Probing the fabric of the rare biosphere

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Abstract: The relatively recent development of high-throughput sequencing (HTS) techniques has revealed a wealth of novel sequences found in very low abundance: the rare biosphere. Today, most studies of diversity of microorganisms are carried out almost exclusively with HTS techniques. However, culturing seems indispensable for diversity studies especially if the aim is exploring the rare biosphere. We have carried out a deep (1 million sequences per sample) pyrosequencing analysis of two marine bacterial samples and isolated a culture collection from one of them. We have shown that the collectors curves of the pyrosequencing data were close to reaching an asymptote. We have estimated the total richness of the samples and the sequencing effort necessary to obtain the total estimated richness experimentally. Comparing the pyrosequencing data and the isolates sequences we have found that isolation retrieves some of the rarest taxa and that the composition of rare taxa follows an annual succession. We have shown that increasing the number of tags sequenced would slowly uncover the isolated bacteria. However, even if the whole bacterial diversity was found by increasing the sampling depth, culturing would still be essential for the study of marine bacterial communities, especially if the target is the rare biosphere.

Introduction

The question of how many species of living beings are there on Earth has intrigued ecologists and evolutionary scientists for decades (May, 1988; Erwin, 1991). One of the most recent estimates considered a number of 8.7 million species, but excluded bacteria and archaea from the estimate due to our ignorance of the microorganisms (Mora *et al*., 2011). The International Census of Marine Microbes attempted to map the diversity of microbes in the oceans with novel high throughput sequencing techniques (Amaral-Zettler *et al*., 2010) but a global estimate was not attempted. Some estimates for marine bacterial species range from 10^4 to 10^6 based on different assumptions (Curtis *et al*., 2002; Hagström *et al*., 2002). Such a range of values, spanning several orders of magnitude, shows that we are far from a reasonable estimate.

Traditionally, bacteria were isolated in pure culture and then characterized biochemically and genetically until a new species could be formally described. It was realized that the bacteria able to grow in culture media were a small fraction of the bacterial cells that could be directly counted on a filter, a discrepancy named the "great plate count anomaly" (Staley & Konopka, 1985). Different studies estimated that only about 1% of the cells in natural waters could be cultivated (Pace, 1997; Eilers *et al*., 2000). Moreover, most of the cells in pure cultures were not the abundant ones in nature.

After the application of molecular cloning to natural systems (Giovannoni *et al*., 1990; Pace, 1997) a wealth of new taxa were found and, this time, they were the abundant ones in the oceans (DeLong, 1997; Pace, 1997). The drawback was that a sequence of the 16S rDNA did not provide much information about the physiology of the organism. Further, the

realization that bacteria obtained in culture were mostly different from bacterial sequences obtained in clone libraries, produced what could be called the "great clone library anomaly". Molecular methods could retrieve many sequences from the abundant organisms but missed the rare ones, and only occasionally a rare clone was found. Isolation, on the other hand, retrieved mostly rare bacteria and, occasionally an abundant one. This anomaly was a consequence of the fact that natural assemblages are formed a by a few taxa in very large concentrations and many taxa in very low concentrations. The problem can be easily visualized by looking at a rank-abundance curve (Pedrós-Alió, 2006). Primers for clone libraries will hybridize with the most abundant sequences over and over again before they find a rare target. Thus, only a fraction of the community will be available to cloning and sequencing. The relatively recent development of high-throughput sequencing (HTS) techniques and their application to natural microbial communities (Sogin *et al*., 2006) now provides an opportunity to solve the "great clone library anomaly".

The study of microbial communities with such technologies has revealed a wealth of novel sequences found in very low abundance: the rare biosphere (Sogin *et al*., 2006). And different properties of the latter have been examined (Galand *et al*., 2009; Jones & Lennon, 2010; Pedrós-Alió, 2012; Caporaso *et al*., 2012; Lynch *et al*., 2012; Gibbons *et al*., 2013). Today, most studies of diversity of microorganisms are carried out almost exclusively with such HTS techniques. Yet, culturing seems indispensable for diversity studies (Donachie *et al*., 2007; Shade *et al*., 2012; Lekunberri *et al*., 2014), especially if the aim is exploring the rare biosphere. In this regard, Shade *et al*. (2012) compared the outputs of a shallow (~ 2 000 sequences per sample) pyrosequencing analysis of the bacteria collected from a soil sample and the isolates cultured from the same sample. They found that 61% of the cultured bacteria

were not present in the pyrosequencing dataset, demonstrating that culturing provided a fruitful route to the rare biosphere that was complementary to sequencing. These authors postulated that they would have found that remaining cultured bacteria in the pyrosequencing dataset if hey had increased the sequencing depth.

But the question "can all the bacterial taxa isolated in culture from a sample be found by HTS?" has not been addressed in a direct and sufficiently exhaustive way. This question has several implications. First, an in depth comparison of both cultures and sequences should eventually solve the "great clone library anomaly". Second, it should provide an estimate of the total number of bacterial taxa in a sample. And third, it would allow a calculation of the sequencing effort necessary to retrieve all the diversity in a sample. We have addressed this question by carrying out a deep (1 million sequences per sample) pyrosequencing analysis of two marine bacterial samples and isolating a culture collection from one of them. Comparison of both data sets allowed us to bracket the dimensions of the rare biosphere, at least in these two marine samples.

Material and methods

1. Study area and sampling

Samples were taken in the NW Mediterranean Sea during cruise SUMMER between 13th and 22nd of September 2011, on board the RV "García del Cid". Specifically, the samples for this study were collected at Station D, an open sea station at 40º52'N and 02º47'E (Table 1, and Pedrós-Alió *et al*., 1999). The surface sample was taken at 5 m on 15th September and the bottom sample was collected at 2 000 m depth on 17th September.

114 Sampling was done with Niskin bottles mounted on a rosette with a conductivity-
115 temperature-depth (CTD) profiler. Water was prefiltered through a 200 µm mesh and
116 immediately processed on board. To collect microbial biomass, between 5 and 15 L of
117 sea-water were prefiltered through a 3 µm pore size Durapore filter (Millipore, Cork, Ireland)
118 and free-living bacterial biomass was collected on a 0.22 µm pore size Sterivex filter
119 (Durapore, Millipore). The filtration was done in succession using a peristaltic pump. The
120 0.22 µm pore size Sterivex unit was filled with 1.8 ml of lysis buffer (40 mM EDTA, 50 mM
121 Tris-HCl, 0.75 M sucrose) and stored at –80ºC. DNA was extracted by a standard protocol
122 using phenol/chloroform (details in Schauer *et al*., 2003).
123
124 *2. 454-pyrosequencing and noise removal*
125 Purified DNA samples were submitted to the Research and Testing Laboratory (Lubbock,
126 Texas, USA) for amplification of the 16S rRNA gene. Tag-pyrosequencing was done with
127 Roche 454 Titanium platform following manufacturer protocols (454 Life Science). Primers
128 28F (5'-GAGTTTGATCNTGGCTCAG) and 519R (5'-GTNTTACNGCGGCKGCTG) were
129 used for amplification of the hypervariable regions V1-V3; approximately 400 bp long tags
130 were obtained. PCR and subsequent sequencing are described in Dowd et al. (2008). 713 076
131 and 970 346 tags were retrieved from the surface and the bottom samples, respectively (Table
132 1). These data has been deposited in EMBL with accession number PRJEB9061.
133
134 The raw tag-sequences were processed using QIIME (Caporaso *et al*., 2010). Briefly, to
135 reduce sequencing errors and their effects, the multiplexed reads were first trimmed, quality-
136 filtered and assigned to the samples, surface or bottom. The filtering criteria included a
137 perfect match to the sequence barcode and primer, at least 400 bp in length, a quality score

138 window of 50 bp and a minimum average quality score of 28. Additionally, denoising was
139 used to reduce the amount of erroneous sequences (Quince *et al*., 2011). The final number of
140 tags was reduced after this processing to 500 262 for the surface sample and to 574 960 for
141 the bottom sample (Table 1). The sequences were then clustered into Operational Taxonomic
142 Units (OTUs) based on the relatedness of the sequences (97% similarity) with UCLUST.
143 Afterwards, a representative sequence from each OTU was selected. To identify potential
144 chimera sequences, the dataset was subjected to the ChimeraSlayer implemented in Mothur
145 (Schloss *et al*., 2011). Then, taxonomy assignment was made with QIIME by searching the
146 representative sequences of each OTU against the SILVA 16S/18S rDNA non-redundant
147 reference dataset (SSU Ref 108 NR) (Quast *et al*., 2013) using the Basic Local Alignment
148 Search Tool (BLAST) and an e-value of 0.03. Chimera, chloroplast, eukarya and archaea
149 sequences were removed from the output fasta file that was used for building a table with the
150 OTU abundance of each sample and the taxonomic assignments for each OTU.
151
152 In addition to the sequences obtained in the present study, we used a 454 pyrosequencing
153 dataset from cruise MODIVUS, for comparative purposes. Cruise MODIVUS took place in
154 September 2007 and sampled a transect between the Blanes Bay Microbial Observatory
155 (BBMO, http://www.icm.csic.es/bio/projects/icmicrobis/bbmo/), a coastal sampling site north
156 of Barcelona (41˚40'N, 02˚48'E) and Station D (40˚52'N, 02˚47'E), the open sea station
157 sampled here. The samples used for pyrosequencing included surface samples along the
158 transect and a vertical profile down to 2000 m at Station D. The MODIVUS data have been
159 published in Pommier *et al*. (2010) and Crespo *et al*. (2013). Due to the limitations of the
160 technique at the time, these sequences only included de V3 region of the 16S rDNA (~68 bp).
161

162 *3. Isolation of bacterial cultures*

163 Isolates were obtained on board by plating 100 µl of undiluted and 10x diluted sea-water
164 from the surface sample, in triplicates, onto modified Zobell agar plates (i.e. 5 g peptone, 1 g
165 yeast extract and 15 g agar in 1 l of 0.2 µm filtered 75% sea water). Agar plates were
166 incubated at *in situ* temperature (~20 °C), in the dark, for 14 days. 326 bacterial colonies
167 were selected and the cultures were subsequently purified by re-isolation three times in a
168 month. Next, isolates were grown at 20 ºC on the same liquid medium and stored at -80 ºC
169 with 25% (v/v) glycerol. 200 µl of these cultures were place in 96 well plates, diluted 1:4 and
170 heated (95ºC, 10 min) to cause cell lysis, so available DNA could be used as a template in
171 Polimerase Chain Reactions (PCR). PCR, using Taq polymerase (Boehringer-Mannheim), of
172 the Internal Transcribed Spacer (ITS) were done to select as many different species as
173 possible from the 326 isolates. ITS length is species specific and therefore allows to
174 differentiate the isolates (Fisher & Triplett 1999; Scheinert *et al*. 1996). ITS amplification
175 was done using primers ITS-F (5'-GTCGTAACAAGGTAGCCGTA) and ITS-R
176 (5'-GCCAAGGCATCCACC) and the following thermal conditions: 94ºC for 2 min, then 32
177 cycles of 94ºC for 15 sec, 55ºC for 30 sec, 72ºC for 3 min, followed by one cycle of 72ºC for
178 4 min and 4ºC on hold. According to their different ITS patterns, 148 isolates were chosen
179 out of 326, including some replicates, and their 16S rRNA gene were then amplified using
180 bacterial 16S rRNA gene primers 27F (5'-AGAGTTTGATCMTGGCTCAG) and 1492R (5'-
181 GTTTACCTTGTTACGACTT). The thermal conditions were as follows: 94ºC for 5 min,
182 then 30 cycles of 94ºC for 1 min, 55ºC for 1 min, 72ºC for 2 min, followed by one cycle of
183 72ºC for 10 min and 4ºC on hold. Nearly the full-length 16S rRNA gene (aprox. 1 300 bp)
184 was sequenced in GENOSCREEN (Lille Cedex, France). Taxonomical assignment was done
185 by BLAST searches in the National Center for Biotechnology Information (NCBI) website.

186 The 16S rRNA sequences have been deposited in EMBL with accession numbers LN845965
187 to LN846112.
188
189 In addition to the SUMMER culture collection obtained for the present study, we also
190 used three previously isolated collections for comparison. The isolation procedures were the
191 same as above, but the samples were collected at the Blanes Bay Microbial Observatory
192 (BBMO). Station D sampled in the present work is about 100 km offshore from the BBMO.
193 Culture collection BBMO-1 consisted of over 300 isolates collected between 2001 and 2004
194 at different times of the year. Collections BBMO-2 and BBMO-3 were smaller collections
195 isolated in February and September 2007 respectively. Since these cultures were isolated and
196 used for different purposes, many of them had only partial sequences of the 16S rDNA. A
197 description of these collections was published in Lekunberri *et al*. (2014).
198
199 *4. Richness, sampling effort estimates, and diversity of 454 pyrosequecing data*
200 Richness (S) was computed as the total number of OTUs (97% similarity) in each sample.
201 Estimates of total richness were calculated using two packages of the free software R (R Core
202 Team, 2013). The "vegan" package (Oksanen *et al*., 2013) was used for non-parametric
203 (S_{Chao}, Abundance-based Coverage Estimator [ACE]) estimations. The "drc" package (Ritz &
204 Streibig, 2005) was used to estimate richness by fitting the species accumulation curves to a
205 mathematical function. We fitted several mathematical functions to our data (Flather, 1996).
206 The best fits were given by Michaelis-Menten, Rational, and Weibull Cumulative functions.
207 The three parameter Weibull Cumulative function was the best of all according to the
208 coefficient of determination (R^2), the residual sum of squares (RSS), and Akaike's

information criterion (AIC) (Supplementary Table 1). The Weibull cumulative function takes the form:

$$a\,(1\text{-}\exp\,(\text{-}bx)^{c})$$

where a, b and c are fitted coefficients, and a is the maximal number of species predicted by the model, i.e. the asymptote.

The sampling effort necessary to obtained 99% and 99.9% of total estimated richness was calculated from the extrapolation of the species accumulation curves by fitting the Weibull Cumulative function and from the non-parametric estimation of Chao 1 using the method described in Chao *et al*. (2009).

Shannon (H') and Simpson (D) diversity indexes were used to calculate diversity:

$$H' = -\sum p_i \ln(p_i) \qquad (1)$$

$$D = 1 - \sum p_i^2 \qquad (2)$$

where $p_i = N_i/N$, the number of individuals of species *i* divided by the total number of individuals in the sample (N). Finally, evenness was computed with the Pielou index:

$$J' = H'/\ H\max \qquad (3)$$

where H' is the Shannon diversity index and H_{max} is the maximal possible Shannon diversity index if all the species were equally abundant:

$$H\max = -\sum (1/S)\ln(1/S) = \ln S \qquad (4)$$

where S is the total number of OTUs (richness). Diversity and evenness of each sample were calculated using the "vegan" package (Oksanen *et al*., 2013).

Rank-abundance plots of the isolated cultures and the 454 pyrosequencing data were done using the "BiodiversityR" package (Kindt & Coe, 2005) and the accumulation curves using the "vegan" package (Oksanen *et al*., 2013) of R (R Core Team, 2013).

232

233 *5. Comparison of 454-pyrosequencing tags and isolates*

234 Comparison between isolates and 454 tag-sequences was done running BLASTn locally.
235 Thus, the isolate sequences were searched for in the 454 tag-sequence datasets and vice
236 versa, and only the reciprocal matches between these two searches were considered. The
237 output was filtered using R (R Core Team, 2013) according to a 99% of identical nucleotide
238 matches, 75%-100% of coverage of the isolate sequence and a bit-score higher than 100. In
239 all the cases the e-value was lower than 0.0001.

240

241 Since the primers used for Sanger sequencing of the isolates and those used for the
242 pyrosequencing of the environmental DNA were different, the possibility existed of different
243 biases that could prevent detection of the cultures in the 454 dataset. Multiple alignments of
244 the sequences of the isolates and the sequences of the primers used in the pyrosequencing
245 analysis were done using the software Genious. The multiple alignments were used to check
246 that the 454 primers hybridized with the sequences of all the isolates.

247

248 In order to estimate the sequencing effort necessary to find all the isolates in the sequence
249 dataset, we did a kind of "rarefaction" analysis with detected isolates in the Y-axis and
250 number of 454 sequences or number of OTUs in the X-axis. The 454 tag-sequences were
251 subsampled in 5% intervals 1000 times and the percentage of coincidence with the isolate
252 sequences was calculated for each new 454 tag-sequence dataset and plotted against the
253 corresponding number of sequence tags analyzed. The same was done with the number of
254 OTUs. Calculations were done using R (R Core Team, 2013).

255

256 **Results**

257 *1. Pyrosequencing dataset*

258 Richness (S), computed as the total number of OTUs, was higher in the bottom (4 460)
259 than in the surface (1 400) sample (Table 1). In both samples only ~17% of the OTUs were
260 singletons (an OTU represented by a single sequence) (Table 1). Evenness (J') and diversity
261 (H' and D) were also higher in the bottom than in the surface sample (Table 1). Richness
262 estimations calculated with non-parametric methods, Chao Index and ACE, and with
263 parametric methods (Figure 1) were slightly higher than the actual number of OTUs (S)
264 observed as expected (Table 1). None of the estimates were significantly different from each
265 other (z-tests on the differences, all $P > 0.05$). The mathematical function that best fitted the
266 species accumulation curves was the Weibull Cumulative function (99% model efficiency or
267 $R^2 = 0.99$) (Figure 1). Fitting the species accumulation curve allowed both calculation of the
268 total richness of the samples by extrapolation (as explained above), and estimation of the
269 sequencing effort necessary to obtain the total estimated richness experimentally (Table 1).
270 Our estimates indicated that the sequencing effort necessary to retrieve 99% and 99.9% of the
271 total estimated richness should be 4 to 8 times higher that the one applied in this study (Table
272 1). These numbers are approximately twice higher that the estimations obtained from the
273 Chao index (Chao *et al*., 2009) (Table 1).

274

275 Rank-abundance curves (Figure 2) showed that the bacterial assemblages from both
276 samples were characterized by few abundant and many rare OTUs. The most abundant OTU
277 was more abundant in the surface than in the bottom sample, in agreement with the lower
278 evenness found for the surface sample (Table 1). The abundance of the most abundant OTU

279 in the bottom sample was close to the abundance of the second most abundant OTU in the
280 surface sample.
281
282 *2. Culture collection*
283 Bacterial isolation from the sample collected at the surface retrieved 148 cultures
284 belonging to 38 different species. The most frequent bacterium in the collection was
285 *Erythrobacter citreus*, isolated 37 times, while 17 species were isolated only once. A rank
286 abundance plot of the 38 species can be seen in Fig. 3. The isolates belonged to the phyla
287 *Actinobacteria* (4 isolates), *Bacteroidetes* (4 isolates) and *Firmicutes* (2 isolates) and to the
288 *Proteobacteria* classes Alpha-*proteobacteria* (18 isolates) and Gamma-*proteobacteria* (10
289 isolates). The names of all the isolates are shown in Table 2 and supplementary Table 2.
290
291 *3. Comparison of isolates and sequences*
292 Only 14 (37%) of the 38 different species were found in the 454 tag-sequence datasets:
293 one *Actinobacteria*, two *Bacteroidetes*, two *Firmicutes*, four Alpha-*proteobacteria* and five
294 Gamma-*proteobacteria* isolates (Figure 3, Table 2). Surprisingly, the number of cultures
295 found in the 454 tag-sequence dataset was higher in the sample collected at 2 000 m (37%)
296 than in the surface sample (24%), even though the latter was the sample used for isolation of
297 the bacterial cultures (Figure 3, Table 2). Nine species were found in the sequences from both
298 samples (maroon in Figure 3), 5 were found in the bottom sample only (green in Figure 3)
299 and 24 were not found in either sample (empty symbols in Figure 3). Practically all the 454
300 tag-sequences that matched the sequences from the isolates belonged to rare OTUs (<1% of
301 the total tags). Only the OTU matching the isolate *Alteromonas macleodii* str. 'Balearic Sea
302 AD45' (Gamma-*Proteobacteria*) was somewhat abundant (1.3%) in the bottom sample

303 (Table 2). Further, all the matching sequences made a larger percentage of the assemblage at
304 the bottom sample than at the surface sample.
305
306 In order to examine the rate of appearance of cultured species in the sequence database,
307 we calculated a kind of "rarefaction curves", by randomly resampling either the OTUs or the
308 454-pyrosequecing tags in 5% increases, and checking how many cultured species had been
309 found in each case (Figure 4). These curves showed that the rate of appearance of the isolates
310 in the 454 tags datasets as the sequencing depth increased was slower for tags than for OTUs
311 but in neither case was an asymptote reached (Figure 4). The rate of increase of retrieved
312 isolates versus OTUs was constant, but the rates were different at the two depths: one new
313 isolate was retrieved every 50 OTUs in the surface sample and every 117 OTUs in the bottom
314 sample (Figures 4A-B). The increase in retrieved isolates with respect to the number of tags
315 showed a nonlinear response, implying that the sampling effort had to increase as the number
316 of isolates increased (Figures 4C-D).
317
318 *4. Comparisons across different times and locations*
319 Three additional culture collections, isolated in the same way as the collection described
320 above (see material and methods), were available for comparisons with 454-pyrosequencing
321 data (A in Table 3). In addition to the 454-pyrosequecing dataset obtained in the present
322 study, 454 sequences from the MODIVUS cruise in September 2007 were also available (see
323 material and methods). These different datasets offered the possibility to compare how
324 effective was the retrieval of isolated species in 454 sequence datasets at different time and
325 space scales (B and C in Table 3). The number of cultures from each collection (columns 2
326 and 4 in Table 3) that could be compared to the two 454 datasets (B and C in Table 3) was

different because the 16S rRNA fragments sequenced were different (see material and methods).

Column 3 (Table 3) shows that the percent of cultures retrieved was much higher from the simultaneously taken culture collection (37%) than form those taken years before (~ 10%). Likewise, column 5 (Table 3) shows that the percent of cultures isolated the same year of the cruise MODIVUS was higher (83% and 80%) than with those isolated earlier (44% in 2001-2004) or later (74% in 2011). The cultures collected the same year but at a different date (February 2007) were retrieved almost with the same efficiency as those collected on the same dates (80%).

The next comparisons examine the efficiency of retrieval at different space scales. Columns 5 and 6 (Table 3) show the difference in percent of cultures found in the MODIVUS database if the whole set of sequences is considered (including a transect and a vertical profile, column 5 in Table 3) or if only the sequences from BBMO are used for the comparison (column 6 in Table 3). For the three BBMO collections the percent increased when a larger area was considered. The same can be observed in columns 5, 7 and 8 (Table 3) for the SUMMER culture collection: when only the sequences from the open sea station were included, the percentages recovered were 24 (for the surface sequences) and 34 (for the bottom sequences). When the whole MODIVUS dataset was included, 74% of the cultures were retrieved. Surprisingly, this percentage is larger than that of the SUMMER 454 dataset. This occurred despite the fact that the SUMMER data set had many more sequences ($1.7x10^6$) than the MODIVUS dataset ($3x10^5$).

351 **Discussion**

352 *1. Estimates of richness.*

353 A large proportion of the microbial world is invisible to traditional cultivation approaches
354 but it can be accessed using molecular tools (DeLong, 1997). The first cloning and Sanger
355 sequencing approaches revealed a wealth of new taxa in the oceans (Giovannoni *et al*., 1990).
356 The number of clones examined however, was still too limited and there was a discrepancy
357 between the taxa obtained in pure culture and by cloning and sequencing (Pedrós-Alió,
358 2006). The development of massive parallel sequencing technologies in the last decade has
359 helped to uncover a large fraction of the hidden diversity of marine microorganisms (Sogin *et*
360 *al*., 2006; Pedrós-Alió, 2012). In a previous study (Pommier *et al*., 2010) we used
361 pyrosequencing of the V6 region of the 16S rDNA gene to estimate richness of the bacterial
362 assemblages in the NW Mediterranean Sea. Around 20 000 tag sequences were obtained per
363 sample. For the surface and deep samples from station D, we found 632 and 2 065 OTUs
364 respectively and using the Chao estimate these translated into estimated richness of 1 289 and
365 4 156 OTUs for surface and deep samples respectively. It is well know that the number of
366 new species retrieved increases with sampling size and sampling effort (Preston, 1960;
367 Magurran, 1988; Rosenzweig, 1995) and a large part of the diversity remains hidden due to
368 sampling limitations (Chao *et al*., 2009; Gotelli & Colwell 2011). Therefore, taking
369 advantage of the increasing sampling depth of pyrosequencing, we obtained 1 million raw
370 16S rRNA gene tag-sequences per sample, trying to achieve realistic estimates of the whole
371 bacterial diversity in our samples.

372

373 Our collector curves were close to reaching an asymptote (Figure 1). The relatively low
374 percentage of singletons (~17%) found in this study compared to the higher percentage (40%-

375 60%) in the previous study (Pommier *et al*., 2010) indicates a good coverage of the whole
376 bacterial richness. By increasing the number of tags per sample from 20 000 to 1 000 000 we
377 increased the number of OTUs from 632 to 1 400 at the surface and from 2 065 to 4 460 at
378 the bottom. The Chao estimators were relatively close in both studies: 1 289 vs 1 643 and
379 4 156 vs 5 029 for surface and bottom samples respectively. This suggests that the
380 sequencing effort carried out in the present study is not necessary for a general evaluation of
381 the richness of a marine sample, which is good news for further routine studies. However, we
382 needed this effort to answer the questions discussed below.
383
384 The Chao index is based on the number of singletons and doubletons. We wanted to use
385 all the information contained in the species accumulation curves to get a more robust estimate
386 of richness. After testing several options, the Weibull cumulative function proved to be
387 excellent. The extraordinary good fit (99% model efficiency) of this function to the species
388 accumulation curves (Figure 2) gives confidence to the richness estimations made by
389 extrapolation. Again, it is good for further studies that there were no significantly differences
390 from the non-parametric estimations (z-tests on the differences, $P > 0.05$). The Weibull
391 cumulative function has been satisfactorily fitted to species accumulation curves of well-
392 sampled communities of birds (Flather, 1996), reptiles (Thompson *et al.*, 2003), snakes (van
393 Rooijen, 2012), butterflies (Jiménez-Valverde *et al.*, 2006) and microplankton (Cermeño *et*
394 *al.*, 2014). We also fitted the model to a marine bacterial sample collected in the Western
395 English Channel (Caporaso *et al.*, 2012; Gibbons *et al.*, 2013). This sample was sequenced at
396 an extraordinary depth (on the order of 10^7 Illumina tags) and we also found a good fit
397 (R^2=0.99). The fit was better when singletons were included in the analysis (the AIC value
398 was lower, supplementary Fig. 1). Therefore, the Weibull cumulative function will be a very

399 useful tool to characterize the species accumulation curves and to obtain robust richness
400 estimates, at least for well-sampled bacterial communities.
401
402 The high abundance of the most abundant OTU in the surface sample (Figure 2) may have
403 caused less OTUs to be uncovered, forcing the richness to appear lower at the surface sample
404 than at the bottom sample. However, higher richness as well as higher diversity at the bottom
405 than at the surface have been reported before for the sampling area (Pommier *et al*., 2010).
406 Also, the high number of sequences examined and the richness estimations (Table 1) leave
407 not doubt that a high percentage of the rare OTUs were sampled. Moreover, the number of
408 OTUs in both samples was close to the number of OTUs estimated by other authors for the
409 upper ocean (Rusch *et al*., 2007; Pommier *et al*., 2010; Crespo *et al*., 2013) and deep waters
410 (Salazar *et al*., submitted).
411
412 The study of the English Channel mentioned above (Caporaso *et al.*, 2012; Gibbons *et al.*,
413 2013) is particularly relevant for our analysis. Station L4 was very deeply sequenced (10
414 million sequences) by Illumina. The sequences were then compared to pyrosequencing data
415 from 72 samples collected along the seasons through six years (Caporaso *et al.*, 2012) or to
416 the ICoMM pyrosequencing samples from around the world's oceans (Gibbons *et al.*, 2013).
417 The purpose of this exercise was to see whether the collectors curve could be saturated with
418 sufficiently deep sequencing and whether the rare biosphere of one site, at one particular
419 time, included all the taxa found at that site through the years. Caporaso *et al*. (2012) found
420 that around 95% of the OTUs in the combined seasonal samples could be found in the one
421 deeply sequenced sample. Thus, the conclusion was that the rare biosphere included all the
422 taxa that were abundant at L4 at one time or another. "This suggested that the vast majority

423 of taxa identified in this ecosystem were always present, but just in different proportions"
424 (Caporaso *et al.*, 2012).
425
426 However, there are some caveats in interpreting this data set. The number of OTUs found
427 by pyrosequencing in the combined 72 samples was 13 424. We think this agrees well with
428 our estimates of 2 000 to 5 000 OTUs in one single sample. A fourfold increase in OTUs
429 when analyzing 72 samples collected through the seasons instead of 1 sample seems
430 reasonable. On the other hand the deep Illumina sampling produced 116 107 OTUs, which is
431 one order of magnitude higher.
432
433 Several issues must be considered. First, these authors found that 45-48% of their OTUs
434 were singletons. Given than the data sets consisted of over $8x10^5$ sequences (seasonal
435 samples) and the other of over 10^7 sequences, these very large percentages of singletons are
436 intriguing. In a previous study of the Mediterranean, we found a similar percentage of
437 singletons (46%) with a lower number of sequences ($\approx 2x10^5$) (Pommier *et al.*, 2010; Crespo
438 *et al.*, 2013). However, with the increase in sequences to $5x10^5$ in the present study of the
439 same area, the number of singletons was reduced to 17%. A reduction in percent of singletons
440 with an increase in sequencing depth is what one would expect and is what other studies have
441 found (Wall *et al.*, 2009; Penton *et al.*, 2013). Thus, we find the results of Caporaso *et al.*
442 (2012) and Gibbons *et al*. (2013) surprising.
443
444 Second, most of the OTUs in Caporaso *et al*. (2012) could not have a taxonomy ascribed,
445 even after exclusion of singletons. More than half were "unclassified bacteria" and about
446 10% were "unclassifiable (reads too short)" (see their Figure 1C). Thus, only about 40% of

447 the OTUs could be classified. Again, this very low figure is intriguing. The short read length
448 cannot be the reason, because in our earlier studies, we used exactly the same methodology
449 and read length as for the seasonal samples from the English Channel or the world ocean
450 samples from ICoMM and yet, 98.9% of our OTUs could be assigned a taxonomy at least at
451 the Phylum level and most of the time at the Class level. Obviously, different criteria for
452 assignment of identity can be responsible for this, but the 10% of sequences labeled as
453 "unclassifiable (reads too short)" should probably have been discarded.
454
455 We used the data from their deep sequenced L4 sample to try the Weibull fit and found a
456 good fit, both with and without the singletons. In both cases the number of OTUs was one
457 order of magnitude higher than our estimates (40 000 and 100 000 OTUs without and with
458 singletons respectively). It is difficult to integrate these very different estimates of richness.
459 We see three possibilities. First, if both data sets and sequence processing are correct the
460 English Channel could have ten times more species than the Mediterranean Sea. We find this
461 possibility very unlikely, since both environments correspond to relatively open seawater.
462 Second, perhaps the procedure chosen for OTU calling with the L4 data set overestimated the
463 number of OTUs. As explained, the number of OTUs found in the seasonal samples was
464 coherent with our estimates. The number of OTUs with the Illumina sequences, on the other
465 hand was one order of magnitude higher. We believe that the current processing of
466 pyrosequencing data is quite robust (Quince *et al.*, 2011). Processing of Illumina tags,
467 however, was still in its infancy when the studies mentioned above were carried out. Thus,
468 the possibility exists of an overestimation of diversity. This is actually what happened in the
469 first application of pyrosequencing to marine bacterial diversity in Sogin *et al*. (2006). Later
470 studies found ways to properly clean the sequences and estimates became lower (Huse *et al.*,

471 2010; Quince *et al.*, 2011). We think this is the most likely explanation. Finally, there could
472 be some methodological issue that caused an increase in diversity when the number of
473 sequences increased by one order of magnitude. Thus, when diversity of marine bacterial
474 communities was estimated from conventional clone libraries (with a few hundred clones)
475 richness estimations were on the order of a few hundred OTUs. When similar samples were
476 analyzed by HTS (with tens of thousands of sequences per sample) the richness estimators
477 gave numbers of several thousand OTUs (as in the present study).
478
479 *2. Comparison of sequencing and isolation*
480 The current power of massive parallel sequencing allows probing the rare biosphere
481 (Caporaso *et al*., 2012; Pedrós-Alió, 2012; Gibbons *et al*., 2013), but culturing is an
482 alternative avenue to explore it (Pedrós-Alió, 2006, Shade *et al*., 2012). Comparing both
483 approaches we have found that isolation retrieves some of the rarest taxa since only 24 to
484 37% of the isolates were found in the 454-pyrosequencing data and, moreover, they were
485 found in extremely low abundance (Figure 3, Table 2).
486
487 In principle, the low percentage of coincidence might have been due to potential PCR bias
488 and differential DNA amplification of the sequencing techniques (Berry *et al.*, 2011; Pinto &
489 Raskin, 2012). However, when tested *in silico*, the primers used for pyrosequencing covered
490 the whole diversity captured by the primers used for Sanger sequencing of the isolates and
491 therefore, a PCR bias affecting the diversity found using both methods was unlikely.
492
493 Our results showed that the deep sequencing approach failed to retrieve 76% of the
494 bacterial cultures that were isolated in the surface sample. In a similar study, but with much

shallower sequencing depth (~2 000 sequences per sample), Shade *et al*. (2012) found out that 61% of their isolates were not retrieved by 454-pyrosequencing. They performed pyrosequencing of a pool of bacterial cultures isolated from soil samples instead of Sanger sequencing of each isolate as we did in this study. Thus both studies, one in soils and another in seawater, produced similar percentages.

The long tail of rare species estimated by fitting the Weibull cumulative function to the accumulation curve (Figure 2, Table 1) and by the non-parametric Chao method (Chao *et al.*, 2009) (Table 1) should harbor the isolates not found with the sequencing depth applied in this study. Increasing the number of tags sequenced would slowly uncover the isolated bacteria in a logarithmic way (Figure 4). Even if the whole bacterial diversity were found by increasing the sampling depth, culturing would still be essential for the study of marine bacterial communities, especially if the target is the rare biosphere (Donachie *et al*., 2007).

Taking advantage of other datasets previously collected from the same area of our sampling, we were able to compare 454-pyrosequecing data and cultured isolates from different times of the year and stations along a horizontal transect and a vertical profile (Table 3). The percentage of cultured isolates sequences found in the 454-pyrosequecing datasets decreased as the time between the collection of samples for isolation and pyrosequencing increased; i.e., cultures isolated from the same sample as the pyrosequencing data were found more easily in the pyrosequencing dataset than the cultures collected further away in time or space (Table 3). The consistency of this pattern within the two datasets, SUMMER and MODIVUS (Table 3), suggests that the composition of the bacteria isolated changes along the year probably following the annual succession of the marine bacterial

519 composition (Alonso-Sáez *et al*., 2007; Alonso-Sáez *et al*., 2008; Gilbert *et al*., 2012).
520 Similarly, Lekunberri *et al*. (2014) found that sequences from cultures obtained from one
521 season of the year tended to cluster together with environmental sequences obtained at the
522 same time of the year. These two findings suggest that the composition of rare taxa also
523 follows an annual succession, supporting the conclusion that the environment determines the
524 marine bacterial composition, not only of the abundant taxa but also of the rare members of
525 the bacterial community (Galand *et al.*, 2009). The shorter length of the 454-tag sequences
526 (and the consequent decrease in precision of taxonomy) was likely responsible for the higher
527 percentage of cultured isolates found on the 454-pyrosequecing datasets of MODIVUS cruise
528 (454-tags sequences of ~68 bp) than of SUMMER cruise (454-tags sequences of ~400 bp).
529
530 In conclusion, by obtaining 10^6 tags per sample and fitting a Weibull cumulative function
531 we have been able to obtain a robust estimate of the richness of the bacterial assemblages in
532 two samples at the surface and deep Mediterranean Sea. This richness is of the order of 3 000
533 to 5 000 taxa. The comparison with cultures shows that many of the isolates are found deep
534 within the rare biosphere, and we have determined the sequencing effort necessary to retrieve
535 them. HTS and culturing appear as two complementary strategies to probe the fabric of the
536 rare biosphere.
537
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686 **Figure legends**

687 Figure 1. OTU accumulation curves of the surface (orange circles) and bottom (green
688 triangles) samples. The black line is the Weibull cumulative function fit with model
689 efficiency of 99% (R^2=0.99).

690

691 Figure 2. Rank-abundance plots of surface (A) and bottom (B) samples. The red line is the
692 rank-abundance plot calculated with the actual data. The blue lines show the estimates of the
693 sampling effort necessary to retrieve 99% (dark blue) or 99.9% (light blue) of the total
694 estimated richness calculated by extrapolation of the species accumulation curve using the
695 Weibull cumulative function. The vertical black line separates the real data (left) from the
696 estimates (right). The percentage of cultured isolates found in the 454-pyrosequencing
697 datasets is indicated at the left side of the black vertical line. The percentage of cultured
698 isolates not found in the 454-pyrosequencing datasets, and that would presumably be found
699 by increasing the sampling effort, is indicated at the right of the black vertical line. Insert
700 pictures show some of the bacterial cultures grown from the surface sample. Font size and
701 pictures are scaled according to the percentage of cultured isolates found or not found in the
702 454-pyrosequencing datasets.

703

704 Figure 3. Rank-abundance plot of the 38 isolated bacterial species. The maroon squares
705 indicate the cultured isolates found in both the surface and bottom 454-pyrosequencing
706 datasets, the green triangles indicate the cultures isolated found only in the bottom 454-
707 pyrosequencing dataset, and the white circles indicate the cultures that were not found in any
708 of the 454-pyrosequencing datasets. A list of the isolated bacterial species can be found in
709 Table 2 and supplementary Table 2.

Figure 4. Accumulation curves of the percentage of cultured isolated found in the 454-pyrosequencing datasets (surface sample: A, C and bottom sample: B, D) when increasing the number of sampled OTUs (A, B) and Tags (C, D).

Table 1. Summary of location and depth (m) of samples, total sequences before (Raw Tags) and after (Final Tags) cleaning, richness (S) computed as total Operational Taxonomic Units (OTUs) clustered at 97% identity, percentage of singletons. Diversity estimates according to the Shannon diversity index (H'), Simpson diversity (D) and Pielou's evenness (J). Richness (S) estimates according the non-parametric methods Chao Index (SChao) and Abundance-base Coverage Estimator (ACE) (S_{ACE}) and the fitting of the accumulation curve to a Weibull Cumulative three parameter function ($S_{WeibullFit}$) which model efficiency was 99% for the surface and the bottom samples fitting (see Fig. 1). Estimates of the sampling effort (number of Tags) that would be needed to obtained the 99% and 99.9% of the total richness estimated by the Chao Index (S_{Chao}) and the Weibull cumulative function fitting ($S_{WeibullFit}$).

	Surface	Bottom
Lat, Long	40º52'N, 02º47'E	40º52'N, 02º47'E
Depth (m)	5	2 000
Raw Tags	713 076	970 346
Final Tags	500 262	574 960
OTUs 97 % identity (S)	1 400	4 460
Singletons (% OTUs)	17.86	17.20
Diversity estimates:		
H' (Shannon diversity index)	3.26	4.75
D (Simpson diversity)	0.45	0.66
J' (Pielou's eveness)	0.45	0.57
Richness estimates (estimated S):		
Chao Index (S_{Chao})	1 643	5 029
ACE (S_{ACE})	1 556	4 924
Weibull Cumulative Fitting ($S_{WeibullFit}$)	1 519	4 946
Sampling effort estimates (Number of Tags) for:		
99 % of S_{Chao}	$1.33x10^6$	$1.04x10^6$
99.9 % of S_{Chao}	$2.47x10^6$	$2.03x10^6$
99 % of $S_{WeibullFit}$	$1.92x10^6$	$1.96x10^6$
99.9 % of $S_{WeibullFit}$	$4.02x10^6$	$3.91x10^6$

735 Table 2. Isolates' closest relative according to BLAST results, % of identity with the BLAST reference strain (identity BLAST),

736 GenBank accession number of the BLAST reference strain, number of tags matching the isolates sequences in the surface and bottom

737 samples (Tags in Surface, Tags in Bottom), percentage of the tags in the surface and bottom samples (% Surface, % Bottom) and number

738 of isolates of each taxa sequenced. *Actino* (*Actinobacteria*), *Bact* (*Bacteroidetes*), *Firm* (*Firmicutes*), Alpha-*P* (Alpha-*Proteobacetria*)

739 and Gamma-*P* (Gamma-*Proteobacteria*).

Isolates' closest relative	Identity BLAST	GenBank accession number	Tags in Surface	% Surface	Tags in Bottom	% Bottom	Isolates number
Uncultured Brevundimonas sp. (Alpha-*P*)	99.9 %	JX047099	76	$1.52x10^{-2}$	172	$2.99x10^{-2}$	1
Alteromonas macleodii str. 'Balearic Sea AD45' (Gamma-*P*)	100 %	CP003873	40	$8.00x10^{-3}$	7526	1.31	2
Sphingobium olei (Alpha-*P*)	100 %	HQ398416	34	$6.80x10^{-3}$	232	$4.04x10^{-2}$	8
Erythrobacter citreus (Alpha-*P*)	100 %	EU440970	31	$6.20x10^{-3}$	861	$1.50x10^{-1}$	37
Citromicrobium sp.(Alpha-*P*)	100 %	HQ871848	22	$4.40x10^{-3}$	39	$6.78x10^{-3}$	1
Acinetobacter baumannii (Gamma-*P*)	100 %	JX966437	16	$3.20x10^{-3}$	128	$2.23x10^{-2}$	4
Bizionia sp. (*Bact*)	100 %	EU143366	13	$2.60x10^{-3}$	66	$1.15x10^{-2}$	1
Muricauda ruestringensis (*Bact*)	99 %	JN791391	4	$8.00x10^{-4}$	92	$1.60x10^{-2}$	2
Microbacterium jejuense (*Actino*)	100 %	AM778450	1	$2.00x10^{-4}$	15	$2.61x10^{-3}$	1
Marinobacter flavimaris (Gamma-*P*)	100 %	AB617558	0	0	174	$3.03x10^{-2}$	5
Bacillus sp. (*Firm*)	100 %	AM950311	0	0	17	$2.96x10^{-3}$	1
Bacillus horikoshii (*Firm*)	100 %	JQ904719	0	0	8	$1.39x10^{-3}$	2
Halomonas aquamarina (Gamma-*P*)	100 %	AB681582	0	0	1	$1.74x10^{-4}$	5
Idiomarina seosinensis (Gamma-*P*)	99.9 %	EU440964	0	0	1	$1.74x10^{-4}$	2

740 Table 3. Percentage of coincidence of the 454 pyrosequencing datasets from cruises SUMMER (September 2011) and MODIVUS
741 (September 2007) with cultures covering the specific hypervariable regions sequenced in each cruise. The cultures belonged to four
742 culture collections from the NW Mediterranean. The — symbol indicates that the comparison was not significant due to the low number
743 of cultures with V1-V3 regions in the BBMO-3 culture collection. The comparison was Not Applicable (NA) when the samples
744 compared did not belong to the same sampling site. The highest percentages of coincidences are indicated in bold type. BBMO means
745 Blanes Bay Microbial Observatory.

A) Culture collection	**B) SUMMER 454 sequences (September 2011)**		**C) MODIVUS 454 sequences (September 2007)**				
1	2	3	4	5	6[b]	7[b]	8[b]
	# cultures[a]	% found with all sequences	# cultures[a]	% found with all sequences	% found with BBMO sequences	% found with Open-Sea, Surface	% found with Open-Sea, Bottom
BBMO-1 (2001-2004)	65	8%	39	44%	23%	NA	NA
BBMO-2 (Feb 2007)	11	9%	20	80%	40%	NA	NA
BBMO-3 (Sept 2007)	2	—	6	**83%**	**67%**	NA	NA
SUMMER (Sept 2011)	38	**37%**	38	74%	NA	26%	**34%**

746 [a] Number of cultures in each collection where the sequence available matched the region targeted in the 454 sequencing (V1-V3
747 in Summer and V6 in MODIVUS).

748 [b] Comparison of the culture collections and the 454 pyrosequencing data of the sample collected at the same site as the sample
749 for culture isolation.

750

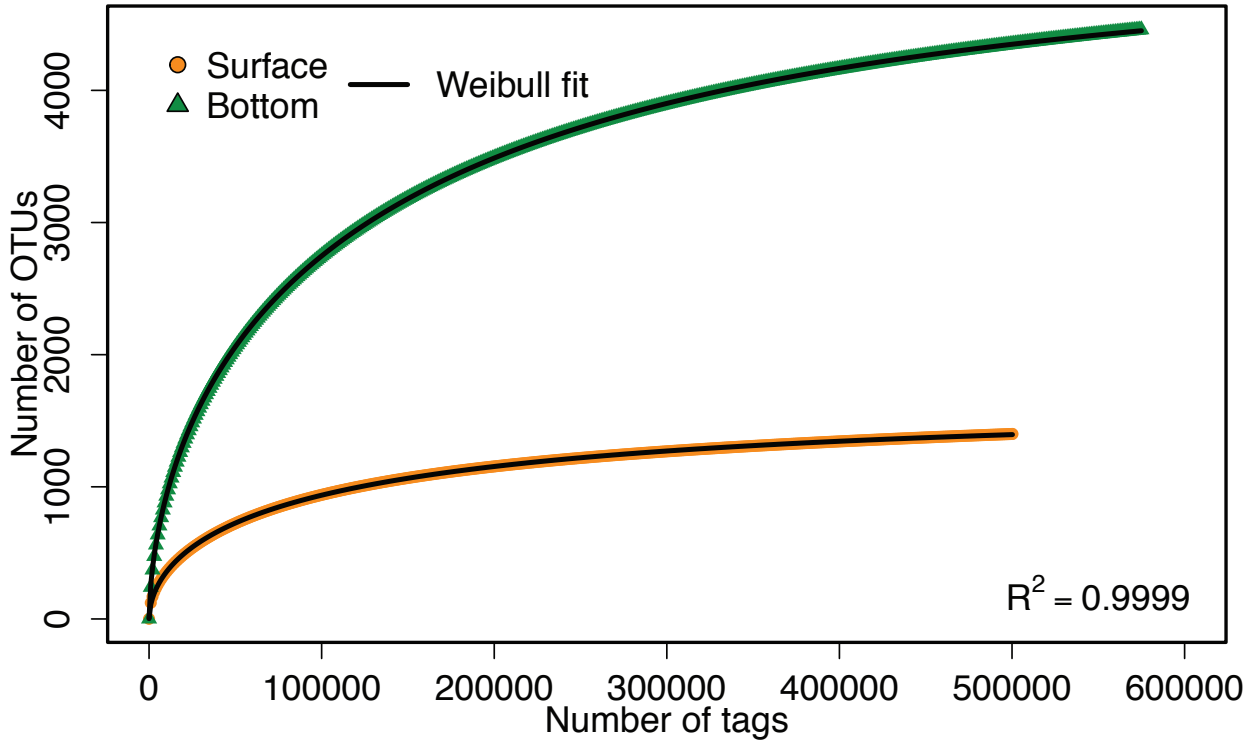

Figure 1
Crespo et al.

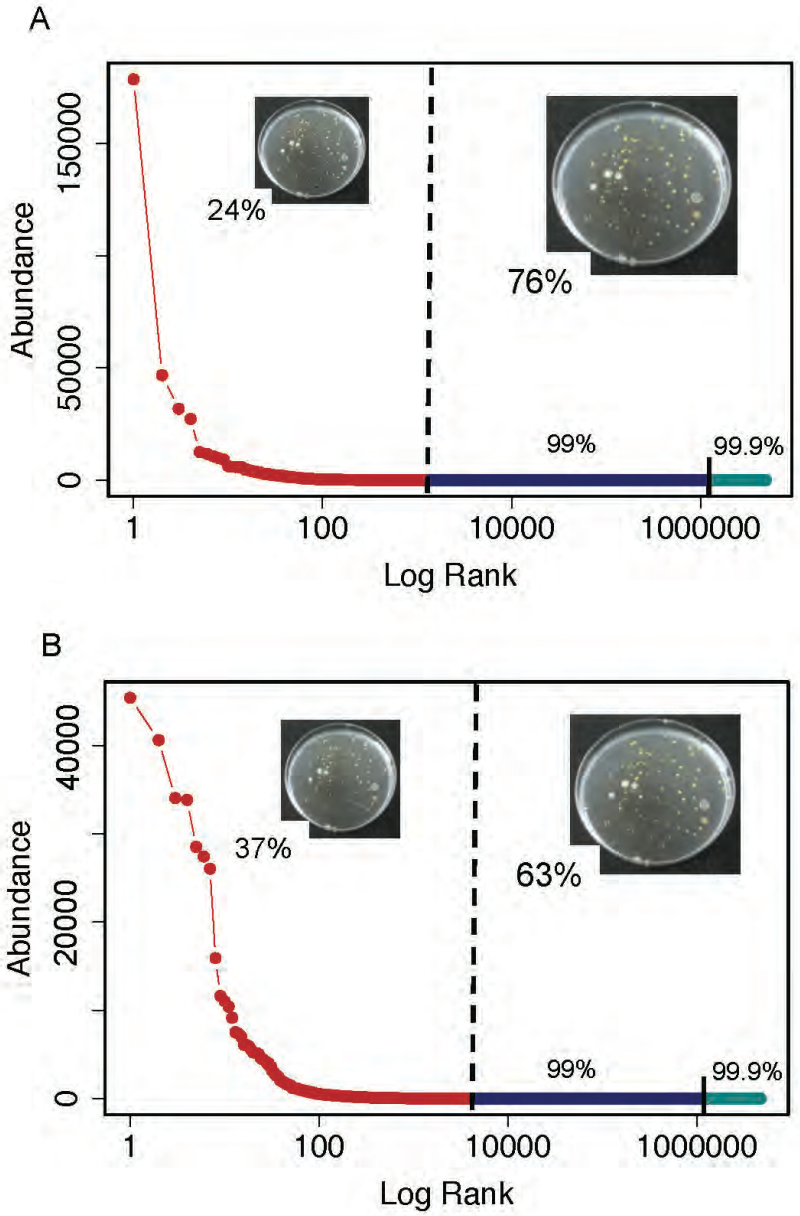

Figure 2
Crespo et al.

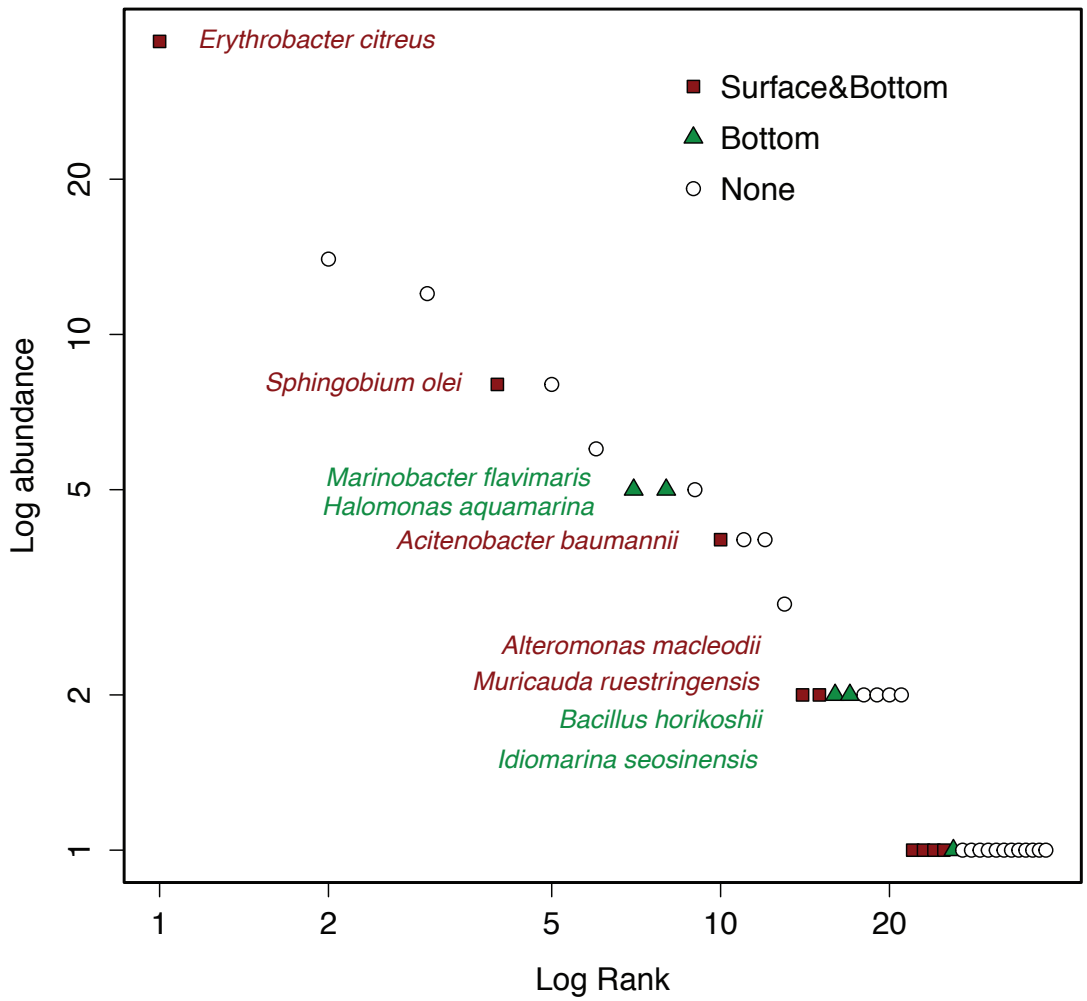

Figure 3
Crespo et al.

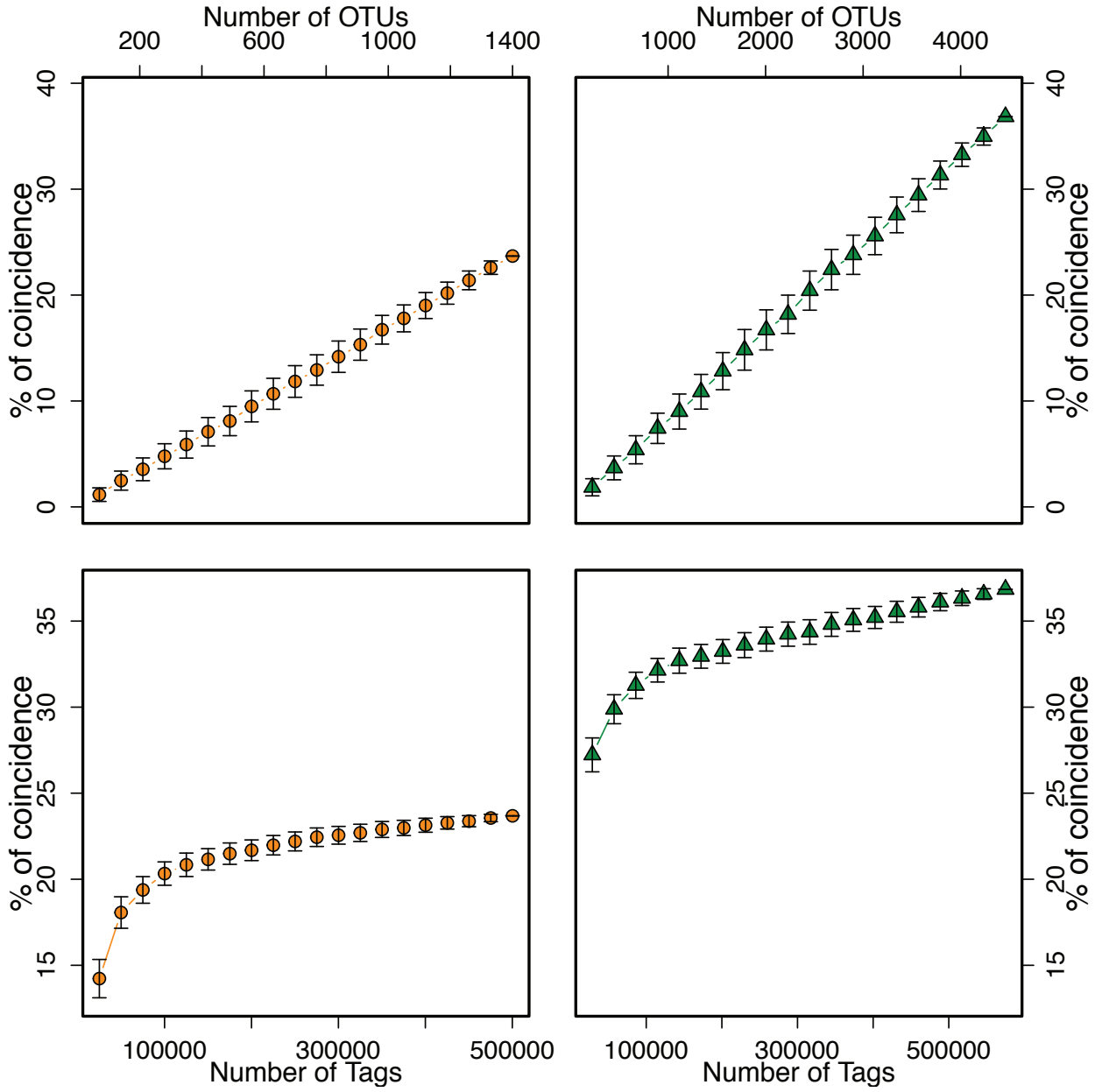

Figure 4
Crespo et al.