



HAL
open science

Evidence of coupled autotrophy and heterotrophy on plastic biofilms and its influence on surrounding seawater

Pascal Conan, Léna Philip, Eva Ortega-Retuerta, Charlène Odobel, Clélia Duran, Caroline Pandin, Carolane Giraud, Anne-Leila Meistertzheim, Valérie Barbe, Alexandra ter Hall, et al.

► To cite this version:

Pascal Conan, Léna Philip, Eva Ortega-Retuerta, Charlène Odobel, Clélia Duran, et al.. Evidence of coupled autotrophy and heterotrophy on plastic biofilms and its influence on surrounding seawater. *Environmental Pollution*, 2022, 315, pp.120463. 10.1016/j.envpol.2022.120463 . hal-03853376

HAL Id: hal-03853376

<https://hal.science/hal-03853376>

Submitted on 27 Oct 2023

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

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

1 **Title:**

2 Evidence of coupled autotrophy and heterotrophy on plastic biofilms
3 and its influence on surrounding seawaters

4

5 **List of authors:**

6 Pascal Conan^{1,2*}, Léna Philip^{1,3}, Eva Ortega-Retuerta¹, Charlène Odobel¹, Clélia Duran¹,
7 Caroline Pandin¹, Carolane Giraud^{1,4}, Anne-Leila Meistertzheim³, Valérie Barbe⁵, Alexandra
8 Ter Hall⁶, Mireille Pujon-Pay¹, Jean-François Ghiglione¹

9

10

11 **Affiliations:**

12 1. Sorbonne Université, CNRS LOMIC - UMR 7621, Laboratoire d'Océanographie Microbienne, 1 Avenue
13 Pierre Fabre, 66650 Banyuls sur Mer, France

14 2. Sorbonne Université, CNRS OSU STAMAR - UAR2017, 4 Place Jussieu, 75252 Paris cedex 05, France

15 3. SAS Plastic@Sea, Sorbonne Université (UPMC), CNRS LOMIC - UMR 7621, Laboratoire
16 d'Océanographie Microbienne, 1 Avenue Pierre Fabre, 66650 Banyuls sur Mer, France

17 4. CNRS, UMR 9220 ENTROPIE, Ifremer (LEAD-NC), IRD, Univ Nouvelle-Calédonie, Univ La
18 Réunion, Nouméa, New Caledonia

19 5. Génomique Métabolique, Genoscope, Institut François Jacob, CEA, CNRS, Univ Evry, Université Paris-
20 Saclay, 91057 Evry, France

21 6. CNRS, Université de Toulouse, Laboratoire des Interactions Moléculaires et Réactivité Chimique et
22 Photochimique (IMRCP), UMR 5623, Toulouse, France

23

24

25 *** Corresponding author:**

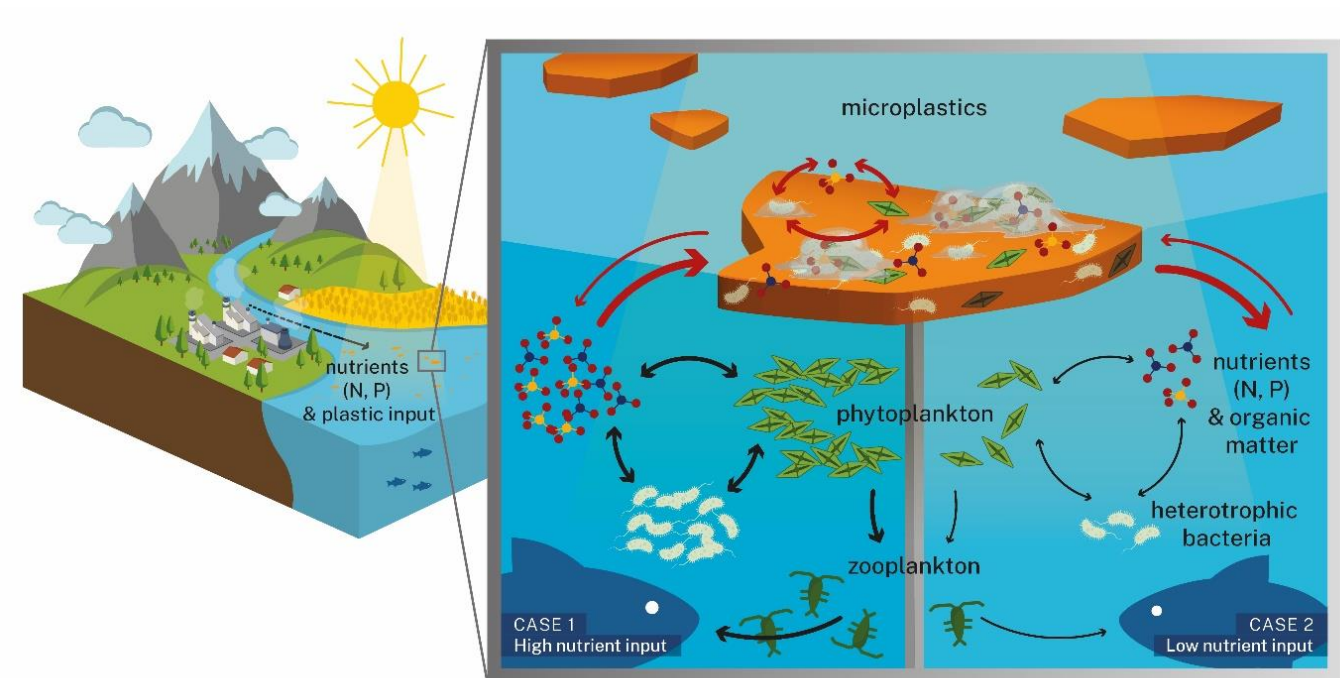
26 Pascal Conan, Sorbonne Université, CNRS LOMIC - UMR 7621, Laboratoire d'Océanographie
27 Microbienne, 1 Avenue Pierre Fabre, 66650 Banyuls sur Mer, France.

28 Email adress: pascal.conan@obs-banyuls.fr

29

30 **Graphical Abstract**

31



33

34

35 **Abstract**

36 We measured phytoplankton primary production and heterotrophic bacterial activities on
37 microplastics and seawater in the Northwestern Mediterranean sea during two 3-month spring
38 periods over consecutive years. Microorganisms growing on a 5 mm diameter low density
39 polyethylene (LDPE) film (200 μm thick) were faced with two contrasting conditions from one
40 year to the next. Spring 2018 was characterized by consistent nutrient inputs and bloom
41 development. In spring 2019, nutrient inputs and bloom were low. For the first time, we
42 observed a clear coupling between primary production and heterotrophic prokaryote production
43 on microplastics during both years, but with different intensity between years that reflected the
44 crucial role of the trophic environmental conditions (nutrient supply) in shaping microbial
45 activities on plastics. Indeed, we proved that high primary production on plastics could support
46 the whole (net autotrophy) or the majority of the bacterial carbon demand needed for
47 heterotrophic activities, supplemented by other carbon sources if surrounding waters are highly
48 productive. We also propose that microbial activity on plastics influence the microbial
49 community in the surrounding seawaters, especially when the environmental conditions are less
50 favorable. An illustrative image of the role of plastics in the environment could be that of an
51 electrical inverter in a circuit that allows for the attenuation of both positive and negative
52 variations. Our results highlight the potential role played by the plastisphere shaping
53 biogeochemical cycles in a context of an increasing amount of plastic particles in the marine
54 environment.

55

56 **Introduction**

57 The growing use of plastic worldwide together with waste mismanagement resulted in an
58 estimated of 24.4 trillion plastic particles floating in the world's oceans, which majority has a
59 particle-size <5 mm, the so-called microplastics, discharged mainly from rivers (Isobe et al.,
60 2021; Weiss et al., 2021). Indeed, the introduction of microplastics into the aquatic ecosystems
61 is mainly related to domestic runoff that contains microbeads and fragments of microplastics
62 (used in cosmetics and other consumer products) and also to the fragmentation of large plastic
63 waste. Plastic manufacturing industries and coastal activities (fishing, aquatic tourism...) are
64 also sources of microplastic pollution in the marine ecosystems (Subhankar and Shivika, 2019).
65 The emissions of microplastic are estimated to increase, even under the most optimistic
66 scenarios (Borrelle et al., 2020). This pollution is considered “poorly reversible” with potential
67 impacts including changes to the carbon and nutrient cycles, co-occurring biological impacts
68 on endangered or keystone species, ecotoxicity and other related societal impacts (MacLeod et
69 al., 2021).

70 Once in the marine environment, plastics are rapidly colonized by microorganisms,
71 forming the so-called plastisphere (Zettler et al., 2013), and interact with the overall ecosystem
72 depending on their size (PVC panels of 5 × 5 cm or 15 × 3.5 cm for Catão et al., 2019; Nano-
73 to Micro-plastics for Ter Halle and Ghiglione, 2021). Most of the studies so far revealed a large
74 diversity and a clear niche partitioning among marine bacteria living on plastics compared to
75 the free-living (Crisafi et al., 2022; Debroas et al., 2017; Zettler et al., 2013) and organic
76 particle-attached fractions (Dussud et al., 2018b; Oberbeckmann et al., 2018). Autotrophic
77 microorganisms such as cyanobacteria and diatoms have been shown to be particularly over-
78 represented in microplastics, suggesting the potentially high impact on the global pelagic
79 primary production and more generally on the carbon and nitrogen biogeochemical cycles in
80 the surface oceans (Amaral-Zettler et al., 2020; Crisafi et al., 2022; Dussud et al., 2018b; Nava

81 and Leoni, 2021). Because plastic debris offer an abundant growth matrix for microalgae while
82 limiting predation pressure by zooplankton (Kong and Koelmans, 2019), it has been proposed
83 that plastic pollution can promote significant proliferations of microalgae, with consequent
84 harmful effects for aquatic ecosystems already disturbed by eutrophication processes (Durrieu
85 de Madron et al., 2011; Zhang et al., 2020). Moreover, processes involved in the nitrogen
86 (nitrogen fixation, ammonia and nitrite oxidation, denitrification) and phosphorus cycling (P
87 accumulation, alkaline phosphatase activity) are overexpressed in the plastisphere, which can
88 modify the nutrient concentration in the surrounding seawater and thus indirectly affect primary
89 producers (Chen et al., 2020). For instance, plastics may represent net autotrophic hot spots in
90 the oligotrophic ocean, with high density of chlorophyll *a* and high oxygen production (Bryant
91 et al., 2016). Despite growing interest on the plastisphere influence on ecosystem functions,
92 direct measurements on microbial activities remain scarce. Some studies found also high
93 heterotrophic prokaryotic production (Dussud et al., 2018b; Odobel et al., 2021) and
94 ectoenzyme activities (Odobel et al., 2021) on plastics. It is surprising that primary production
95 in the plastisphere was never recorded in marine ecosystems. Both primary production and
96 heterotrophic activities play a key role in the carbon cycle. The former participating in about
97 half of global primary production (Behrenfeld and Falkowski, 1997), and the latter channeling
98 half of the oceanic primary production through the microbial loop (Del Giorgio and Cole, 2000).
99 A recent review underlined the need of coupling primary production and heterotrophic activities
100 to evaluate the potential role of the plastisphere on carbon cycling in the oceans (Jacquin et al.,
101 2019). In oceanic systems, the supply of organic matter from autochthonous (autotrophic) or
102 allochthonous (heterotrophic) primary production is mainly dependent on nitrogen and
103 phosphorus availability and will defined the trophic status of these ecosystems, and in turn, the
104 potential coupling between phytoplankton and bacteria (Dodds and Cole, 2007). Finally, the

105 characterization of the trophic state is necessary for understanding food web linkages as well
106 as biogeochemical features and subsequently water quality, including human influence.

107 Our study provides the first measurements to our knowledge of the marine plastisphere
108 primary production together with bacterial heterotrophic activities over time. We hypothesize
109 that natural environmental factors (such as temperature, salinity, nutrient availability...) play a
110 major role in plastisphere activities, thus influencing the net autotrophy *vs.* heterotrophy
111 budgets over time. More precisely, trophic links within the niche created by the plastisphere
112 would be strengthened when external conditions become less favorable (i.e. meso *vs.*
113 oligotrophic). Polyethylene-based microplastics were incubated in natural seawater for two 3-
114 month periods, including a classical spring phytoplanktonic bloom event that occurs every year
115 at the long-term SOLA marine observatory station (NW Mediterranean Sea, France). The
116 experiments revealed a clear link between autotrophic and heterotrophic productions of the
117 plastisphere over time, as well as a possible influence of the microbial activities on
118 microplastics in surrounding seawaters.

119

120

121 **2. Material and methods**

122 **2.1. Experimental conditions during 3 months in two following years**

123 We incubated 200 circular pieces of polyethylene of 5 mm diameter and 200 μm thickness
124 (LD-PE, Borealis, ref. FA6224, Austria) in a 50 L aquarium with direct circulation to the sea.
125 The incubation was repeated twice at one year interval: the first incubation was performed from
126 12 February to 7 May 2018 (44th to 127th day of the year, here after D44-127¹; period of 85
127 days) and the second incubation was performed from 19 February to 8 May 2019 (D50-133;

¹ D1 correspond to the 1st January with this time scale

128 period of 91 days). Each plastic piece was first sterilized with 70% ethanol and rinsed 3-times
129 with sterile seawater before incubation. The aquarium was placed outside with natural light
130 conditions, and covered by a transparent screen. Seawater circulating through the aquarium was
131 pumped from 4 m depth and 30 m from the coast in the Banyuls bay (NW Mediterranean Sea,
132 France) and the seawater flow rate in the aquarium was ~5 L per hour.

133 Triplicate plastic pieces were sampled 12 times during each experiment with sterile
134 forceps at each sampling time (*i.e.* D44, D46, D50, D53, D57, D60, D72, D79, D85, D99, D113,
135 D127 for 2018 and D50, D57, D64, D72, D86, D93, D100, D106, D114, D120, D126, D133
136 for 2019). In parallel, 3 L of seawater were sampled in a sterilized glass vial at the same
137 sampling days from the aquarium or at the SOLA marine observatory located at 0.5 nautical
138 miles from the coast in the Banyuls Bay (42°29'300 N; 03°08'700 E).

139

140 **2.2 Heterotrophic bacterial production**

141 Heterotrophic bacterial production was measured in triplicate on each plastic and
142 seawater sample at each sampling time by the ³H-leucine incorporation into proteins method,
143 as previously described in Dussud et al. (2018b). Briefly, the plastic pieces were transferred
144 into 1.5 mL of sterilized seawater and a soft cell detachment pre-treatment was applied for each
145 sample consisting in 3 cycles of 1 minute vortexing followed by 3 minutes in an ultrasound
146 bath. This pre-treatment greatly improves the signal, especially in the case of mature biofilms
147 (Dussud et al., 2018b). Immediately after cell-detachment, ³H-leucine (specific activity 4.2 x
148 10¹² Bq.mmol⁻¹; Perkin Elmer) was added at a final concentration of 0.9975 x 10⁻⁹ mol.L⁻¹
149 (completed with cold leucine to 1.49 x 10⁻⁷ mol.L⁻¹). A same ³H-leucine concentration of 3,97
150 x 10⁻⁹ mol.L⁻¹ (completed with cold leucine to 3.6 x 10⁻⁸ mol.L⁻¹) was used for seawater from
151 the aquarium and from the SOLA marine station. No cell detachment pretreatment was used for
152 seawater samples, since Dussud et al. (2018b) showed that did not influence the signal for free-

153 living bacteria in seawater. All samples were incubated in the dark at 18°C for 2-3 h. The
154 theoretical conversion factor of 1.55 ngC.pmol⁻¹ of incorporated leucine was used to calculate
155 heterotrophic bacterial production (Simon and Azam, 1989). Data were normalized for
156 microplastics with blank values according to Dussud et al. (2018b).

157

158 **2.3 Primary production**

159 Primary production (PP) was measured using a modified protocol of the radioactive ¹⁴C
160 tracer technique (Fitzwater et al., 1982). Measurements were carried out in triplicate. One
161 plastic piece was transferred in 10 mL of sterilized seawater. The same volume was taken for
162 seawater from the aquarium and from the SOLA marine station. Each sample was inoculated
163 with Na₂H¹⁴CO₃ (final activity of 18.5 kBq.mL⁻¹). The introduced quantity was measured by
164 mixing 100 µL ethanolamine to 100 µL of inoculated sample and 10 mL of scintillation cocktail
165 Ultima Gold uLLT. The samples were placed for 5 to 8 h in a thermic and light regulated
166 incubator (14 to 18°C – 500 to 2000 µE.m⁻².s⁻¹ according to the season). Plastics were isolated
167 and acidified with 6 N HCl and dried during 8 h at 50 °C. Seawater samples were acidified with
168 6N HCl (final pH = 2) and agitated, lid open, for at least 12 h at 130 rpm and then mixed with
169 scintillation cocktail during 4 hours before measuring radioactivity with the scintillation counter
170 300 SL Hidex.

171 The percentage of carbon originating from the extracellular release (ER) that is theoretically
172 available for bacterial heterotrophic activity was calculated as previously described in Van
173 Wambeke et al. (2002). Briefly, the theoretical ER associated to the autotrophic carbon fixation
174 was calculated for a range of 5 and 20% of the PP to cover at least 90% of the wide range of all
175 values found in the literature (Conan et al., 1999). It has been compared to the minimal and
176 maximal theoretical bacterial carbon demand (BCD) ranging from 1 to 25% of the ER (review
177 in Van Wambeke et al., 2002). Comparison between microbial activities on microplastic and in

178 the seawater was calculated by integrating their respective dynamics over the 3 months
179 sampling periods in 2018 and 2019.

180

181 **2.4 Environmental parameters**

182 Temperature, salinity, nutrients and chlorophyll *a* were measured in the aquarium with
183 direct circulation to the sea and at the SOLA marine observatory station all along both 3-month
184 incubations. Temperature, salinity and fluorescence were continuously recorded with a CTD
185 probe (Seabird SBE16+) equipped with a fluorimeter (ECO FLNTU WETLab). All chemical
186 measurements were carried out following standard procedures defined by SOMLIT protocols
187 (www.somlit.fr/parametres-et-protocoles/). Briefly, ammonium was detected at nanomolar
188 concentrations by fluorimetric detection according to Holmes et al. (1999) using a Turner
189 Designs Trilogy fluorimeter. Nitrate, nitrite and phosphate concentrations were simultaneously
190 measured in 10 mL of sample, on a continuous flow Autoanalyser III Seal-Bran&Luebbe
191 (Aminot and K erouel, 2007). For Chlorophyll *a*, 250 mL samples were filtered using pre-
192 combusted 25 mm diameter Whatman® GFF filters (~0.4-0.7 µm porosity). Concentrations
193 were determined by fluorimetry (Lorenzen, 1966) on a turner design Trilogy fluorimeter.

194

195 **2.5 Statistical analysis**

196 All statistical and graphical analyses as well as application condition checks were
197 performed using StatEL software v3 for excel (www.adscience.fr).

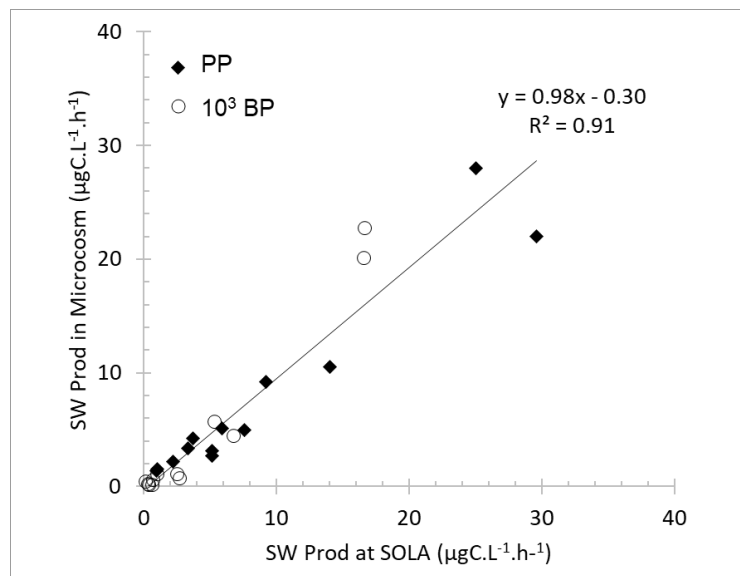
198

199 **3. Results**

200 **3.1 Representativeness of aquarium with circulating seawater compared to *in situ***
201 **conditions**

202 We measured the temporal evolution of several environmental parameters in order to test
203 that the experimental setup in the 50 L aquarium with continuous circulating seawater
204 originating from the bay of Banyuls (flow rate of ~5.0 L per hour) was representative of the *in*
205 *situ* conditions classically observed at the coastal observatory marine station (SOLA located in
206 the Banyuls bay). We found significant correlations for all parameters ($R > 0.78$, $p < 0.05$)
207 between our experimental aquaria and the natural seawater in both experiments performed in
208 2018 and 2019.

209 In particular, we compared the primary production (PP) and heterotrophic bacterial
210 production (BP) in the aquarium with continuous seawater circulation and the measurements
211 carried out with water sampled at SOLA station (Fig. 1). Analysis of the comparison points
212 showed a linear regression slope of 0.98 ± 0.17 ($p < 0.00001$; $n = 24$, slope is not significantly
213 different from 1 and the origin is not significantly different from 0; $p < 0.05$). The same patterns
214 were obtained with temperature, salinity, chlorophyll *a* and nutrients thus confirming the
215 absence of an “aquarium effect” during our 3 month-experiments.



216

217 **Figure 1:** Comparison of phytoplankton primary production (PP = ◆) and heterotrophic
 218 bacterial production (BP = ○) in the aquarium with continuous seawater circulation and at
 219 the long-term observatory SOLA marine station (Banyuls bay, NW Mediterranean sea). Note
 220 that the heterotrophic bacterial production units are 1000x. The linear regression is
 221 represented by the black line and the corresponding equation is indicated ($p < 0.00001$; $n =$
 222 24).

223

224

225 3.2 Biogeochemical conditions during 2 years experiments in a local temporal context

226 Our two experiments from 2018 and 2019 were done using the same 50-L aquarium with
 227 circulating seawater pumped in the Banyuls Bay, in the vicinity of the SOLA observatory
 228 station. Weekly measurements are made at SOLA since 1997 as part of the National
 229 Observation Service (SNO-SOMLIT). We compared the biogeochemical conditions of our
 230 experiments, *i.e.* from 13 February 2018 (D44) to 14 May 2019 (D133), to the nearly 24 years
 231 of observation at the SOLA station (see www.somlit.fr/mysomlit/). Very contrasted
 232 environmental conditions were observed between 2018 and 2019, with higher variations of

233 temperature, salinity, nutrients and chlorophyll *a* concentrations during the first year (Fig. 2).
234 Indeed, when comparing the data of the 2 years with respect to the long-term average values
235 represented by the continuous line (Fig. 2A and 2B), the 2018 measurements are variable and
236 distributed rather below the normals, while the 2019 measurements are more stable, close to
237 the normals in temperature (Fig. 2A) but largely above for salinity (Fig 2B). This leads to
238 important differences in terms of nutrients, particularly visible on nitrates (Fig. 2E), with 2018
239 being rich compared to 2019 marked by minimal nutrient concentrations.

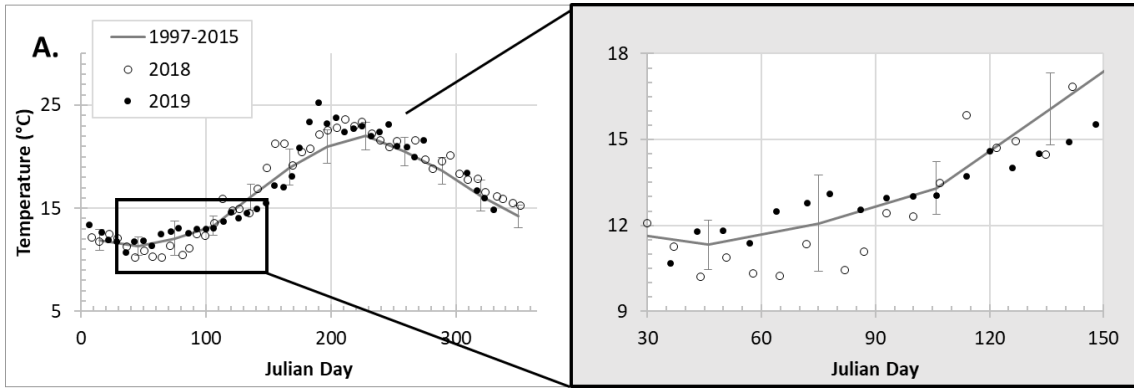
240 Then, the spring conditions in our 2018 experiment were particularly cold between D30
241 and D90 (Fig. 2A) and marked by two episodes of low salinity water at D72 (36.4) and D105
242 to D115 (35.3 and even 33 for D156; Fig. 2B). These desalted episodes caused strong variations
243 in nutrient concentrations during 2018, especially phosphate, marked by 2 peaks with nearly
244 0.1 μM (Fig. 2C). While ammonium concentrations were rather low ($\sim 0.1 \mu\text{M}$) compared to
245 “usual values”, we still observed 2 peaks approaching 0.3 μM each (Fig. 2D). Nitrate
246 concentrations were high throughout the period, with peaks above 3 μM (Fig. 2E). The
247 abundance of nutrients in 2018 resulted in a particularly pronounced spring bloom with
248 chlorophyll *a* maximal concentrations close to 3.5 and 4.1 $\text{mgCHL}\cdot\text{m}^{-3}$ for D72 and D107
249 respectively (Fig. 2F).

250 In 2019, the temperatures remained close to the climatologic curve during the
251 experimental period, while the summer period was warmer (Fig. 2A). Throughout the
252 experiment, salinity was high, with values varying around 38 but the time series was marked
253 by 2 weak decreases for D72 (37.7) and D120 (37.5) (Fig. 2B). As a result, all nutrient
254 concentrations were rather low. Phosphate concentrations were relatively stable at about 0.03
255 μM and marked by 2 maxima (0.05 μM for D86 and 0.11 μM for D114; Fig. 2C). Ammonium
256 concentrations were close to the detection limit, but again, we observed 2 peaks (0.2 μM for
257 D93 and 0.23 μM for D114; Fig. 2D). A similar pattern was observed for nitrate, with very low

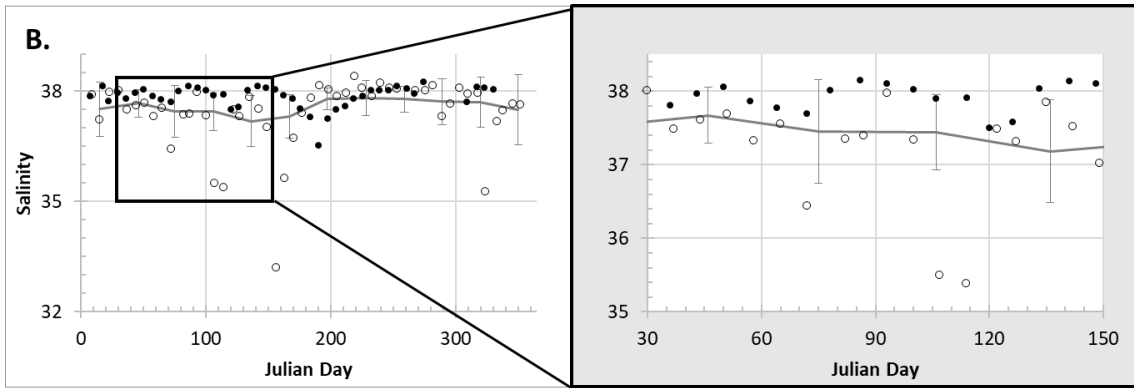
258 concentrations throughout the period, and 2 minor peaks at D64 and D100 (Fig. 2E). The low
259 abundance of nutrients in 2019 resulted in a rather weak spring bloom with chlorophyll *a*
260 maximal concentrations of 1.5 mgCHL.m⁻³ recorded between D115 and D125 (Fig. 2F).

261

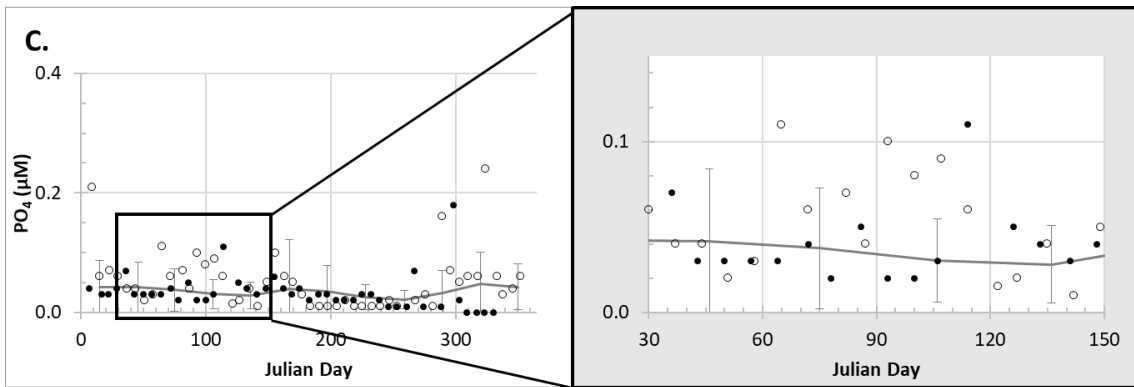
262



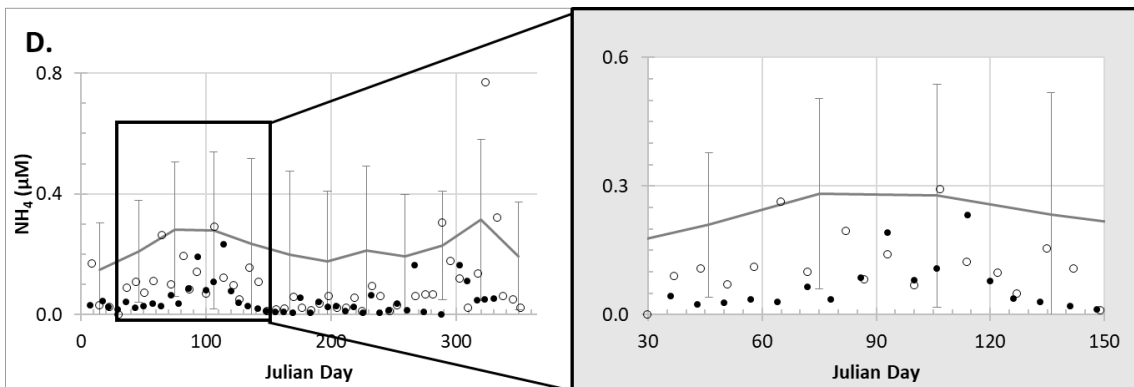
263



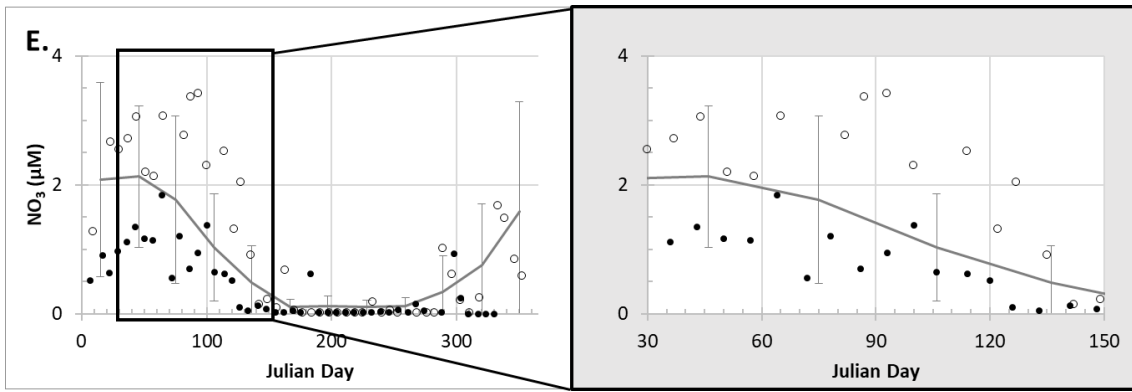
264



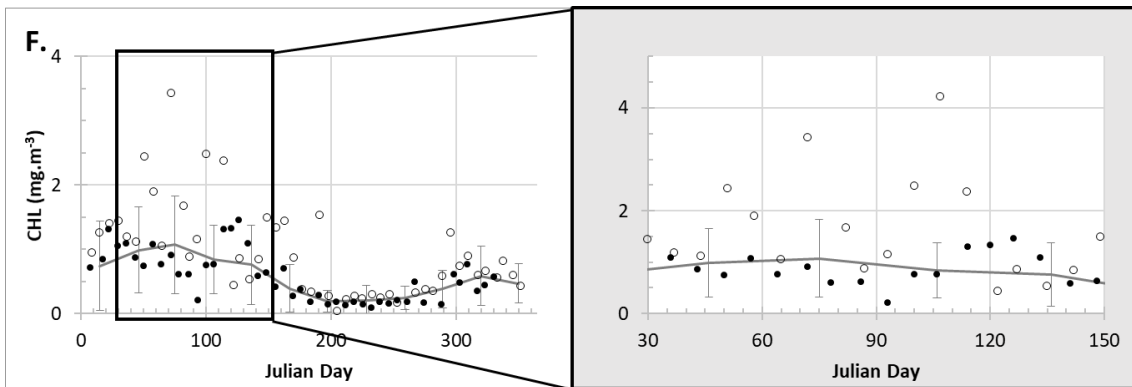
265



266



267



268 **Figure 2:** Seasonal evolution at SOLA observatory station for 2018 (D44-127, open dots) and
269 2019 (D50-133, full dots) compared to the 1997-2015 climatology (black solid line and
270 confidence interval) of A. temperature in °C, B. salinity, C. phosphate in μM , D. ammonium
271 in μM , E. nitrate in μM , and F. chlorophyll a in $\text{mgCHL}\cdot\text{m}^{-3}$. The grey inset on the right of
272 each main graph focuses on the experimental period D30 to D150.

273

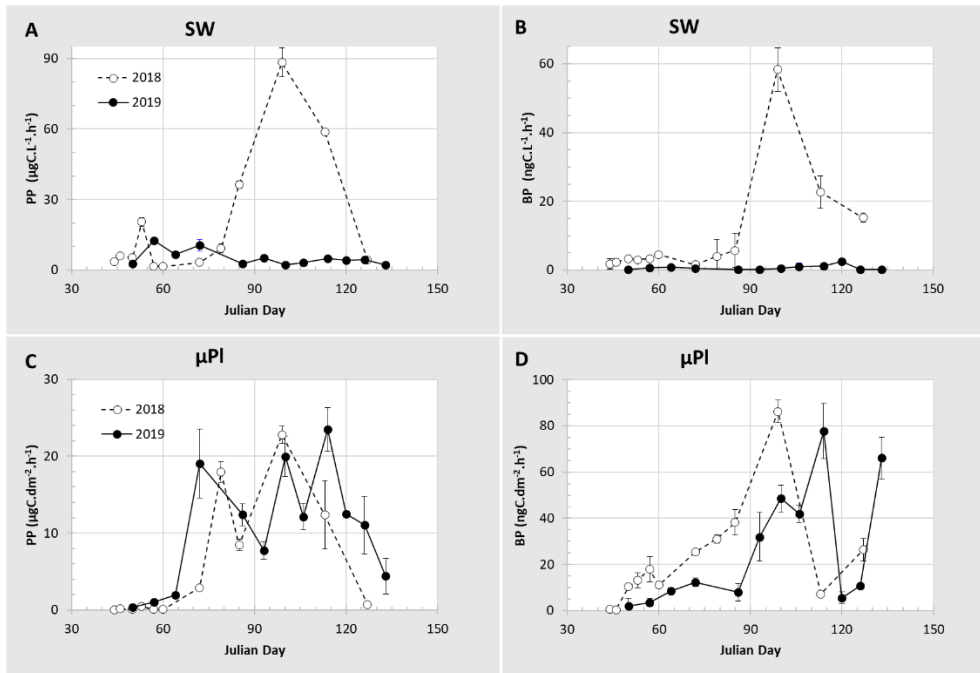
274

275 3.3. Primary production and heterotrophic bacterial production in seawater and on 276 microplastics

277 Significant differences were found when comparing the evolution of both primary and
278 heterotrophic bacterial productions in seawater between the experiments conducted in 2018 and
279 2019 (Fig. 3A & 3B). In 2018, primary and heterotrophic bacterial productions presented a
280 succession pattern over the 3 months spring period. Production rates varied from low activities

281 between D40 and D80 (on average $5.9 \pm 5.0 \mu\text{gC.L}^{-1}.\text{h}^{-1}$ for PP [Fig. 3A] and $3.3 \pm 1.3 \text{ngC.L}^{-1}.\text{h}^{-1}$ for heterotrophic bacterial production [Fig. 3B]) to a high peak observed at D100 for both
282 activities ($88.2 \pm 6.1 \mu\text{gC.L}^{-1}.\text{h}^{-1}$ and $58.3 \pm 6.4 \text{ngC.L}^{-1}.\text{h}^{-1}$ for PP and heterotrophic bacterial
283 production, respectively) followed by a rapid decrease until the end of the incubation (~D130).
284 In 2019, the evolution of primary and heterotrophic bacterial productions were clearly different
285 compared to 2018, with no synchronicity or succession observed between the 2 types of
286 productions. Primary production varied over time with maximal values at the beginning of the
287 experiment between D50 and D90 (maximum rate at $12.5 \pm 0.1 \mu\text{gC.L}^{-1}.\text{h}^{-1}$) and then remained
288 low and relatively stable until the end of incubation ($<5.1 \pm 0.1 \mu\text{gC.L}^{-1}.\text{h}^{-1}$; Fig. 3A). In
289 contrast, heterotrophic bacterial production had a similar evolution to 2018, but with lower
290 values and a low later peak (maximum for D120 with $2.5 \pm 0.5 \text{ngC.L}^{-1}.\text{h}^{-1}$; Fig. 3B).

292 Years 2018 and 2019 showed sharp contrasted spring conditions, reflected in the distinct
293 evolution of primary and heterotrophic bacterial productions in seawater. On the contrary, the
294 productions measured on microplastics showed a surprisingly similar evolution during the two
295 years (Fig. 3C & 3D). Primary production increased rapidly after D60 to reach maximum
296 activities of about $20 \pm 3 \mu\text{gC.dm}^{-2}.\text{h}^{-1}$ (Fig. 3C) and remained variable (from 8 ± 1 to 23 ± 2
297 $\mu\text{gC.dm}^{-2}.\text{h}^{-1}$) until D100 in 2018 and D115 in 2019 to finally drop rapidly until the end of the
298 experiment. Heterotrophic bacterial production increased during about 80 days to reach a
299 maximum of $86 \pm 5 \text{ngC.dm}^{-2}.\text{h}^{-1}$ in 2018 at D99 and $78 \pm 10 \text{ngC.dm}^{-2}.\text{h}^{-1}$ in 2019 at D114.
300 During both years, peaks were followed by a rapid decrease and a second phase of increase
301 until the end of the incubation (Fig 3D).



302

303 **Figure 3:** Temporal evolution during the incubation time in 2018 (D44-127, open dots and
 304 dashed line) and 2019 (D50-133, full dots and black line) of **A.** Primary production, PP (in
 305 $\mu\text{gC}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$), **B.** Heterotrophic bacterial production, BP ($\text{ngC}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$) in aquarium seawater
 306 (SW) and of **C.** Primary production (in $\mu\text{gC}\cdot\text{dm}^{-2}\cdot\text{h}^{-1}$), **D.** Heterotrophic bacterial production
 307 ($\text{ngC}\cdot\text{dm}^{-2}\cdot\text{h}^{-1}$) on microplastics (μPI). Whiskers represent standard deviations.

308

309

310 3.4. Comparison of microbial activities on microplastics and in seawater

311 We calculated the percentage of carbon originating from the extracellular release (ER)
 312 that was available for bacterial heterotrophic activity, based on the theoretical ranges of ER
 313 (from 5 to 20% of the PP) and the bacterial carbon demand (BCD) considering a Bacterial
 314 Growth Efficiency (BGE) of 10 to 30%. Indeed, BGE is the amount of new bacterial biomass
 315 produced per unit of organic C substrate assimilated. The wide ranges used in our calculation
 316 are sufficient to cover about all natural and mesocosm situations for phytoplanktonic excretion
 317 (Baines and Pace, 1991; López-Sandoval et al., 2010; Moran et al., 2002), or BGE (Del Giorgio

318 and Cole, 1998; Lemee et al., 2002) and match also with the rates found in benthic communities
319 (Hubas et al., 2007).

320 During the spring sampling periods, we found that the free-living seawater bacteria might
321 theoretically consume between 2 and 25% of the carbon excreted by autotrophs in the 2018
322 conditions and between 0.5 and 6% in the 2019 conditions (Tab. I). The situation was quite
323 different on microplastics, where we found that between 14 to 167% of the extracellular release
324 was needed to cover the BCD of the heterotrophic community in 2018 and between 8 to 101%
325 in 2019.

326

327

328 **Table I. Comparison between microbial activities on microplastics and in the surrounding**
329 **seawater.** *On top:* integrated values of primary production and bacterial heterotrophic
330 production (BP) in seawater (in mgC.L⁻¹) and on microplastics (mgC.dm⁻²) over the 88 days
331 of incubation. *In the middle:* theoretical extracellular release (range for 5 to 20% excretion,
332 as mentioned by Conan et al., 1999) and theoretical bacterial carbon demand (with a BGE
333 of 10 to 30% as mentioned by Van Wambeke et al., 2002). *At the bottom:* theoretical carbon
334 from extracellular release available for (BP) bacterial heterotrophic activity (see text for
335 more explanation).

Year	Nb day	SEAWATER				μPLASTIC			
		Integrated PP	sigma	Integrated BP	sigma	Integrated PP	sigma	Integrated BP	sigma
2018	88	26.7	6.0	0.0339	0.0294	7.3	3.1	0.061	0.025
2019	88	4.6	1.1	0.0013	0.0004	9.6	4.5	0.049	0.075
		Excretion 5 % - 20%		BCD 10% - 30%		Excretion 5 % - 20%		BCD 10% - 30%	
2018	88	1.3	5.3	0.339	0.113	0.4	1.5	0.611	0.204
2019	88	0.2	0.9	0.013	0.004	0.5	1.9	0.486	0.162
		Potential Carbon PP-source consumed for BP							
2018	88	MIN - MAX (%)		2	25	MIN - MAX (%)		14	167
2019	88	MIN - MAX (%)		0.5	6	MIN - MAX (%)		8	101

336

337

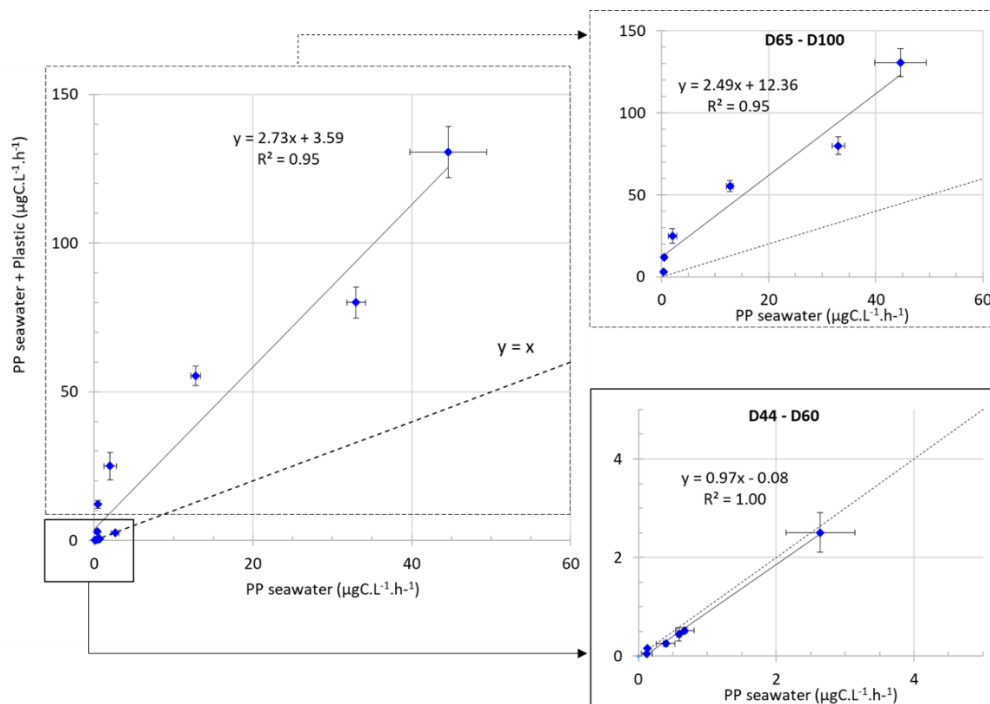
338

339 3.5. Influence of microplastic microbial activities on the surrounding seawater

340 In the 2018 experiment, we compared measurements of total primary production in the
341 seawater samples that were incubated with or without microplastics (Fig. 4). Primary
342 production in seawater incubated in the presence of plastic is higher than when no plastic is
343 present. The positive linear correlation between samples is estimated using a Spearman's test
344 ($p < 0.005$), and then the regression is calculated using Pearson's regression ($PP_{\text{seawater} + \text{Plastic}} =$
345 $2.73 \times PP_{\text{seawater}} + 3.59$; $R^2 = 0.95$; $p < 0.00001$). The intercept of the regression is not different
346 from 0 ($p < 0.05$), and so the increase in the rate of primary production of seawater in the
347 presence of plastic is about 2.8 over the incubation period.

348 In order to clarify the origin of this significant increase, we separate the data into 2 subsets
349 (Fig. 4), the first grouping the measurements during the development of the platisphere (D44 -
350 D60), and the second including the data in the presence of the “mature platisphere” (D65 -
351 D100). Finally, there was no significant difference between the PP of seawater incubated with

352 or without plastic during the first 26 days ($PP_{\text{seawater} + \text{Plastic}} = 0.97 \times PP_{\text{seawater}} - 0.08$; $R^2 = 0.99$;
 353 $p < 0.00001$). The slope of the regression model was not different from 1 (Ancova after a Mann-
 354 Whitney test, $p < 0.05$) and the intercept was not different from 0 ($p < 0.05$). The situation was
 355 quite different for the second period (D65 - D100), when the platisphere was well developed
 356 (Fig. 4). In this case, the PP in seawater incubated with plastic increased by 2.5 times compared
 357 to PP in seawater that has not been in contact with plastic ($PP_{\text{seawater} + \text{Plastic}} = 2.49 \times PP_{\text{seawater}} +$
 358 12.36 ; $R^2 = 0.95$; $p < 0.00085$). The slope of this regression model is significantly different
 359 from 1 (Ancova after a Mann-Whitney test, $p < 0.00067$) and the intercept is significantly
 360 different from 0 ($p < 0.00085$).



361
 362 **Figure 4:** Comparison of primary production (PP) in seawater without (SW) or with
 363 microplastic (SW+MP) during the 2018 experiment. Linear regression are full line and
 364 significant equations are indicate ($p < 0.001$; $n = 12$). Dashed line represents $y = x$. Pooled
 365 data are presented on the left, whereas on the right, date are separated into 2 periods as
 366 symbolized by the squares (D44 – D60 on the bottom, D65 - D100 on the top)

367

368 4. DISCUSSION

369 The impact of plastic pollution on biogeochemical cycles can no longer be considered
370 limited today, since the amount of microplastics found at sea could soon cover more than 4.2
371 million km² of the sea surface (Eriksen et al., 2014; Hidalgo-Ruz et al., 2012). To date, most of
372 the research dealing with the plastisphere has been focused on its biodiversity (including
373 putative pathogens or harmful algae), with little documentation on how the plastisphere may
374 influence the biogeochemical cycles (Jacquin et al., 2019). Here, we present the first data of PP
375 coupled with heterotrophic bacterial production on microplastics. After a month of colonization
376 of polyethylene microplastics in seawater, we observed that the mature biofilm presented high
377 PP levels, up to $20 \pm 3 \mu\text{gC}\cdot\text{dm}^{-2}\cdot\text{h}^{-1}$ compare to the beginning of the experiment. Consistent to
378 our results, phototrophs such as diatoms and cyanobacteria have been commonly described in
379 the plastisphere, at least on plastics that are exposed to sunlight (Amaral-Zettler et al., 2020;
380 Decelle et al., 2015), confirming that microplastics floating at the ocean surface provide good
381 substrates for the development of autotrophic microorganisms. For example, Crisafi et al.
382 (2022) recently studied the growth of microbial biofilms on medical masks in a coastal area
383 affected by different anthropogenic inputs. The authors observed that after one month in the
384 field, the masks were colonized by a bacterial community significantly different from that
385 detected in natural matrices in the same areas (seawater and sediments), and allowed the growth
386 and enrichment of phototrophic microorganisms such as Oxyphotobacteria, Ruminococcaceae,
387 Gracilibacteria, and Holophageae in particular.

388 Plastics in the environment are composed by a large variety of organic and inorganic
389 constituents according to their surface properties and mediated by physical forces common to
390 all molecular systems (*i.e.* van der Waals, electrostatic and others), the so-called eco-corona
391 (Monopoli et al., 2012; Ter Halle and Ghiglione, 2021). Together with light and CO₂
392 availability, nutrients such as NO₃²⁻, NH₄⁺ and PO₄³⁻ are abundant in the biomolecular corona

393 of microplastics (Galloway et al., 2017), thus potentially fueling the intense PP observed in our
394 experimental conditions.

395 Our results also showed a direct link between PP and heterotrophic bacterial production
396 (BP) within the microplastic biofilms. BP reached $86 \pm 5 \text{ ngC.dm}^{-2}.\text{h}^{-1}$, which was in the same
397 order of magnitude than the few previous studies recording this parameter on microplastics in
398 marine waters (Dussud et al., 2018b; Odobel et al., 2021). Heterotrophic bacterial activities play
399 a key role in different biogeochemical cycles such as carbon, since it is known that half of the
400 oceanic primary production on average is re-mineralized by bacteria into the microbial loop
401 (Azam et al., 1983; Cole et al., 1988), thus transforming the particulate organic matter to
402 dissolved organic matter (Grossart et al., 2007). Here, we propose for the first time that
403 heterotrophic microbes have the ability to process considerable amounts of organic matter
404 produced on microplastics by phytoplankton activities. Here, we propose for the first time that
405 heterotrophic microbes have the capacity to process considerable amounts of organic matter
406 produced on microplastics by phytoplankton activities. Indeed, photosynthates are known to be
407 particularly labile and rapidly consumed by bacteria (Conan et al., 1999; Van Wambeke et al.,
408 2002). The authors showed that the lability/quality of this material increased with its freshness
409 (age) and with trophic conditions (i.e. material produced in oligotrophic environments is
410 generally less labile than that of mesotrophic and eutrophic environments). The spatial
411 proximity of the protagonists and their greater number within the plastisphere would be a factor
412 in strengthening the trophic link, both in the autotrophic to heterotrophic direction and in the
413 other direction. Interestingly, our results also indicate that PP can theoretically support most of
414 the heterotrophic activities within the microplastic biofilm. If we assume that taking the
415 extremes, the orders of magnitude cover most values encountered in natural environments and
416 in biofilms, and considering the ranges of ER between 5 and 20% and BGE on labile material
417 between 10 and 30% (Baines and Pace, 1991; Conan et al., 1999; Del Giorgio and Cole, 1998;

418 Hubas et al., 2007; Lemee et al., 2002; López-Sandoval et al., 2010; Moran et al., 2002; Van
419 Wambeke et al., 2002), we observed that the carbon requirement of free-living heterotrophic
420 bacteria could be largely covered by PP for both years.

421 Similarly, ER might have theoretically covered most of the BCD in 2018 (min. 14% and
422 max. 167%, with <100% corresponding to the BCD totally covered by ER) and in 2019 (from
423 8-101%). Thus, while in 2019 the BCD appeared to be fulfilled by autotrophic production on
424 microplastics (*i.e.* when PP in surrounding seawater was low), it is possible that in 2018 an
425 additional organic carbon source was required to supplement the needs of attached
426 heterotrophic bacteria. This observation is consistent with the fact that in 2018, PP in the
427 surrounding water was particularly strong and could logically have been a supplemental source.
428 However, our results suggest that the use of such a complementary carbon source by the
429 plastisphere and the depletion of carbon and nitrogen in the surrounding seawater would rather
430 be an exception than a rule. This confirms that microplastic is an ecological niche in itself
431 (Dussud et al., 2018b), where strong phytoplankton-bacteria interactions exist that control
432 nutrient cycling and biomass production at the scale of microplastic pieces. Roughly, plastics
433 appear to be comparatively less autotrophic than surrounding seawater during our experiments.

434 Another originality of our study was to take into account two contrasted environmental
435 conditions during each of the 2 years. It is indeed very likely that biofilm composition and
436 microbial interactions within plastic surfaces are in turn influenced by environmental
437 perturbations (Crisafi et al., 2022). For example, the works of Allgaier et al. (2008) in natural
438 mesocosms were designed to test whether the predicted change in $p\text{CO}_2$ will affect the
439 communities of heterotrophic bacteria during a phytoplankton bloom development. The authors
440 concluded that bacterial abundance and activities were similar among the various treatments
441 but the community structure of free-living bacteria changed with $p\text{CO}_2$ on the contrary of that
442 of attached bacteria. These latter were tightly coupled to phytoplankton bloom development.

443 During spring 2018, we observed conditions favoring a classical phytoplankton bloom in
444 seawater triggered by nutrient inputs from coastal water intrusions (Olita et al., 2014). Less
445 favorable conditions were observed in spring 2019, where low nutrient concentrations limited
446 the phytoplankton bloom development. Such irregular nutrient supply from year to year is a
447 classical observation in the North Western Mediterranean sea (Sánchez-Pérez et al., 2020), that
448 strongly structures microbial communities by promoting planktonic blooms and by stimulating
449 the growth of certain microbes (Céa et al., 2015; Conan et al., 2007; Ghiglione et al., 2005;
450 Lambert et al., 2019). In contrast, we observed that microplastic biofilms were not influenced
451 by the irregularity of the nutrient supply in the seawater. Indeed, primary and secondary
452 productions were similar on microplastics over the two years, whereas a clear decrease in these
453 activities was observed in spring 2019 in seawater, when the environmental conditions were
454 less favorable as compared to spring 2018. It is classically admitted that sessile microorganisms
455 forming a biofilm on natural or engineered materials have greater access to nutrients and any
456 resources that accumulate and concentrate on the biofilms surface (Salgar-Chaparro et al.,
457 2020), which are classically diluted in the open ocean and less accessible for planktonic
458 microorganisms (Dang and Lovell, 2016). Again, these results strengthen the vision of
459 microplastic biofilm as a niche in itself, with the presence of an eco-corona together with strong
460 phytoplankton-bacteria interactions that will control the exchange and interaction with
461 materials, minerals and other components of the surrounding seawater. We propose that biofilm
462 development on microplastics is a possible strategy for microbial survival in the marine
463 environment, especially in oligotrophic seawaters such as the Mediterranean Sea, which is one
464 of the most microplastic-polluted areas in the world ocean (Cózar et al., 2015; Dussud et al.,
465 2018a).

466 Interactions between microplastic biofilms and surrounding seawater could be finally bi-
467 directional, *i.e.* nutrient and organic matter inputs on microplastics support the phytoplankton

468 development together with heterotrophic activities (see above discussion), and *vice versa* with
469 the release of materials nutrients from the microplastic biofilm to the seawater. In our study, we
470 also incubated seawater with and without microplastics in spring 2018 and we evidenced a 2-3
471 fold increase of PP when microplastics were present together with their biofilm. As mentioned
472 earlier, a more thorough assessment of the spatial scale of the different processes reported is
473 necessary. ER and the release of other molecules produced by the microplastic biofilm or even
474 the breakdown of cells may explain the positive effect on PP in the surrounding waters (example
475 with DOC; Romera-Castillo et al., 2018). Further experiments are obviously needed to
476 investigate the molecular exchanges related to this positive effect. Comparing oxygen
477 measurements with and without microplastics, a previous study in the North Pacific gyre
478 measured a net autotrophic production of about 30-60 $\mu\text{gC}\cdot\text{L}^{-1}\cdot\text{h}^{-1}$ for communities attached to
479 microplastics harvested by manta net, while they found zero or even net heterotrophic bacterial
480 production in the surrounding waters (Bryant et al., 2016). These authors proposed that
481 microplastic particles create net autotrophic 'hot spots' in the oligotrophic ocean. However, such
482 comparison is difficult because of the method used, as oxygen measurements in their
483 experiment integrated the activities of the microplastic biofilms and also of planktonic
484 organisms surrounding the microplastics during incubation. The use of radioactive carbon
485 incorporation removes this ambiguity and confirms the clear influence of the microplastic
486 biofilm on the increased productivity in the surrounding seawater, despite the contrasted
487 environmental conditions encountered in spring 2018 and 2019. Moreover, it is actually the
488 presence of the platisphere that is at the origin of the increase in production since it is necessary
489 to wait for the installation of the biofilm to observe the stimulation of 2 to 3 times of the PP in
490 the surrounding sea water. Our results are nevertheless limited by the size of the microplastic
491 pieces incubated in 10 mL of seawater. Further studies are needed to evaluate the volume of
492 seawater that could be impacted around the microplastic particles in more realistic conditions.

493 Interestingly, a previous study estimated that globally up to 23,600 metric tons of
494 dissolved organic compounds (from truly dissolved substances to any polymeric nanoplastic
495 that might have been also fragmented from the plastic surface) are released from the estimated
496 35,000 metric tons of all the microplastics floating in the ocean (Romera-Castillo et al., 2018).
497 These numbers consider the release of compounds from the microplastic itself, but do not take
498 into account the biofilm covering its surface. Finally, a funny and illustrative image of the role
499 of plastics in the environment could be that of an electrical inverter in a circuit that allows the
500 attenuation of both positive and negative variations. A better estimation of the carbon fluxes
501 generated by microplastic biofilm exudates may help to refine the balance between direct
502 microplastics leaching and the contribution of their associated biofilm.

503

504 **5. CONCLUSION**

505 Our study provides an essential step in understanding the importance of the coupling
506 between phytoplankton autotrophy and bacterial heterotrophic production on microplastics and
507 its relationship with surrounding seawater. The plastic waste quantity entering the oceans is
508 predicted to increase by up to one order of magnitude by 2025 (Gewert et al., 2015), with
509 potential major consequences for marine microbes and the biogeochemical cycles in the ocean.
510 Further studies considering the influence of microplastic features and water environmental
511 characteristics are needed. This will enable the development of predicting models for the impact
512 of biofilm activities on the carbon cycle in marine ecosystems.

513

514

515

516 **Acknowledgment:** This project was supported by the MITI-CNRS “Défi Plastiques et micro-
517 plastiques en milieux aquatiques” project BIOGEOPLAST, by the European project JRA-
518 ASSEMBLE+ and the Tara Ocean Foundation project MICROPLASTIC 2019. We are grateful
519 to the sailors of RV Néréis II, to the SNO SOMLIT (Service d’Observation en Milieu Littoral
520 ; www.somlit.fr), to Nolwenn Callac for assistance during experiments and to Guigui PA, VF
521 and JPJS, JJV for insightful comments on the manuscript.

522

523 **References**

- 524 Allgaier, M., Riebesell, U., Vogt, M., Thyrraug, R., Grossart, H.P., 2008. Coupling of
525 heterotrophic bacteria to phytoplankton bloom development at different pCO₂ levels: a
526 mesocosm study. *Biogeosciences* 5, 1007-1022.
- 527 Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., 2020. Ecology of the plastisphere. *Nat. Rev.*
528 *Microbiol.* 18, 139-151.
- 529 Aminot, A., K erouel, R., 2007. Dosage automatique des nutriments dans les eaux marines.
530 M ethodes en flux continu, in: Ifremer-Quae, E. (Ed.), p. 188.
- 531 Azam, F., Fenchel, T., Field, J.G., Gray, J.S., Meyerreil, L.A., Thingstad, F., 1983. The
532 ecological role of water-column microbes in the sea *Mar. Ecol. Prog. Ser.* 10, 257-263.
- 533 Baines, S.B., Pace, M.L., 1991. The production of dissolved organic matter by phytoplankton
534 and its importance to bacteria: Patterns across marine and freshwater systems. *Limnol.*
535 *Oceanogr.* 36, 1078-1090.
- 536 Behrenfeld, M.J., Falkowski, P.G., 1997. A consumer's guide to phytoplankton primary
537 productivity models. *Limnol. Oceanogr.* 42, 1479-1491.
- 538 Borrelle, S.B., Ringma, J., Law, K.L., Monnahan, C.C., Lebreton, L., McGivern, A., et al.,
539 2020. Predicted growth in plastic waste exceeds efforts to mitigate plastic pollution. *Science*
540 369, 1515-1518.
- 541 Bryant, J.A., Clemente, T.M., Viviani, D.A., Fong, A.A., Thomas, K.A., Kemp, P., et al., 2016.
542 Diversity and Activity of Communities Inhabiting Plastic Debris in the North Pacific Gyre.
543 *mSystems* 1, e00024-00016.
- 544 Cat o, E.C.P., Pollet, T., Misson, B., Garnier, C., Ghiglione, J.-F., Barry-Martinet, R., et al.,
545 2019. Shear Stress as a Major Driver of Marine Biofilm Communities in the NW
546 Mediterranean Sea. *Front. Microbiol.* 10.
- 547 C ea, B., Lef evre, D., Chirurgien, L., Raimbault, P., Garcia, N., Charri ere, B., et al., 2015. An
548 annual survey of bacterial production, respiration and ectoenzyme activity in coastal NW
549 Mediterranean waters: temperature and resource controls. *Environ. Sci. Pollut. Res. Int.* 22,
550 13654-13668.
- 551 Chen, C.-T.A., Yu, S., Huang, T.-H., Lui, H.-K., Bai, Y., He, X., 2020. Changing
552 Biogeochemistry in the South China Sea, in: Chen, C.-T.A., Guo, X. (Eds.), *Changing Asia-*
553 *Pacific Marginal Seas.* Springer Singapore, Singapore, pp. 203-216.
- 554 Cole, J.J., Findlay, S., Pace, M.L., 1988. Bacterial production in fresh and saltwater: a cross-
555 system overview. *Mar. Ecol. Prog. Ser.* 43, 1-10.

556 Conan, P., Søndergaard, M., Kragh, T., Thingstad, F., Pujo-Pay, M., Williams, P.J.I.B., et al.,
557 2007. Partitioning of organic production in marine plankton communities: The effects of
558 inorganic nutrient ratios and community composition on new dissolved organic matter.
559 *Limnol. Oceanogr.* 52, 753-765.

560 Conan, P., Turley, C.M., Stutt, E., Pujo-Pay, M., Van Wambeke, F., 1999. Relationship between
561 Phytoplankton Efficiency and the Proportion of Bacterial Production to Primary Production
562 in the Mediterranean Sea. *Aquat. Microb. Ecol.* 17, 131-144.

563 Cózar, A., Sanz-Martín, M., Martí, E., González-Gordillo, J.I., Ubeda, B., Gálvez, J.Á., et al.,
564 2015. Plastic Accumulation in the Mediterranean Sea. *PLOS ONE* 10, e0121762.

565 Crisafi, F., Smedile, F., Yakimov, M.M., Aulenta, F., Fazi, S., La Cono, V., et al., 2022.
566 Bacterial biofilms on medical masks disposed in the marine environment: a hotspot of
567 biological and functional diversity. *Sci. Total Environ.* 837, 155731.

568 Dang, H., Lovell, C.R., 2016. Microbial Surface Colonization and Biofilm Development in
569 Marine Environments. *Microbiol. Mol. Biol. Rev.* 80, 91-138.

570 Debroas, D., Mone, A., Ter Halle, A., 2017. Plastics in the North Atlantic garbage patch: A
571 boat-microbe for hitchhikers and plastic degraders. *Sci. Total Environ.* 599-600, 1222-1232.

572 Decelle, J., Romac, S., Stern, R.F., Bendif, E.M., Zingone, A., Audic, S., et al., 2015.
573 PhytoREF: a reference database of the plastidial 16S rRNA gene of photosynthetic
574 eukaryotes with curated taxonomy. *Mol. Ecol. Resour.* 15, 1435-1445.

575 Del Giorgio, P.A., Cole, J.J., 1998. Bacterial Growth Efficiency in Natural Aquatic Systems.
576 *Annu. Rev. Ecol. Syst.* 29, 503-541.

577 Del Giorgio, P.A., Cole, J.J., 2000. Bacterial energetics and growth efficiency, in: Kirchman,
578 D.L. (Ed.), *Microbial ecology of the oceans*. Wiley-Liss, New York, pp. 289–325.

579 Dodds, W.K., Cole, J.J., 2007. Expanding the concept of trophic state in aquatic ecosystems:
580 It's not just the autotrophs. *Aquat. Sci.* 69, 427-439.

581 Durrieu de Madron, X., Guieu, C., Sempéré, R., Conan, P., Cossa, D., D'Ortenzio, F., et al.,
582 2011. Marine ecosystems' responses to climatic and anthropogenic forcings in the
583 Mediterranean. *Prog. Oceanogr.* 91, 97-166.

584 Dussud, C., Hudec, C., George, M., Fabre, P., Higgs, P., Bruzard, S., et al., 2018a. Colonization
585 of Non-biodegradable and Biodegradable Plastics by Marine Microorganisms. *Front.*
586 *Microbiol.* 9.

587 Dussud, C., Meistertzheim, A.L., Conan, P., Pujo-Pay, M., George, M., Fabre, P., et al., 2018b.
588 Evidence of niche partitioning among bacteria living on plastics, organic particles and
589 surrounding seawaters. *Environ. Pollut.* 236, 807-816.

590 Eriksen, M., Lebreton, L.C.M., Carson, H.S., Thiel, M., Moore, C.J., Borerro, J.C., et al., 2014.
591 Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over
592 250,000 Tons Afloat at Sea. PLOS ONE 9, e111913.

593 Fitzwater, S.E., Knauer, G.A., Martin, J.-M., 1982. Metal contamination and its effect on
594 primary production measurements. *Limnol. Oceanogr.* 27, 544-551.

595 Galloway, T.S., Cole, M., Lewis, C., 2017. Interactions of microplastic debris throughout the
596 marine ecosystem. *Nat. Ecol. Evol.* 1, 0116.

597 Gewert, B., Plassmann, M.M., MacLeod, M., 2015. Pathways for degradation of plastic
598 polymers floating in the marine environment. *Environ. Sci. Process. Impact* 17, 1513-1521.

599 Ghiglione, J.F., Larcher, M., Lebaron, P., 2005. Spatial and temporal scales of variation in
600 bacterioplankton community structure in the NW Mediterranean Sea. *Aquat. Microb. Ecol.*
601 40, 229-240.

602 Grossart, H.-P., Tang, K.W., Kiørboe, T., Ploug, H., 2007. Comparison of cell-specific activity
603 between free-living and attached bacteria using isolates and natural assemblages. *FEMS*
604 *Microbiol. Lett.* 266, 194-200.

605 Hidalgo-Ruz, V., Gutow, L., Thompson, R.C., Thiel, M., 2012. Microplastics in the marine
606 environment: a review of the methods used for identification and quantification. *Environ.*
607 *Sci. Technol.* 46, 3060-3075.

608 Holmes, R.M., Aminot, A., K erouel, R., Hooker, B.A., Peterson, B.J., 1999. A simple and
609 precise method for measuring ammonium in marine and freshwater ecosystems. *Can. J. Fish.*
610 *Aquat. Sc.* 56, 1801-1808.

611 Hubas, C., Artigas, L.F., Davoult, D., 2007. Role of the bacterial community in the annual
612 benthic metabolism of two contrasted temperate intertidal sites (Roscoff Aber Bay, France).
613 *Mar. Ecol. Prog. Ser.* 344, 39-48.

614 Isobe, A., Azuma, T., Cordova, M.R., C zar, A., Galgani, F., Hagita, et al., 2021. A multilevel
615 dataset of microplastic abundance in the world's upper ocean and the Laurentian Great
616 Lakes. *Microplastics and Nanoplastics* 1, 16.

617 Jacquin, J., Cheng, J., Odobel, C., Pandin, C., Conan, P., Pujo-Pay, et al., 2019. Microbial
618 Ecotoxicology of Marine Plastic Debris: A Review on Colonization and Biodegradation by
619 the "Plastisphere". *Front. Microbiol.* 10.

620 Kong, X., Koelmans, A.A., 2019. Modeling Decreased Resilience of Shallow Lake Ecosystems
621 toward Eutrophication due to Microplastic Ingestion across the Food Web. *Environ. Sci.*
622 *Technol.* 53, 13822-13831.

623 Lambert, S., Tragin, M., Lozano, J.-C., Ghiglione, J.-F., Vaultot, D., Bouget, et al., 2019.
624 Rhythmicity of coastal marine picoeukaryotes, bacteria and archaea despite irregular
625 environmental perturbations. *ISME J.* 13, 388-401.

626 Lemée, R., Rochelle-Newall, E., Van Wambeke, F., Pizay, M.-D., Rinaldi, P., Gattuso, J.-P.,
627 2002. Seasonal variation of bacterial production, respiration and growth efficiency in the
628 open NW Mediterranean Sea. *Aquat. Microb. Ecol.* 29, 227 - 237.

629 López-Sandoval, D.C., Marañón, E., Fernández, A., González, J., Gasol, J.M., Lekunberri, I.,
630 et al., 2010. Particulate and dissolved primary production by contrasting phytoplankton
631 assemblages during mesocosm experiments in the Ría de Vigo (NW Spain). *J. Plankton Res.*
632 32, 1231-1240.

633 Lorenzen, C.J., 1966. A method for the continuous measurement of in vivo chlorophyll
634 concentration. *Deep-Sea Res. Oceanogr. Abstr.* 13, 223-227.

635 MacLeod, M., Arp, H.P.H., Tekman, M.B., Jahnke, A., 2021. The global threat from plastic
636 pollution. *Science* 373, 61-65.

637 Monopoli, M.P., Åberg, C., Salvati, A., Dawson, K.A., 2012. Biomolecular coronas provide
638 the biological identity of nanosized materials. *Nat. Nanotechnol.* 7, 779-786.

639 Moran, X.A.G., Estrada, M., Gasol, J.-M., Pedrós-Alió, C., 2002. Dissolved primary production
640 and the strength of Phytoplankton – Bacterioplankton coupling in contrasting marine
641 regions. *Microb. Ecol.* 44, 217-223.

642 Nava, V., Leoni, B., 2021. A critical review of interactions between microplastics, microalgae
643 and aquatic ecosystem function. *Water Res.* 188, 116476.

644 Oberbeckmann, S., Kreikemeyer, B., Labrenz, M., 2018. Environmental Factors Support the
645 Formation of Specific Bacterial Assemblages on Microplastics. *Front. Microbiol.* 8.

646 Odobel, C., Dussud, C., Philip, L., Derippe, G., Lauters, M., Eyheraguibel, B., et al., 2021.
647 Bacterial Abundance, Diversity and Activity During Long-Term Colonization of Non-
648 biodegradable and Biodegradable Plastics in Seawater. *Front. Microbiol.* 12.

649 Olita, A., Sparnocchia, S., Cusí, S., Fazioli, L., Sorgente, R., Tintoré, J., et al., 2014.
650 Observations of a phytoplankton spring bloom onset triggered by a density front in NW
651 Mediterranean. *Ocean Sci.* 10, 657-666.

652 Romera-Castillo, C., Pinto, M., Langer, T.M., Álvarez-Salgado, X.A., Herndl, G.J., 2018.
653 Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean.
654 *Nat. Commun.* 9, 1430.

655 Salgar-Chaparro, S.J., Lepkova, K., Pojtanabuntoeng, T., Darwin, A., Machuca, L.L., Stams,
656 A.J.M., 2020. Nutrient Level Determines Biofilm Characteristics and Subsequent Impact on

657 Microbial Corrosion and Biocide Effectiveness. *Appl. Environ. Microbiol.* 86, e02885-
658 02819.

659 Sánchez-Pérez, E.D., Pujo-Pay, M., Ortega-Retuerta, E., Conan, P., Peters, F., Marrasé, C.,
660 2020. Mismatched dynamics of dissolved organic carbon and chromophoric dissolved
661 organic matter in the coastal NW Mediterranean Sea. *Sci. Total Environ.* 746, 141190.

662 Simon, M., Azam, F., 1989. Protein content and protein synthesis rates of planktonic marine
663 bacteria. *Mar. Ecol. Prog. Ser.* 51, 201-213.

664 Subhankar, C., Shivika, S., 2019. Microplastics in our oceans and marine health, in: *Field*
665 *Actions Science Reports*, Special Issue 19, 54-61.

666 Ter Halle, A., Ghiglione, J.F., 2021. Nanoplastics: A Complex, Polluting Terra Incognita.
667 *Environ. Sci. Technol.* 55, 14466-14469.

668 Van Wambeke, F., Heussner, S., Diaz, F., Raimbault, P., Conan, P., 2002. Small-scale
669 variability in the coupling/uncoupling of bacteria, phytoplankton and organic carbon fluxes
670 along the continental margin of the Gulf of Lions, Northwestern Mediterranean Sea. *J. Mar.*
671 *Syst.* 33-34, 411-429.

672 Weiss, L., Ludwig, W., Heussner, S., Canals, M., Ghiglione, J.F., Estournel, C., et al., 2021.
673 The missing ocean plastic sink: Gone with the rivers. *Science* 373, 107-111.

674 Zettler, E.R., Mincer, T.J., Amaral-Zettler, L.A., 2013. Life in the “Plastisphere”: Microbial
675 Communities on Plastic Marine Debris. *Environ. Sci. Technol.* 47, 7137-7146.

676 Zhang, Y., Liang, J., Zeng, G., Tang, W., Lu, Y., Luo, Y., Xing, W., et al., 2020. How climate
677 change and eutrophication interact with microplastic pollution and sediment resuspension in
678 shallow lakes: A review. *Sci. Total Environ.* 705, 135979.