	93	39.43890971	3.944210131	0.870187215	0.424074298	0.025355671	T10.T7.3	INOCUL	R3	116	Control	3.94421	
T10.T8.1	166	42.21993156	4.083087617	0.798727968	0.254336937	0.023685496	T10.T8.1	INOCUL	R1	110	Control	4.08309	
T10.T8.2	132	45.36915441	4.136098168	0.84707474	0.343705715	0.022041407	T10.T8.2	INOCUL	R2	114	Control	4.1361	
T10.T8.3	91	48.60877442	4.072871344	0.902903613	0.534162356	0.020572417	T10.T8.3	INOCUL	R3	116	Control	4.07287	
T14.C1.1.2	139	26.6325972	3.522960835	0.713948616	0.191601419	0.037547971	T14.C1.1.2	ATB	R1	114	Stress	3.52296	
T14.C1.2.2	179	27.10209912	3.553855546	0.685095669	0.151408375	0.036897511	T14.C1.2.2	ATB	R2	114	Stress	3.55386	
T14.C1.3.2	91	26.02346602	3.466769225	0.768538506	0.285972154	0.038426887	T14.C1.3.2	ATB	R3	114	Stress	3.46677	
T14.C1.4.2	56	23.4850157	3.335479527	0.828618164	0.41937528	0.042580342	T14.C1.4.2	ATB	R4	114	Stress	3.33548	
T14.C2.1.2	272	75.26543255	4.674614986	0.833888698	0.276711149	0.013286312	T14.C2.1.2	NATUR	R1	114	Stress	4.67461	
T14.C2.2.2	217	62.60492596	4.601035183	0.855227318	0.288501963	0.015973184	T14.C2.2.2	NATUR	R2	114	Stress	4.60104	
T14.C2.3.2	155	74.61757064	4.561388604	0.904422788	0.481403682	0.013401669	T14.C2.3.2	NATUR	R3	114	Stress	4.56139	
T14.T1.2	190	53.79228637	4.281279434	0.81594431	0.283117297	0.018590026	T14.T1.2	INOCUL	R1	114	Stress	4.28128	
T14.T2.2	189	56.61200628	4.306787689	0.821632115	0.299534425	0.017664098	T14.T2.2	INOCUL	R2	114	Stress	4.30679	
T14.T3.2	189	40.99063856	4.114243293	0.784899249	0.216881686	0.024395814	T14.T3.2	INOCUL	R3	114	Stress	4.11424	
T14.T4.2	233	49.92241343	4.345744892	0.797232478	0.214259285	0.020031083	T14.T4.2	INOCUL	R4	114	Stress	4.34574	
T16.C1.1.3	90	28.25051255	3.597787761	0.799542208	0.313894584	0.035397588	T16.C1.1.3	ATB	R1	116	Stress	3.59779	
T16.C1.2.3	78	26.81241268	3.49944082	0.803231113	0.343748881	0.037296159	T16.C1.2.3	ATB	R2	116	Stress	3.49944	
T16.C1.3.3	84	24.28141145	3.463833842	0.781759662	0.289064422	0.041183767	T16.C1.3.3	ATB	R3	116	Stress	3.46383	
T16.C1.4.3	140	28.88896355	3.697664293	0.74826626	0.20634974	0.034615295	T16.C1.4.3	ATB	R4	116	Stress	3.69766	
T16.C2.1.3	204	79.81586584	4.683226149	0.880616864	0.391254244	0.012528837	T16.C2.1.3	NATUR	R1	116	Stress	4.68323	
T16.C2.2.3	186	77.55819577	4.679194648	0.895411688	0.416979547	0.012893544	T16.C2.2.3	NATUR	R2	116	Stress	4.67919	
T16.C2.3.3	160	82.08859129	4.651729504	0.916565555	0.513053696	0.012181961	T16.C2.3.3	NATUR	R3	116	Stress	4.65173	
T16.C2.4.3	148	79.66507831	4.632648617	0.927046594	0.538277556	0.012552552	T16.C2.4.3	NATUR	R4	116	Stress	4.63265	
T16.T1.3	147	50.17991874	4.185223671	0.838649475	0.341359991	0.019928291	T16.T1.3	INOCUL	R1	116	Stress	4.18522	
T16.T2.3	139	48.8280097	4.161652927	0.843383304	0.351280645	0.020480048	T16.T2.3	INOCUL	R2	116	Stress	4.16165	
T16.T3.3	146	42.16212629	4.111702288	0.825045514	0.288781687	0.023717969	T16.T3.3	INOCUL	R3	116	Stress	4.1117	
T16.T4.3	160	43.49963987	4.204619415	0.828468062	0.271872749	0.022988696	T16.T4.3	INOCUL	R4	116	Stress	4.20462	

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501 **Table S5: NSTI values**

SampleID	Culture	Replicate	Time series	Treatment	NSTI
T0.C1.1.1	ATB	R1	t0	Control	0.05677776
T0.C1.2.1	ATB	R2	t0	Control	0.0480
T0.C1.3.1	ATB	R3	t0	Control	0.0496
T0.C1.4.1	ATB	R4	t0	Control	0.05315927
T0.C2.1.1	NATUR	R1	t0	Control	0.04720949
T0.C2.2.1	NATUR	R2	t0	Control	0.05315927
T0.C2.3.1	NATUR	R3	t0	Control	0.04734416
T0.C2.4.1	NATUR	R4	t0	Control	0.04673616
T0.T1.1	INOCUL	R1	t0	Control	0.0553017
T0.T2.1	INOCUL	R2	t0	Control	0.05546127
T0.T3.1	INOCUL	R3	t0	Control	0.07043085
T0.T4.1	INOCUL	R4	t0	Control	0.06053751
T10.C1.5.1	ATB	R1	t10	Control	0.04864208
T10.C1.5.2	ATB	R2	t14	Control	0.04340053
T10.C1.5.3	ATB	R3	t16	Control	0.04382899
T10.C1.6.1	ATB	R1	t10	Control	0.04341665
T10.C1.6.2	ATB	R2	t14	Control	0.04851226
T10.C1.6.3	ATB	R3	t16	Control	0.04374442
T10.C1.7.1	ATB	R1	t10	Control	0.04311913
T10.C1.7.2	ATB	R2	t14	Control	0.04358509
T10.C1.7.3	ATB	R3	t16	Control	0.04304645
T10.C1.8.1	ATB	R1	t10	Control	0.04264456
T10.C1.8.2	ATB	R2	t14	Control	0.04164816
T10.C1.8.3	ATB	R3	t16	Control	0.04409102
T10.C2.5.1	NATUR	R1	t10	Control	0.05293795
T10.C2.5.2	NATUR	R2	t14	Control	0.05307948
T10.C2.5.3	NATUR	R3	t16	Control	0.05537418
T10.C2.6.1	NATUR	R1	t10	Control	0.05197292
T10.C2.6.2	NATUR	R2	t14	Control	0.05423166
T10.C2.6.3	NATUR	R3	t16	Control	0.05245814
T10.C2.7.1	NATUR	R1	t10	Control	0.05202842
T10.C2.7.2	NATUR	R2	t14	Control	0.05386173
T10.C2.7.3	NATUR	R3	t16	Control	0.05369354
T10.C2.8.1	NATUR	R1	t10	Control	0.05183283
T10.C2.8.2	NATUR	R2	t14	Control	0.05072544
T10.C2.8.3	NATUR	R3	t16	Control	0.05721365
T10.T5.1	INOCUL	R1	t10	Control	0.04151147
T10.T5.2	INOCUL	R2	t14	Control	0.04244061
T10.T5.3	INOCUL	R3	t16	Control	0.04461342
T10.T6.1	INOCUL	R1	t10	Control	0.03788673
T10.T6.2	INOCUL	R2	t14	Control	0.0398021
T10.T6.3	INOCUL	R3	t16	Control	0.03852778
T10.T7.1	INOCUL	R1	t10	Control	0.03395527
T10.T7.2	INOCUL	R2	t14	Control	0.03544289
T10.T7.3	INOCUL	R3	t16	Control	0.03448663
T10.T8.1	INOCUL	R1	t10	Control	0.03623997
T10.T8.2	INOCUL	R2	t14	Control	0.03998218
T10.T8.3	INOCUL	R3	t16	Control	0.03943479
T14.C1.1.2	ATB	R1	t14	Stress	0.04345972
T14.C1.2.2	ATB	R2	t14	Stress	0.04259941
T14.C1.3.2	ATB	R3	t14	Stress	0.04323101
T14.C1.4.2	ATB	R4	t14	Stress	0.04309568
T14.C2.1.2	NATUR	R1	t14	Stress	0.05366224
T14.C2.2.2	NATUR	R2	t14	Stress	0.05228219
T14.C2.3.2	NATUR	R3	t14	Stress	0.05131831
T14.T1.2	INOCUL	R1	t14	Stress	0.04079558
T14.T2.2	INOCUL	R2	t14	Stress	0.03898642
T14.T3.2	INOCUL	R3	t14	Stress	0.04335328
T14.T4.2	INOCUL	R4	t14	Stress	0.04521808
T16.C1.1.3	ATB	R1	t16	Stress	0.04490096
T16.C1.2.3	ATB	R2	t16	Stress	0.04253589
T16.C1.3.3	ATB	R3	t16	Stress	0.04382073
T16.C1.4.3	ATB	R4	t16	Stress	0.04592268
T16.C2.1.3	NATUR	R1	t16	Stress	0.05481751
T16.C2.2.3	NATUR	R2	t16	Stress	0.05781305
T16.C2.3.3	NATUR	R3	t16	Stress	0.05333084
T16.C2.4.3	NATUR	R4	t16	Stress	0.05764996
T16.T1.3	INOCUL	R1	t16	Stress	0.04373309
T16.T2.3	INOCUL	R2	t16	Stress	0.03842605
T16.T3.3	INOCUL	R3	t16	Stress	0.04360146
T16.T4.3	INOCUL	R4	t16	Stress	0.04543375

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