



**HAL**  
open science

## Efficiency of photoprotection in microphytobenthos: role of vertical migration and the xanthophyll cycle against photoinhibition

Joao Serôdio, Joao Ezequiel, Alexandre Barnett, Jean-Luc Mouget, Vona Méléder, Martin Laviale, Johann Lavaud

### ► To cite this version:

Joao Serôdio, Joao Ezequiel, Alexandre Barnett, Jean-Luc Mouget, Vona Méléder, et al.. Efficiency of photoprotection in microphytobenthos: role of vertical migration and the xanthophyll cycle against photoinhibition. *Aquatic Microbial Ecology*, 2012, 67, pp.161-175. 10.3354/ame01591 . hal-01096446v1

**HAL Id: hal-01096446**

**<https://hal.science/hal-01096446v1>**

Submitted on 17 Dec 2014 (v1), last revised 19 Dec 2014 (v2)

**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 Efficiency of photoprotection in microphytobenthos: the role of vertical migration and  
2 the xanthophyll cycle against photoinhibition

3  
4  
5  
6  
7 João Serôdio<sup>1,2\*</sup>, João Ezequiel<sup>1</sup>, Alexandre Barnett<sup>2</sup>, Jean-Luc Mouget<sup>3</sup>, Vona  
8 Méléder<sup>2,4</sup>, Martin Laviale<sup>1,4</sup>, Johann Lavaud<sup>2</sup>

9  
10 <sup>1</sup> Departamento de Biologia and CESAM – Centro de Estudos do Ambiente e do Mar,  
11 Universidade de Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal

12  
13 <sup>2</sup> UMR 7266 ‘LIENSs’, CNRS-University of La Rochelle, Institute for Coastal and  
14 Environmental Research (ILE), 2 rue Olympe de Gouges, 17 000 La Rochelle, France

15  
16 <sup>3</sup> Mer Molécules Santé – MMS EA 2160, Université du Maine. Av. O. Messiaen, 72085  
17 Le Mans Cedex 9, France

18  
19 <sup>4</sup> Mer Molécules Santé – MMS EA 2160, Université de Nantes. BP 92 208, 44322,  
20 Nantes Cedex 3, France

21  
22  
23  
24 \* Corresponding author: jserodio@ua.pt

25

26 Abstract

27 The capacity of estuarine microphytobenthos to withstand the variable and extreme  
28 conditions of the intertidal environment, prone to cause photoinhibition of the  
29 photosynthetic apparatus, has been attributed to particularly efficient photoprotection  
30 mechanisms. However, little is known regarding its actual photoprotection capacity or  
31 the mechanisms responsible for the protecting against photoinhibition. This study  
32 addressed these questions by (i) quantifying the photoprotection capacity and the extent  
33 of photoinhibition under high light exposure, (ii) estimating the contribution of vertical  
34 migration and the xanthophyll cycle to overall photoprotection and (iii) evaluating the  
35 effects of photoacclimation state. A new experimental protocol was developed,  
36 combining (i) chlorophyll fluorescence imaging, for the simultaneous measurement of  
37 replicates and experimental treatments, (ii) specific inhibitors for vertical migration and  
38 for the xanthophyll cycle, to quantify the relative contribution of each process, and (iii)  
39 recovery kinetics analysis of photosynthetic activity during light stress-recovery  
40 experiments, to distinguish reversible downregulation from photoinhibition. The results  
41 showed a high photoprotective capacity in both studied periods, May and October, with  
42 photoinhibition rates remaining below 20%. A clear change in photoacclimation state  
43 was observed, following the seasonal change in solar radiation, with acclimation to  
44 lower irradiances in autumn being associated with higher susceptibility to  
45 photoinhibition. Also the relative importance of vertical migration and the xanthophyll  
46 cycle varied between the sampling periods. While the two processes displayed a similar  
47 role in spring/summer, vertical migration became the dominant photoprotective process  
48 in autumn. However, the contribution of the two processes to overall photoprotection

49 reached only ca. 20%, suggesting the participation of other photoprotective  
50 mechanisms.

51

52 Running head: Photoprotection and photoinhibition in microphytobenthos

53

54 Key index words: microphytobenthos; photoinhibition; photoprotection; xanthophyll  
55 cycle; vertical migration; non-photochemical quenching; chlorophyll fluorescence;  
56 diatoms

57

## INTRODUCTION

Benthic microalgae inhabiting estuarine intertidal flats are exposed to extreme and highly variable environmental conditions. Particularly during low tide, the sedimentary environment is characterized by the exposure to high levels of solar irradiance (Serôdio & Catarino 1999), including UV radiation (Waring et al. 2007, Mouget et al. 2008), extreme temperatures and salinities (Brotas et al. 2003, Rijstenbil 2005), intense rates of desiccation (Coelho et al. 2009), supersaturated oxygen concentrations (Chevalier et al. 2010), and nutrient and carbon depletion (Miles & Sundbäck 2000, Cook & Røy 2006). Being potentially damaging to the photosynthetic apparatus when acting individually, the combined effects of all these factors likely concur to the photoinhibition of photosynthesis of microphytobenthos microalgae. Of particular importance is the exposure to direct sunlight, which can result in excessive reductant pressure and in the formation of intracellular reactive oxygen species (ROS; Roncarati et al. 2008, Waring et al. 2010). High levels of ROS cause the permanent inactivation of photosystem II (PSII) protein D1, negatively impacting on photosynthetic yield and on primary productivity (Nishiyama et al. 2006).

Despite these harsh conditions, microphytobenthos of intertidal flats typically exhibit high growth rates, forming dense and diverse sedimentary biofilms, and are recognized as a major contributor to ecosystem-level carbon fixation and primary productivity (Underwood & Kromkamp 1999). Furthermore, the apparent lack of photoinhibition in microphytobenthic biofilms has been repeatedly reported (Kromkamp et al. 1998, Underwood 2002, Blanchard & Cariou-LeGall 1994, Blanchard et al. 2004, Underwood et al. 2005, Van Leeuwe et al. 2008). This success in coping with high light stress may be explained by the combined operation of two processes, the xanthophyll cycle and vertical migration, which could result in an overall particularly

83 efficient photoprotection (Serôdio et al. 2008, Perkins et al. 2010). In diatoms, the group  
84 of microalgae that typically dominate in microphytobenthos assemblages, the  
85 xanthophyll cycle has been reported to provide an exceptionally high photoprotective  
86 capacity (Lavaud 2007, Brunet & Lavaud 2010, Goss & Jakob 2010). This is  
87 particularly true for microphytobenthos *in situ* (Serôdio et al. 2005, Van Leuwee et al.  
88 2008, Jordan et al. 2010, Chevalier et al. 2010). To this also seems to contribute the  
89 activation of the xanthophyll cycle in the dark, attributed to chlorespiratory activity,  
90 which has been considered as potentially advantageous during prolonged periods of  
91 darkness (Jakob et al. 2001, Cruz et al. 2011), a situation common in the sedimentary  
92 environment.

93           On the other hand, the negative phototactic behavior of benthic diatoms, mostly  
94 raphid pennates, under high light has long been interpreted as a form of avoidance of  
95 excessive light levels that would otherwise cause photoinhibition (Admiraal 1984,  
96 Underwood & Kromkamp 1999, Consalvey et al. 2004, Waring et al. 2007).

97           This subject has attracted substantial attention in recent years, particularly  
98 centered on the effects of vertical migration on biofilm photophysiology (Consalvey et  
99 al. 2004, Jesus et al. 2006, Waring et al. 2007, Mouget et al. 2008, Perkins et al. 2010,  
100 Cartaxana et al. 2011), and became facilitated by the introduction of a diatom motility  
101 inhibitor (Cartaxana et al. 2008). However, these studies have been focused on the  
102 response of photosynthetic activity during (Waring et al. 2007, Perkins et al. 2010) or  
103 shortly after light stress (Mouget et al. 2008), mostly through *in vivo* measurements of  
104 electron transport rate of PSII (ETR) or non-photochemical quenching (NPQ) of  
105 chlorophyll fluorescence (PAM fluorometry, see below; Table 1) (Perkins et al. 2011).  
106 Perhaps surprisingly, none of these studies has actually evaluated the efficiency of the  
107 photoprotection provided by these two processes or compared their role against

108 photoinhibition in microphytobenthos biofilms. The distinction between  
109 photoprotection and photoinhibition processes from chlorophyll fluorescence cannot be  
110 inferred from the decrease in ETR or formation of NPQ under high light, but requires  
111 the analysis of the recovery kinetics of photosynthetic activity following exposure to  
112 high light stress (Horton & Hague 1988, Walters & Horton 1991, Müller et al. 2001). In  
113 diatoms, a rapid (within minutes) component of this recovery can be attributed to the  
114 reversal of the xanthophyll cycle ( $q_E$ , or ‘energy-dependent quenching’) while  
115 photoinhibitory effects ( $q_I$ , or ‘photoinhibitory quenching’) can be quantified from a  
116 second, much slower (within hours) component (Müller et al. 2001, Lavaud 2007). The  
117  $q_T$  (state-transition related quenching) component of NPQ recovery, which shows  
118 intermediate relaxation kinetics, does not exist in diatoms (Owens, 1986). As such,  
119 questions like ‘How efficient are photoprotective processes in preventing  
120 photoinhibition in microphytobenthos biofilms?’, ‘What is the relative contribution of  
121 migration and the xanthophyll cycle for overall photoprotection?’ or ‘To what extent  
122 does photoinhibition occur in microphytobenthos?’ are mostly unanswered.

123         This study was set out to address these questions, for which a new experimental  
124 protocol was designed, based on the combination of (i) chlorophyll fluorescence  
125 imaging, to allow the simultaneous measurement of a large number of samples and  
126 experimental treatments, (ii) the use of specific inhibitors for vertical migration and for  
127 the xanthophyll cycle, to quantify the relative contribution of each process to overall  
128 photoprotection, and (iii) the analysis of the recovery kinetics of photosynthetic activity  
129 following light stress, to distinguish downregulation due to the xanthophyll cycle and  
130 photoinhibition. This approach was further used to test the influence of  
131 photoacclimation state on photoprotection capacity and susceptibility to photoinhibition  
132 in microphytobenthic biofilms inhabiting a temperate intertidal mudflat.

133

134

## MATERIALS AND METHODS

135

**Sampling and sample preparation.** Sediment samples were collected in the

136

upper zone of an intertidal mudflat in the Baie de l'Aiguillon (46°15'18" N, 01°08'33"

137

W), France, in late spring (May) and autumn (October) 2010, expected to show

138

contrasting photoacclimation states following the seasonal variation in solar radiation

139

(see below). The sampling site is composed of fine muddy sediments (< 63 µm) where

140

microphytobenthic biofilms are largely dominated by diatoms (Herlory et al. 2004).

141

During low tide, samples of the surface layers of sediment (approximately the top 1 cm)

142

were collected using a spatula. In the laboratory, the sediment was sieved through a

143

500-µm mesh, to remove the mud snails *Hydrobia* sp. and other meio- and macrofauna,

144

and was thoroughly mixed and spread in 4 cm deep plastic trays. The sediment was

145

covered by water collected in the sampling site and left undisturbed overnight. In the

146

next morning, at the start of the photoperiod, the slurries were again homogenized and

147

identical portions of the resulting slurry were transferred to 24-well plates using a small

148

spatula, filling the wells completely (ca. 3 ml). The well plates were exposed to

149

homogeneous light field provided by two LED panels (equal contribution of red, far-

150

red, blue and white LEDs; FloraLEDs panels, Plant Climatics, Germany) delivering a

151

constant irradiance of 70 µmol quanta m<sup>-2</sup> s<sup>-1</sup> at the sample surface, in order to induce

152

the upward migration of microalgae and the formation of the biofilm. Daily global solar

153

radiation were obtained from a Meteo-France weather station located approximately 9

154

kms southwest from the sampling site, for two-week periods preceding the sampling

155

dates, 15-30 May and 5-20 October 2010.

156

**Fluorescence measurements.** Chlorophyll fluorescence was measured using an

157

imaging-PAM fluorometer (Maxi-PAM M-series, Walz GmbH, Effeltrich, Germany).



158 The measuring area of the fluorometer covered each entire well plate, so that up to a  
159 total of 24 sediment samples could be monitored simultaneously. All experiments were  
160 carried out after biofilm formation. This was determined by measuring the fluorescence  
161 level  $F_s$ , taken as a proxy for surface microalgal biomass, in a replicated set of samples  
162 exposed to constant low light of  $55 \mu\text{mol quanta m}^{-2} \text{ s}^{-1}$ . Experiments were started after  
163  $F_s$  reached a plateau following the initial rise after on the onset of the light period which  
164 typically took 2-3 hours of low light exposure. For each sample, the fluorescence signal  
165 was calculated by averaging the values of all pixels included in an area of ca.  $63.6 \text{ mm}^2$   
166 (area of interest), which corresponded to ca. 1500 pixels, centered inside each well. This  
167 area is smaller than the total area of each well ( $95.0 \text{ mm}^2$ ), the difference being due to  
168 the exclusion of the edge of each sample, often not representative of the rest of the  
169 biofilm. To minimize sample heating during prolonged exposure to high light, the  
170 experiments were carried out in a temperature-controlled room, at  $20 \text{ }^\circ\text{C}$ , and the  
171 fluorometer Perspex hood was maintained open at all times.

172 **Photoacclimation: light-response curves.** The photoacclimation state of the  
173 samples was characterized by measuring light-response curves of ETR and of NPQ in  
174 the two sampling periods. Light-response curves were generated by sequentially  
175 exposing the samples to 7 levels of actinic light, up to  $700 \mu\text{mol quanta m}^{-2} \text{ s}^{-1}$ . Samples  
176 were exposed to each light level for 3 min (a period previously confirmed allowing for  
177 reaching a steady-state), after which a saturation pulse was applied and fluorescence  
178 levels  $F_s$  and  $F_m'$  were recorded. Six replicated measurements (on six different wells)  
179 were made for each light level. For each irradiance level,  $E$ , the relative ETR was  
180 calculated from the product of  $E$  and the PSII effective quantum yield,  $\Delta F/F_m'$  (Genty et  
181 al. 1989):

182

183 
$$\text{ETR} = E \frac{F_m' - F_s'}{F_m'} \quad (1)$$

184

185 ETR vs  $E$  curves were quantitatively described by fitting the model of Eilers & Peeters  
 186 (1988), and by estimating the parameters  $\alpha$  (the initial slope of the curve),  $\text{ETR}_m$   
 187 (maximum ETR) and  $E_k$  (the light-saturation, or photoacclimation, parameter):

188 
$$\text{ETR}(E) = \frac{E}{aE^2 + bE + c} \quad (2)$$

189 where

190 
$$\alpha = \frac{1}{c}, \text{ETR}_m = \frac{1}{b + \sqrt{ac}} \text{ and } E_k = \frac{c}{b + \sqrt{ac}} \quad (3)$$

191

192 Due to the unavoidable confounding effects of vertical migration on the measurement of  
 193  $F_m$ , NPQ was calculated using the adapted index, based on the relative difference  
 194 between the maximum fluorescence measured during the construction of the light curve,  
 195  $F_m'$ , and upon exposure to light,  $F_m'$  (Serôdio et al. 2005):

196

197 
$$\text{NPQ} = \frac{F_{m,m}' - F_m'}{F_m'} \quad (4)$$

198

199 NPQ vs  $E$  curves were described by fitting the model of Serôdio & Lavaud (2011), and  
 200 by estimating the parameters  $\text{NPQ}_m$  (maximum NPQ),  $E_{50}$  (irradiance corresponding to  
 201 half of  $\text{NPQ}_m$ ) and  $n$  (sigmoidicity parameter):

202

$$\text{NPQ} (E) = \text{NPQ}_m \frac{E^n}{E_{50}^n + E^n} \quad (5)$$

These models were fitted using a procedure written in MS Visual Basic and based on MS Excel Solver. Model parameters were estimated iteratively by minimizing a least-squares function, forward differencing, and the default quasi-Newton search method. The model was fitted to individual light-response curves. Estimates of model parameters were compared using the Student's *t*-test. The standard errors of the parameter estimates were calculated following Ritchie (2008).

**Photoprotection vs photoinhibition: light stress-recovery experiments.** The photoprotection capacity of microphytobenthos biofilms was estimated by quantifying the recovery of  $\Delta F/F_m'$  following a prolonged exposure to supersaturating irradiance. Three replicates were sequentially exposed to: (i) low light level of  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , for a minimum of 15 min, to ensure full light-activation of the photosynthetic apparatus and to determine pre-stress reference levels of  $\Delta F/F_m'$ ; (ii) supersaturating light level of  $1200 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$  for 3 hrs, to potentially induce photoinhibitory effects; (iii) low light ( $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ) for a minimum of 15 min to record the recovery kinetics. During the whole experiment,  $\Delta F/F_m'$  was measured by applying saturating pulses every 90 s. The recovery of  $\Delta F/F_m'$  upon the return to low light conditions was described by fitting an exponential function, adapted from a first-order kinetics model derived for describing the kinetics of NPQ (Olaizola & Yamamoto 1994, Serôdio et al. 2005):

$$\Delta F / F_m' (t) = \Delta F / F_{m,rec}' + \left[ \Delta F / F_m' (0) - \Delta F / F_{m,rec}' \right] e^{-kt} \quad (6)$$

227 where  $t$  is the time during recovery,  $\Delta F/F_m'(0)$  and  $\Delta F/F_m'_{,rec}$  represent the PSII quantum  
228 yield levels at the start of the recovery period and after full recovery (associated to  $q_E$ ),  
229 and  $k$  is the rate constant of  $\Delta F/F_m'$  recovery. The values of  $\Delta F/F_m'$  estimated by the  
230 model for  $t = 10.5$  min, expressed as a percentage of the pre-stress levels, were used for  
231 estimating the effective photoprotective capacity of the biofilm. The remaining relative  
232 difference between pre- and post-stress levels of  $\Delta F/F_m'$  was used as an estimate of the  
233 photoinhibitory effects imposed by high light.

234 The photoprotective roles of vertical migration and of the xanthophyll cycle  
235 were studied by applying specific inhibitors of the two processes. Vertical migration  
236 was inhibited by the diatom motility inhibitor Latrunculin (Lat) A, shown to effectively  
237 inhibit cell motility without causing appreciable effects on the photosynthetic activity  
238 (Cartaxana et al. 2008). To inhibit the activity of the xanthophyll cycle, the inhibitor of  
239 the diadinoxanthin de-epoxidase (DDE) dithiothreitol (DTT) was used. DTT is  
240 commonly used to inhibit the conversion of the pigment diadinoxanthin (DD) into the  
241 photoprotective form diatoxanthin (DT) (Lavaud et al. 2002a). DTT was applied in  
242 combination with Lat A, in order to ensure that the cells having the xanthophyll cycle  
243 inhibited remained exposed to high light.

244 The contribution of vertical migration to overall photoprotection capacity of the  
245 biofilm was estimated by the difference between the levels of  $\Delta F/F_m'$  recovery in  
246 control (free moving cells) and Lat A-treated (vertical migration inhibited) samples. The  
247 contribution of the xanthophyll cycle was estimated by comparing the levels of  $\Delta F/F_m'$   
248 recovery in the samples treated with Lat A (only vertical migration inhibited) and in  
249 those treated with both Lat A and DTT (both vertical migration and the xanthophyll  
250 cycle inhibited). The inhibitor solutions were added after biofilm was fully formed, in a  
251 total of 200  $\mu$ L for both the Lat A and the Lat A + DTT solutions. The same volume of

252 filtered seawater was added to the control samples. The solutions were added carefully  
253 to minimize biofilm disturbance, by pipetting small volumes onto the sediment surface.  
254 A minimum of 30 min was given for the inhibitors to diffuse and for the biofilms to  
255 stabilize before measurements were started.

256 **Inhibitor preparation and effective dosage.** Solutions of Lat A of different  
257 concentrations, ranging from 5 to 15  $\mu\text{M}$ , were prepared from a concentrated solution (1  
258 mM) prepared from dissolving purified Lat A (Sigma-Aldrich) in dimethylsulfoxide.  
259 The minimum effective dosage of Lat A to induce inhibition of vertical migration was  
260 determined following Cartaxana & Serôdio (2008). Samples treated with different  
261 concentrations of Lat A (final volume, 200  $\mu\text{L}$ ) were darkened close to the time  
262 expected for tidal flood, known to induce a rapid downward migration. The degree of  
263 migration inhibition was estimated from the decrease in surface biomass following  
264 darkening, as estimated from dark-adapted fluorescence level,  $F_o$ . Three replicated  
265 samples were tested for each Lat A concentration.

266 DTT (BDH-Prolabo) was prepared fresh as in Lavaud et al. (2002a). A stock  
267 solution of 300 mM (in ethanol) was diluted in filtered seawater to prepare working  
268 solutions of concentrations ranging from 3.3 to 15 mM. The minimum effective dosage  
269 of DTT was determined by measuring NPQ development upon exposure to 400  $\mu\text{mol}$   
270 quanta  $\text{m}^{-2} \text{s}^{-1}$  for 30 min in samples treated with increasing concentration of DTT (final  
271 volume, 200  $\mu\text{L}$ ). Three replicated samples were tested for each DTT concentration. For  
272 the light stress experiments, samples were treated with 200  $\mu\text{L}$  of a combined solution  
273 of Lat A and DTT, prepared using the concentration of each inhibitor determined from  
274 the effective dosage tests (see Results).

275 **Taxonomic composition.** In one of the trays, microalgae were collected by  
276 covering the sediment with two layers of a 100  $\mu\text{m}$ -mesh. The trays were exposed to

277 low indirect natural light from a north facing window ( $< 200 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ )  
278 during the day following the sampling. The upper mesh was removed at the time of  
279 middle emersion period and it was washed with filtered ( $0.2 \mu\text{m}$ ) natural sea water. The  
280 samples were fixed in Lugol and preserved at  $4^\circ\text{C}$  until their analysis. Diatom species  
281 were identified and counted using definitive mounts in Naphrax after cleaning the cells  
282 by cremation (2 h,  $450^\circ\text{C}$ ) (Méléder et al. 2007). Taxonomic determination was  
283 performed by microscope on the basis of morphological criteria. A total of ca. 300  
284 diatom frustules were counted to determine specific abundances.

285

286

## RESULTS

287

288

### Taxonomic composition

289 In both sampling periods, the microphytobenthic assemblages were dominated  
290 by long biraphid diatoms (length  $> 30 \mu\text{m}$ ). In May, the assemblages were mainly  
291 dominated by *Navicula cf. spartinentensis* (61%,  $n = 350$ ). *Staurophora salina*  
292 represented less than 20% of the assemblages but this species was two times longer than  
293 *N. cf. spartinentensis* ( $22 \mu\text{m}$  and  $44 \mu\text{m}$  long, respectively). In October, the  
294 assemblages were co-dominated by *Plagiotropis seriata* (22%,  $n = 335$ ) and  
295 *Staurophora salina* (19%); the size of *P. seriata* ( $190 \mu\text{m}$  long) was four times the one  
296 of *S. salina* one ( $44 \mu\text{m}$  long) strengthening its dominance in terms of biovolume. A  
297 third species, *Pleurosigma strigosum* ( $300 \mu\text{m}$  length) represented more than 10% of the  
298 assemblage abundance.

299

300

### Photoacclimation

301

302 Significant differences were found between the light-response of ETR measured  
303 in May and October. In comparison with the ETR vs  $E$  curves measured in May, the  
304 ones measured in October presented significantly higher values of  $\alpha$  (+26.7%,  $t$ -test,  $p <$   
305 0.001) and lower values of  $ETR_m$  (-41.5%,  $t$ -test,  $p < 0.001$ ) (Fig. 1A). As a  
306 consequence, the photoacclimation parameter  $E_k$  was significantly lower in October  
307 than in May (-53.5%;  $t$ -test,  $p < 0.001$ ). Regarding NPQ, significant differences were  
308 found between the light-response curves measured in the two periods (Fig. 1B). NPQ vs  
309  $E$  curves measured in May reached lower levels within the range of applied irradiances  
310 (on average, 2.19 and 3.25 at  $700 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , in May and October,  
311 respectively), although the values of  $NPQ_m$  were not significantly different ( $t$ -test,  $p =$   
312 0.425). The light-response curves were more sigmoid in May than in October ( $t$ -test,  $p =$   
313 0.001), the largest differences being found regarding the light level required for  
314 induction of NPQ, indicated by the parameter  $E_{50}$ , which was significantly lower in  
315 October than in May (-38.5%;  $t$ -test,  $p = 0.003$ ).

316 The light conditions in the region of the sampling area varied greatly between  
317 the two-week periods preceding the sampling periods, with global solar radiation  
318 reaching a daily average of  $2369 \text{ J cm}^{-2}$  in May, more than double the value observed in  
319 October,  $1008 \text{ J cm}^{-2}$ .

320

### 321 Inhibitor dosage

322

323 Vertical migration was strongly inhibited for most of the Lat A concentrations  
324 tested, with an inhibition level above 75% being obtained with only  $5 \mu\text{M}$  (Fig. 2). The  
325 inhibitory response to the increase in Lat A concentration presented a clear saturation-  
326 like pattern, with the increase from  $10$  to  $15 \mu\text{M}$  resulting in an increase in inhibition of

327 only 8.5%. Considering that 10  $\mu$ M was enough to inhibit vertical migration by more  
328 than 90%, and the small increase obtained by applying the higher concentrations,  
329 solutions of 10  $\mu$ M Lat A were used in all experiments.

330 The response of NPQ to the increase in DTT also showed a saturation-like  
331 pattern, characterized by a strong decrease for concentrations up to 5 mM, and a  
332 virtually constancy for concentrations above this value (NPQ decreased by 19%  
333 between 5 and 15 mM; Fig. 3). However, even when the highest DTT concentration was  
334 applied, NPQ was never completely eliminated, remaining above 1.0. In all further  
335 experiments, a concentration of DTT of 10 mM was used.

336

### 337 **Light stress exposure and recovery**

338

339 Figure 4 exemplifies the variation of  $\Delta F/F_m'$  during a light stress-recovery  
340 experiment. On control samples, exposure to high light induced an immediate and  
341 marked decrease in  $\Delta F/F_m'$  from ca. 0.63 to values slightly below 0.1 (Fig. 4).  $\Delta F/F_m'$   
342 further decreased to values close to zero during the first 15 min of exposure, after which  
343 it gradually recovered, stabilizing at values around 0.1 after 90 min and until the end of  
344 the high light period. On inhibitor-treated samples,  $\Delta F/F_m'$  also decreased to values  
345 close to zero upon the start of high light exposure, but, as opposed to control samples,  
346 never showed any appreciable recovery, remaining below 0.05 (Fig. 4). However,  
347  $\Delta F/F_m'$  levels were usually higher in Lat A-treated samples than in those treated with  
348 both inhibitors (Figs. 4, 5). Following the transition to low light, a clear recovery  
349 response was observed for all samples, with  $\Delta F/F_m'$  reaching in all cases over 60% of  
350 initial values after 15 min. Treatment with Lat A effectively inhibited vertical migration  
351 during the whole experiment, as indicated by the small variation in  $F_s$  in Lat A-treated



352 samples (on average, -12.1% for samples treated with Lat A and Lat A+DTT) as  
353 compared with the controls (-43.5%; Fig. 6). The effects of inhibitors were particularly  
354 evident during recovery under low light, during which  $\Delta F/F_m'$  followed the negative  
355 exponential pattern described by Eq. (6), the fit of which was very good in all cases ( $r^2$   
356  $> 0.91$ ; Fig. 7). Control samples recovered more rapidly than those treated with  
357 inhibitors, so that after 3 min after return to low light,  $\Delta F/F_m'$  of non-inhibited samples  
358 was over 70% and 60% higher than on samples treated with Lat A in May and October,  
359 respectively. In both periods these differences were gradually reduced during exposure  
360 to low light, but after 10.5 min the percentage of recovery was significantly different  
361 among treatments and sampling periods (two-way ANOVA,  $p < 0.001$  for both factors).  
362 In both May and October, the recovery of  $\Delta F/F_m'$  was higher in the controls than in the  
363 Lat A-treated samples (Control vs Lat A; Tukey's post-hoc test,  $p = 0.043$  and  $p =$   
364  $0.010$ , respectively), which was in turn higher than in samples treated with Lat A and  
365 DTT (Lat A vs Lat A+DTT; Tukey's post-hoc test,  $p = 0.042$  and  $p = 0.030$ ,  
366 respectively). The percentage of recovery was in all cases significantly higher in May  
367 than in October (Tukey's post-hoc test,  $p < 0.05$ ), with the exception of samples treated  
368 with both inhibitors (Tukey's post-hoc test,  $p = 0.107$ ).

### 369 370 **Photoprotection efficiency and extent of photoinhibition**

371  
372 Depending on the species, the full recovery of the xanthophyll cycle after a  
373 transition from high to low light mainly occurs after 6 min to 15 min (Goss et al. 2006,  
374 Lepetit & Lavaud, pers. obs.). Considering the intermediate period of 10.5 min, the  
375 recovery of  $\Delta F/F_m'$  at this time was used as an estimate of the photoprotection capacity  
376 and to calculate the extent of photoinhibition occurred. The results indicate that the

377 microphytobenthos biofilms had a large photoprotective capacity in both periods, with a  
378 correspondingly low percentage of photoinhibition below 25%, although higher in May  
379 than in October (87.7 and 78.0%; Fig. 8, Table 2). From the reduction in the  
380 photoprotection capacity measured in samples treated with inhibitors, the contribution  
381 of vertical migration and of the xanthophyll cycle to overall photoprotection were  
382 estimated to reach a combined value only slightly above 20% (Table 2). While in May  
383 the two processes had a comparable contribution to photoprotection, the relative  
384 importance of the xanthophyll cycle was reduced to 7.2% in October.

385

386

387

## DISCUSSION

388

### **Photoacclimation and susceptibility to photoinhibition**

389

390

391 Comparatively to May, samples collected in October appeared acclimated to lower light  
392 levels, showing the pattern typically associated to ‘shade-acclimation’: a combination of  
393 higher values of  $\alpha$  and of lower values of  $ETR_m$ , resulting in lower values of  $E_k$ , usually  
394 taken as an indication of photosynthesis saturating at lower irradiances. This change in  
395 photoacclimation state between May and October was consistent with the observed  
396 seasonal change in solar light conditions preceding the two sampling periods (i.e. global  
397 solar radiation more than two times higher in May than in October). These results also  
398 generally confirmed previous observations on the seasonal variability of  
399 microphytobenthos photosynthetic performance, showing patterns of acclimation to  
400 higher light levels during spring/summer and to lower levels in autumn/winter  
401 (Blanchard et al. 1997, Migné et al. 2004, Serôdio et al. 2006). They were also

402 consistent with the photoacclimation response of benthic diatoms grown in culture  
403 exposed to low and high-light regimes (Perkins et al. 2006, Schumann et al. 2007, Cruz  
404 & Serôdio 2008). Increases of  $\alpha$ , as the observed from May to October, are commonly  
405 attributed to an increase in the cellular content of light-harvesting pigments, increasing  
406 the fraction of incident light that is intercepted and absorbed for photosynthesis;  
407 decreases in  $ETR_m$  are typically associated with the decrease of the activity of the  
408 electron transport chain or the Calvin cycle, limiting factors of light-saturated  
409 photosynthesis (Henley 1993, MacIntyre et al. 2002, Behrenfeld et al. 2004).

410 A change in light response was also noticeable regarding NPQ, with the samples  
411 collected in October showing NPQ activation starting at lower light levels (lower  $E_{50}$ )  
412 and higher values of NPQ for most irradiances (higher  $NPQ_m$ ). As with ETR, the  
413 observed variation in the NPQ vs  $E$  curves was consistent with the previously reported  
414 for microphytobenthos (Serôdio et al. 2006) or for benthic diatoms acclimated to  
415 different light regimes (Cruz & Serôdio 2008).

416 However, while changes in the light-response of ETR may be interpreted and  
417 related to underlying physiological processes in a relatively straightforward manner, the  
418 physiological meaning of changes in NPQ levels is more difficult to ascertain. This is  
419 because the two components of NPQ,  $q_E$  (photoprotection) and  $q_I$  (photoinhibition) can  
420 only be distinguished through the analysis of the recovery kinetics after exposure to  
421 high light, but not from NPQ light curves. In this study, the light stress-recovery  
422 experiments allowed to conclude that the observed change in the NPQ light-response  
423 curves was due to a decrease in the  $q_E$  component and a concomitant increase in the  $q_I$   
424 component. In the absence of information from NPQ recovery kinetics, similar  
425 increases in NPQ vs  $E$  curves in autumn/winter periods have been, perhaps wrongly,

426 interpreted as being due to an increase in photoprotective capacity (Serôdio et al. 2005,  
427 2006).

428 Furthermore, the results from the light stress-recovery experiments revealed an  
429 association between photoacclimation status and photoprotection efficiency, not shown  
430 before for these communities. Whatever the cause (see below), the acclimation to high  
431 light levels in summer was associated to a high photoprotection capacity and the low  
432 light-acclimation in autumn to a general loss in photoprotection and a higher  
433 susceptibility to photoinhibition.

434

### 435 **Photoprotection vs photoinhibition**

436

437 A central finding of this study is that photoinhibition was in all cases  
438 considerably low (ca. 20%), indicating photoprotection to be particularly efficient in the  
439 studied microphytobenthos biofilms. Despite the general view that these assemblages  
440 are largely immune to photoinhibition (Blanchard et al. 2004, Waring et al. 2007,  
441 Mouget et al. 2008), this process has been shown to occur under *in situ* conditions  
442 (Serôdio et al. 2008). Curiously, the rates of photoinhibition estimated in the cited  
443 study, reaching up to ca. 18%, are similar to the values here reported, despite the fact  
444 that they were estimated from hysteresis patterns observed during entire low tide  
445 exposure periods. The results of the present study therefore confirm that the  
446 photoprotective mechanisms available to benthic diatoms are not completely efficient in  
447 preventing some degree of photoinhibitory damage. However, it should be stressed the  
448 difficulty in comparing the measured rates of photoinhibition with results published for  
449 other habitats, or for other estuarine primary producers such as phytoplankton,  
450 seagrasses or macroalgae. Apart from the light history and the species-specific

451 differences, the extent of photoinhibition is directly related to light dosage, determined  
452 by light intensity and duration of exposure, both largely variable amongst the different  
453 experimental protocols used in different laboratory and field studies.

454           A number of unaccounted factors may have contributed for the measured low  
455 values of  $q_I$ . Firstly, the well-known effect of depth-integration of subsurface  
456 fluorescence (Forster & Kromkamp 2004, Serôdio 2004). This effect is caused by the  
457 fact that only the cells at or near the surface are actually exposed to measured levels of  
458 high light, and that the fluorescence signal measured at the surface also accounts for  
459 cells positioned deeper in the photic zone and exposed to lower light levels. The  
460 expected effect is a light-dependent overestimation of biofilm-level  $\Delta F/F_m'$  relatively to  
461 the inherent, physiological values of the cells at the surface, which is then expected to  
462 cause a systematic overestimation of  $q_E$  and the underestimated of  $q_I$  (Serôdio 2004).  
463 However, besides this static effect, also dynamic effects can be expected. During  
464 prolonged exposure to high light, the downward migration of microalgae to less  
465 illuminated layers is likely to induce a gradual increase of  $\Delta F/F_m'$  (as measured at the  
466 surface), independently of any photophysiological changes, thus causing the  
467 overestimation of  $q_E$ . It is also conceivable that these types of effects may affect the  
468 measurement of  $\Delta F/F_m'$  during the recovery under low light, due to upward migration as  
469 a response to the decrease in incident irradiance. This, however, seems less likely due to  
470 the relatively short time of this period and to the fact that a transition from high to low  
471 light is a weaker stimulus for vertical migration, especially if coinciding with the end of  
472 the low tide period (Coelho et al. 2011).

473           A second factor that might explain the low values of  $q_I$  is the light doses applied  
474 during the light stress-recovery experiments in the laboratory. Because these (3 hrs,  
475  $1200 \mu\text{mol quanta m}^{-2} \text{ s}^{-1}$ ) were likely lower than the ones received during a typical

476 period of exposure at low tide (up to 8-10 hrs, 1500-2000  $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ), larger,  
477 but still ecologically relevant, light doses could have been applied which would likely  
478 induce larger cumulative photoinhibitory effects. The light exposure conditions applied  
479 in this study, both regarding light intensity and duration, resulted from a compromise  
480 between inducing measurable effects, instrument limitations (maximum PAR irradiance  
481 provided by the imaging fluorometer) and minimizing uncontrollable experimental  
482 conditions (excessive sample heating and desiccation caused by the fluorometer LED  
483 panel). Despite these limitations, mostly instrument-related, the laboratory experimental  
484 approach used in this study has the advantage over studies carried out under *in situ*  
485 conditions (e.g. Serôdio et al. 2008; Perkins et al. 2010) of allowing applying controlled  
486 and reproducible conditions, making it possible to directly compare the migratory and  
487 physiological responses of samples collected in different places and occasions.

488 The estimation of  $q_E$  and  $q_I$  is also directly affected by the type of analysis made  
489 on the recovery kinetics in order to distinguish the two components of NPQ. For higher  
490 plants,  $q_E$  and  $q_I$  are distinguished on the basis of the recovery rate of  $F_v/F_m$ , typically  
491 10-15 min, assumed to correspond to the full reversal of the xanthophyll cycle (Horton  
492 & Hague 1988, Ruban & Horton 1995). Following the common practice for the  
493 distinction of  $q_E$  and  $q_I$ , in this study these two components of NPQ were estimated  
494 based on a relaxation time of the xanthophyll cycle of 10.5 min. However, to evaluate  
495 the possible effects of considering different times for the reversal of the xanthophyll  
496 cycle on the relative magnitude of  $q_E$  and  $q_I$ , a sensitivity analysis was performed,  
497 consisting on the re-calculation of these estimates when considering 6 and 15 min,  
498 values matching the range of relaxation times of the xanthophyll cycle expectable for  
499 diatoms (Gross et al. 2006, Lepetit & Lavaud, pers. obs.). The use of these different  
500 recovery periods did not alter significantly the general findings of the study, including

501 high levels of recovery and low photoinhibition rates, the increase in photoinhibition  
502 levels from May to October, and a relatively low (< 30%) combined contribution of  
503 vertical migration and xanthophyll cycle to overall photoprotection (Table 2).  
504 Nonetheless, this analysis shows some effects, although largely expected from the  
505 asymptotic pattern of  $\Delta F/F_m'$  recovery during the considered period: the use of a shorter  
506 period resulted in the estimation of lower rates of recovery, leading to a likely  
507 overestimation of photoinhibition rates; conversely, longer periods resulted in larger  
508 rates of recovery and probably overestimated levels of photoprotection (Table 2).  
509 Moreover, due to the different relaxation patterns of samples exposed to different  
510 treatments, the evaluation of the relative importance of vertical migration and the  
511 xanthophyll cycle was also affected by the time period considered, with shorter and  
512 longer recovery periods resulting in a higher apparent contribution of vertical migration  
513 and of the xanthophyll cycle, respectively. These effects, however, did not affect  
514 substantially the overall pattern of variation of the role of the two photoprotective  
515 processes between the two sampling periods.

516 Recently, more sophisticated methods, based on the mathematical modeling and  
517 deconvolution of the recovery curve, were proposed to trace the recovery of each  
518 individual component of NPQ (Roháček 2010). This method could not be applied in this  
519 study because of the particularities of the xanthophyll cycle in diatoms, which may not  
520 verify the assumptions of the method. Firstly, the lack of  $q_T$  (the state-transition  
521 quenching) in diatoms (Owens 1986, Lavaud 2007, Goss & Jakob 2010), which called  
522 for the modification of this model to a two-component NPQ. Secondly, the  
523 impossibility of using changes in  $F_v/F_m$  in biofilms as an indication of photoinhibition,  
524 as this requires the darkening of the samples, known to induce changes in  $F_m$  levels due  
525 to vertical migration. Furthermore, in benthic diatoms, dark adaptation often causes the

526  $F_m$  level to decrease to values below  $F_m'$  levels measured under low light (Serôdio et al.  
527 2006). These reasons also prevented the use of other recently proposed methods to  
528 quantify the components of NPQ (Ahn et al. 2009, Guadagno et al. 2010).

529         The formation of DT in the dark and thus anoxic subsurface layers of the  
530 sediment, known to occur in diatoms (Jakob et al. 2001), and especially in benthic  
531 assemblages (Serôdio et al. 2006), is a likely explanation for the apparent impossibility  
532 to completely eliminate NPQ by applying the xanthophyll cycle inhibitor DTT (Fig. 3).  
533 The DT thus formed would remain present despite the treatment with DTT, which  
534 prevents new conversion of DD to DT, but does not induce the reversed reaction. Upon  
535 exposure to high light, the oxygenation of DT-rich subsurface layers would allow for  
536 the observed rise in NPQ, as the formation of NPQ from DT is known to be inhibited by  
537 anoxia (Cruz et al. 2011).

### 538

539                   **Photoprotection: vertical migration vs xanthophyll cycle**

540

541         The use of specific inhibitors for vertical migration and for the operation of the  
542 xanthophyll cycle allowed estimating the relative contribution of each of these  
543 processes to overall photoprotection of the biofilm. The results showed a change with  
544 season and photoacclimation state of their relative importance. While in May the two  
545 processes seemed to contribute similarly to biofilm photoprotection, the loss of  
546 photoprotection capacity from May to October was associated to a decrease in the  
547 contribution of the xanthophyll cycle, so that vertical migration became the dominant  
548 photoprotective process. The observed change in the species composition of the  
549 microphytobenthic assemblage may explain this difference as the activity of the  
550 xanthophyll cycle can differ from a species to another (Lavaud et al. 2004, Goss et al.



551 2006). It may be also hypothesized that this difference is related to the decrease in rates  
552 of enzymatic conversion between DD and DT associated to photoacclimation or due to  
553 acclimation to lower temperatures (Van Leuwee et al. 2008), an effect that is also  
554 species-related (Salleh & McMinn, 2011). Nevertheless, these results indicate that  
555 behavioral photoprotection seems able to maintain the overall photoprotection capacity,  
556 compensating for the decrease in the contribution of the xanthophyll cycle during the  
557 winter season.

558           The change in species composition, involving a dominance of larger cells in  
559 October, could also have affected the migratory response of the assemblages to high  
560 light. However, although some studies have shown a relation between migratory cell  
561 size and migratory behaviour in sediments (Hay et al. 1993, Underwood et al. 2005),  
562 there is no evidence that cell size is an important factor regarding the migratory  
563 response to light stress.

564           Vertical migration and the xanthophyll cycle have been considered as the main  
565 photoprotective mechanisms in microphytobenthos biofilms (Serôdio et al. 2005, Jesus  
566 et al. 2006, Mouget et al. 2008, Serôdio et al. 2008; Perkins et al. 2010). A perhaps  
567 surprising result of this study is the relative low contribution of these two processes to  
568 global photoprotection. This calls for the potential role of other processes responsible  
569 for the observed low rates of photoinhibition. Likely candidates include the cyclic  
570 electron flow around PSII (Lavaud et al. 2002b, 2007), the efficient scavenging of  
571 reactive oxygen species (Roncarati et al. 2008, Waring et al. 2010) or high turnover  
572 rates of the PSII protein D1 (Wu et al. 2011).

573

574

#### **Use of inhibitors on microphytobenthic biofilms**

575

576 An aim of this study was the introduction of a new experimental protocol to  
577 estimate photoprotection efficiency and the extent of photoinhibition in  
578 microphytobenthos biofilms. This involved the combination of: (i) the use of specific  
579 inhibitors for different photoprotective processes, applied alone and in combination with  
580 each other, allowing the estimation of the relative contribution of each process to overall  
581 photoprotection, and (ii) the use of imaging fluorometry on replicated samples in well  
582 plates, taking advantage of the self-forming nature of microphytobenthos biofilms from  
583 homogenized sediments, which allowed for adequate replication and low variability  
584 between replicates, and for the simultaneous testing of different treatments.

585 Some potential pitfalls exist regarding the use of inhibitors on biofilms and the  
586 interpretation of results. Firstly, it must be noted that when comparing controls (no  
587 inhibitor added) with Lat A-treated samples, it is likely that the differences in  
588 fluorescence parameters observed over time may not be attributed only to changes in  
589 cell physiological conditions but also to changes in cell composition in the upper layers  
590 of the sediment. This is because in the controls, as opposed to Lat A-treated samples,  
591 cells initially at the surface likely migrated down into layers below the photic zone,  
592 therefore changing the contribution to the fluorescence signal measured at the surface.  
593 As a consequence, any observed differences are expected to represent mainly changes at  
594 the biofilm (i.e., community)-level, and not only changes in the physiology of  
595 individual cells. This also explains the need to combine Lat A and DTT if the effect of  
596 inhibiting the xanthophyll cycle is to be evaluated in the same microalgal assemblage.  
597 By adding DTT to samples treated with Lat A, it is ensured that the same cells remain in  
598 the photic zone of the sediment and that measured changes in fluorescence are due to  
599 changes in their physiological status and not to changes in community composition. If  
600 only DTT is applied (Perkins et al. 2010), only biofilm-level effects can be evaluated, as

601 many cells will likely respond to high light by migrating downward and become  
602 unobservable (Oxborough et al. 2000).

603

604 *Acknowledgements.* We thank Dr. Céline Vincent for providing solar radiation data.  
605 This study was supported by FCT – Fundação para a Ciência e a Tecnologia, through  
606 grants SFRH/BSAB/962/2009 (J. Serôdio), SFRH/BD/44860/2008 (J. Ezequiel), and  
607 project MigROS (PTDC/MAR/112473/2009), and by the CNRS – Centre National de la  
608 Recherche Scientifique (‘chercheurs invités’ program, J. Serôdio and J. Lavaud), the  
609 region Charente-Maritime/CG17 (A. Barnett Ph.D. grant), and the French consortium  
610 CPER-Littoral., . We thank two anonymous reviewers for critical comments on the  
611 manuscript.

612

## LITERATURE CITED

- 613  
614       Admiraal, W (1984) The ecology of estuarine sediment-inhabiting diatoms. *Progr*  
615                *Phycol Res* 3:269-322
- 616       Ahn, TK, Avenson, TJ, Peers, G, Li, Z, Dall'Osto, L, Bassi, R, Niyogi, KK, Fleming,  
617                GR (2009) Investigating energy partitioning during photosynthesis using an  
618                expanded quantum yield convention. *Chem Phys* 357:151-158
- 619       Behrenfeld MJ, Prasil O, Babin M, Bruyant, F (2004) In search of a physiological basis  
620                for covariations in light-limited and light-saturated photosynthesis. *J Phycol*  
621                40:4-25
- 622       Blanchard GF, Guarini J-M, Dang C, Richard P (2004) Characterizing and quantifying  
623                photoinhibition in intertidal microphytobenthos. *J Phycol* 40:692-696
- 624       Blanchard GF, Cariou-Le Gall V (1994) Photosynthetic characteristics of  
625                microphytobenthos in Marennes-Oléron Bay, France: Preliminary results. *J Exp*  
626                *Mar Biol Ecol* 182:1-14
- 627       Blanchard GF, Guarini JM, Gros P, Richard P (1997) Seasonal effect on the the  
628                relationship between the photosynthetic capacity of intertidal microphytobenthos  
629                and temperature. *J Phycol* 33:723-728
- 630       Brotas V, Risgaard-Petersen N, Ottosson L, Serôdio J, Ribeiro L, Dalsgaard T (2003) *In*  
631                *situ* measurement of photosynthetic activity and respiration of intertidal benthic  
632                microalgal communities undergoing vertical migration. *Ophelia* 57:13-26
- 633       Cartaxana P, Ruivo M, Hubas C, Davidson I, Serôdio J, Jesus B (2011) Physiological  
634                versus behavioural photoprotection in intertidal epipelagic and epipsamic benthic  
635                diatom communities. *J Exp Mar Biol Ecol* 405:120-127

636 Cartaxana P, Serôdio J (2008) Inhibiting diatom motility: a new tool for the study of the  
637 photophysiology of intertidal microphytobenthic biofilms. *Limnol Oceanogr*  
638 *Meth* 6:466-476

639 Cartaxana P, Brotas V, Serôdio J (2008) Effects of two motility inhibitors on the  
640 photosynthetic activity of the diatoms *Cylindrotheca closterium* and  
641 *Pleurosigma angulatum*. *Diatom Res* 23:65-74

642 Chevalier EM, Gévaert F, Créach A (2010) In situ photosynthetic activity and  
643 xanthophylls cycle development of undisturbed microphytobenthos in an  
644 intertidal mudflat. *J Exp Mar Biol Ecol* 385:44-49

645 Coelho H, Vieira S, Serôdio J (2009) Effects of desiccation on the photosynthetic  
646 activity of intertidal microphytobenthos biofilms as studied by optical methods. *J*  
647 *Exp Mar Biol Ecol* 381:98-104

648 Coelho H, Vieira S, Serôdio J (2011) Endogenous versus environmental control of  
649 vertical migration by intertidal benthic microalgae. *Eur J Phycol* 46:271-281

650 Consalvey M, Paterson DM, Underwood GJC (2004) The ups and downs of life in a  
651 benthic biofilm: migration of benthic diatoms. *Diatom Res* 19:181-202

652 Cook PLM, Røy H (2006) Advective relief of CO<sub>2</sub> limitation in microphytobenthos in  
653 highly productive sandy sediments. *Limnol Oceanogr* 51:1594-1601

654 Cruz S, Goss R, Wilhelm C, Leegood R, Horton P, Jakob T (2011) Impact of  
655 chlororespiration on non-photochemical quenching of chlorophyll fluorescence  
656 and on the regulation of the diadinoxanthin cycle in the diatom *Thalassiosira*  
657 *pseudonana*. *J Exp Bot* 62:509-519

658 Cruz S, Serôdio J (2008) Relationship of rapid light curves of variable fluorescence to  
659 photoacclimation and non-photochemical quenching in a benthic diatom. *Aquat*  
660 *Bot* 88:256-264

661 Eilers PHC, Peeters JCH (1988) A model for the relationship between light intensity  
662 and the rate of photosynthesis in phytoplankton. *Ecol Model* 42:199-215

663 Forster RM, Kromkamp JC (2004) Modelling the effects of chlorophyll fluorescence  
664 from subsurface layers on photosynthetic efficiency measurements in  
665 microphytobenthic algae. *Mar Ecol Prog Ser* 284:9-22

666 Genty B, Briantais J-M, Baker, NR (1989) The relationship between the quantum yield  
667 of photosynthetic electron transport and quenching of chlorophyll fluorescence.  
668 *Biochim Biophys Acta* 990:87-92

669 Goss R, Pinto AE, Wilhelm C, Richter M (2006) The importance of a highly active and  
670  $\Delta$ pH-regulated diatoxanthin epoxidase for the regulation of the PS II antenna  
671 function in diadinoxanthin containing algae. *J Plant Physiol* 163:1008-1021

672 Goss R, Jakob T (2010) Regulation and function of xanthophyll cycle-dependent  
673 photoprotection in algae. *Photosynth Res* 106:103-122

674 Grouneva I, Jakob T, Wilhelm C, Goss, R (2008) A new multicomponent NPQ  
675 mechanism in the diatom *Cyclotella meneghiniana*. *Plant Cell Physiol* 49:1217-  
676 25

677 Guadagno CR, Virzo De Santo A, D'Ambrosio N (2010) A revised energy partitioning  
678 approach to assess the yields of non-photochemical quenching components.  
679 *Biochim Biophys Acta* 1797:525-30

680 Hay SI, Maitland TC, Paterson DM (1993) The speed of diatom migration through  
681 natural and artificial substrata. *Diatom Res* 8:371-384

682 Henley, WJ (1993) Measurement and interpretation of photosynthetic light-response  
683 curves in algae in the context of photoinhibition and diel changes. *J Phycol*  
684 29:729-739

685 Herlory O, Guarini J-M, Richard P, Blanchard G (2004) Microstructure of  
686 microphytobenthic biofilm and its spatio-temporal dynamics in an intertidal  
687 mudflat (Aiguillon Bay, France). *Mar Ecol Prog Ser* 282:33-44

688 Horton P, Hague A (1988) Studies on the induction of chlorophyll fluorescence in  
689 isolated barley protoplasts. 4. Resolution of non-photochemical quenching.  
690 *Biochim Biophys Acta* 932:107-115

691 Jakob T, Goss R, Wilhelm, C (2001) Unusual pH-dependence of diadinoxanthin de-  
692 epoxidase activation causes chlororespiratory induced accumulation of  
693 diatoxanthin in the diatom *Phaeodactylum tricornutum*. *J Plant Physiol* 158:383-  
694 390

695 Jordan L, McMinn A, Thompson P (2010) Diurnal changes of photoadaptive pigments  
696 in microphytobenthos. *J. Mar Biol Ass UK* 90:1025-1032

697 Jesus B, Perkins RG, Consalvey M, Brotas V, Paterson DM (2006) Effects of vertical  
698 migrations by benthic microalgae on fluorescence measurements of  
699 photophysiology. *Mar Ecol Prog Ser* 315:55-66

700 Kromkamp J, Barranguet C, Peene J (1998) Determination of microphytobenthos PSII  
701 quantum efficiency and photosynthetic activity by means of variable chlorophyll  
702 fluorescence. *Mar Ecol Prog Ser* 162: 45-55

703 Lavaud J, Gorkom HJV, Etienne A-L (2002b) Photosystem II electron transfer cycle  
704 and chlororespiration in planktonic diatoms. *Photosynth Res* 74:51-59

705 Lavaud J, Rousseau B, Etienne A-L (2002a) In diatoms, a transthylakoidal proton  
706 gradient alone is not sufficient to induce a non-photochemical fluorescence  
707 quenching. *FEBS Lett* 523:163-166



708 Lavaud J, Rousseau B, Etienne A-L (2004) General features of photoprotection by  
709 energy dissipation in planktonic diatoms (Bacillariophyceae). *J Phycol*40:130-  
710 137

711 Lavaud L, Kroth PG (2006) In diatoms, the transthylakoidal proton gradient regulates  
712 the photoprotective non-photochemical fluorescence quenching beyond its  
713 control on the xanthophyll cycle. *Plant Cell Physiol* 47:1010-1016

714 Lavaud, J (2007) Fast Regulation of Photosynthesis in Diatoms: Mechanisms, Evolution  
715 and Ecophysiology. *Funct Plant Sci Biotechnol* 1:267-287

716 Lavaud J, Rousseau B, Etienne AL (2004) General features of photoprotection by  
717 energy dissipation in planktonic diatoms (Bacillariophyceae). *J Phycol*40:130-  
718 137

719 Li Z, Wakao S, Fischer BB, Niyogi KK (2009) Sensing and responding to excess light.  
720 *Ann Rev Plant Biol* 60:239-260

721 Macintyre HL, Kana TM, Anning T, Geider RJ (2002) Photoacclimation of  
722 photosynthesis irradiance response curves and photosynthetic pigments in  
723 microalgae and cyanobacteria. *J Phycol* 38:17-38

724 Méléder V, Rincé Y, Barillé L, Gaudin P, Rosa P (2007). Spatio-temporal changes in  
725 microphytobenthos assemblages in a macrotidal flat (Bourgneuf Bay, France). *J*  
726 *Phycol* 43: 1177–1190

727 Migné A, Spilmont N, Davoult D (2004) In situ measurements of benthic primary  
728 production during emersion: seasonal variations and annual production in the  
729 Bay of Somme (eastern English Channel, France). *Cont Shelf Res* 24:1437-1449

730 Miles A, Sundbäck K (2000) Diel variation in microphytobenthic productivity in areas  
731 of different tidal amplitude. *Mar Ecol Prog Ser* 205:11-22

732 Mouget J-L, Perkins R, Consalvey M (2008) Migration or photoacclimation to prevent  
733 high irradiance and UV-B damage in marine microphytobenthic communities.  
734 *Aquat Microb Ecol* 52:223-232

735 Müller P, Li XP, Niyogi KK (2001) Non-photochemical quenching. A response to  
736 excess light energy. *Plant Physiol* 125:1558-1566

737 Nishiyama Y, Allakhverdiev SI, Murata N (2006) A new paradigm for the action of  
738 reactive oxygen species in the photoinhibition of photosystem II. *Biochim*  
739 *Biophys Acta* 1757:742-749

740 Olaizola M, Yamamoto HY (1994) Short-term response of the diadinoxanthin cycle and  
741 fluorescence yield to high irradiance in *Chaetoceros muelleri*  
742 (Bacillariophyceae). *J Phycol* 30:606-612

743 Owens TG (1986) Light-harvesting function in the diatom *Phaeodactylum tricorutum*  
744 II. Distribution of excitation energy between the photosystems. *Plant Physiol*  
745 80:732-738

746 Owens TG, Wold ER (1986) Light-harvesting function in the diatom *Phaeodactylum*  
747 *tricorutum* I. Isolation and characterization of pigment-protein complexes.  
748 *Plant Physiol* 80:732-738

749 Oxborough K, Hanlon ARM, Underwood GJC, Baker NR (2000) In vivo estimation of  
750 the photosystem II photochemical efficiency of individual microphytobenthic  
751 cells using high-resolution imaging of chlorophyll a fluorescence. *Limnol*  
752 *Oceanogr* 45:1420-1425

753 Perkins RG, Mouget J-L, Lefebvre S, Lavaud J (2006) Light response curve  
754 methodology and possible implications in the application of chlorophyll  
755 fluorescence to benthic diatoms. *Mar Biol* 149:703-712.

756 Perkins RG, Lavaud J, Serôdio J, Mouget, J-L, Cartaxana P, Rosa P, Barillé L, Brotas  
757 V, Jesus BM (2010) Vertical cell movement is the primary response of intertidal  
758 benthic biofilms to increasing light dose. *Mar Ecol Prog Ser* 416:93–103

759 Perkins RG, Kromkamp J, Serôdio J, Lavaud J, Jesus B, Mouget J-L, Lefebvre S,  
760 Forster R. The application of variable chlorophyll fluorescence to  
761 microphytobenthic biofilms. *In* Sugget D, Prasil O, Borowitzka MA (eds)  
762 Chlorophyll *a* Fluorescence in Aquatic Sciences: Methods and Applications,  
763 Series: Developments in Applied Phycology Vol. 4-Chapter 12, Springer, pp  
764 237-276.

765 Rijstenbil, JW (2005) UV- and salinity-induced oxidative effects in the marine diatom  
766 *Cylindrotheca closterium* during simulated emersion. *Mar Biol* 147:1063-1073

767 Ritchie RJ (2008) Fitting light saturation curves measured using modulated fluorometry.  
768 *Photosynth Res* 96:201-15

769 Roháček K (2010) Method for resolution and quantification of components of the non-  
770 photochemical quenching ( $q_N$ ). *Photosynth Res* 105:101-113

771 Roncarati F, Rijstenbil JW, Pistocchi R (2008) Photosynthetic performance, oxidative  
772 damage and antioxidants in *Cylindrotheca closterium* in response to high  
773 irradiance, UVB radiation and salinity. *Mar Biol* 153:965-973

774 Ruban, AV, Lavaud, J, Rousseau, B, Guglielmi, G, Horton, P, Etienne, AL (2004) The  
775 super-excess energy dissipation in diatom algae: comparative analysis with  
776 higher plants. *Photosyn Res* 82:165-175

777 Salleh S, McMinn A (2011) The effects of temperature on the photosynthetic parameter  
778 *s* and recovery of two temperate benthic microalgae, *Amphora* cf. *coffeaeformis*  
779 and *cocconeis* cf. *sublittoralis* (Bacillariophyceae). *J Phycol* 47:1413-1424

780 Serôdio J (2004) Analysis of variable chlorophyll fluorescence in microphytobenthos  
781 assemblages: implications of the use of depth-integrated measurements. *Aqua*  
782 *Microb Ecol* 36:137-152

783 Serôdio J, Cruz S, Vieira S, Brotas V (2005) Non-photochemical quenching of  
784 chlorophyll fluorescence and operation of the xanthophyll cycle in estuarine  
785 microphytobenthos. *J Exp Mar Biol Ecol* 326:157-169

786 Serôdio J, Lavaud J (2011) A model for describing the light response of the non-  
787 photochemical quenching of chlorophyll fluorescence. *Photosynth Res* 108:61-  
788 76

789 Serôdio J, Vieira S, Cruz S, Coelho H (2006) Rapid light-response curves of  
790 chlorophyll fluorescence in microalgae: relationship to steady-state light curves  
791 and non-photochemical quenching in benthic diatom-dominated assemblages.  
792 *Photosynth Res* 90:29-43

793 Serôdio J, Catarino, F (1999) Fortnightly light and temperature variability on estuarine  
794 intertidal sediments and implications for microphytobenthos primary  
795 productivity. *Aquat Ecol* 33:235-241

796 Serôdio J, Vieira S, Cruz S (2008) Photosynthetic activity, photoprotection and  
797 photoinhibition in intertidal microphytobenthos as studied in situ using variable  
798 chlorophyll fluorescence. *Cont Shelf Res* 28:1363-1375

799 Underwood GJC (2002) Adaptations of tropical marine microphytobenthic assemblages  
800 along a gradient of light and nutrient availability in Suva Lagoon, Fiji. *Eur J*  
801 *Phycol* 37:449-462

802 Underwood GJC, Kromkamp J (1999) Primary production by phytoplankton and  
803 microphytobenthos in estuaries. *Adv Ecol Res* 29:93-153

804 Underwood GJC, Perkins RG, Consalvey MC, Hanlon ARM, Oxborough K, Baker NR,  
805 Paterson, DM (2005) Patterns in microphytobenthic primary productivity:  
806 Species-specific variation in migratory rhythms and photosynthetic efficiency in  
807 mixed-species biofilms. *Limnol Oceanogr* 50:755-767

808 Van Leeuwe MA, Brotas V, Consalvey M, Forster RM, Gillespie D, Jesus B,  
809 Roggeveld J, Gieskes WWC (2008) Photoacclimation in microphytobenthos and  
810 the role of xanthophyll pigments. *Eur J Phycol* 43:123-132

811 Walters RG, Horton P (1991) Resolution of components of non-photochemical  
812 chlorophyll fluorescence quenching in barley leaves. *Photosynth Res* 27:121-133

813 Waring J, Baker NR, Underwood GJC (2007) Responses of estuarine intertidal  
814 microphytobenthic algal assemblages to enhanced ultraviolet B radiation. *Global*  
815 *Change Biol* 13:1398-1413

816 Waring J, Klenell M, Bechtold U, Underwood GJC, Baker NR (2010) Light-induced  
817 responses of oxygen photoreduction, reactive oxygen species production and  
818 scavenging in two diatom species. *J Phycol* 46:1206-1217

819 Wu H, Cockshutt AM, McCarthy A, Campbell DA (2011) Distinctive photosystem II  
820 photoinactivation and protein dynamics in marine diatoms. *Plant Physiol*  
821 156:2184-2195

822

823	Table 1. Notation
824	
825	$\alpha$ , initial slope of the ETR vs $E$ curve
826	$a, b, c$ , parameters of the Eilers and Peeters (1988) model
827	DTT, dithiothreitol
828	$\Delta F/F_m'$ , effective quantum yield of PSII
829	DD, diadinoxanthin
830	DT, diatoxanthin
831	DDE, diadinoxanthin de-epoxidase
832	$E$ , PAR irradiance
833	$E_{50}$ , Irradiance level corresponding to 50% of $NPQ_m$ in a NPQ vs $E$ curve
834	$E_k$ , photoacclimation parameter of an ETR vs $E$ curve
835	ETR, PSII electron transport rate
836	$ETR_m$ , maximum ETR level in an ETR vs $E$ curve
837	$F_o, F_m$ , Minimum and maximum fluorescence of a dark-adapted sample
838	$F_s, F_m'$ , Steady state and maximum fluorescence of a light-adapted sample
839	Lat A, Latrunculin A
840	$n$ , sigmoidicity coefficient of the NPQ vs $E$ curve
841	NPQ, non-photochemical quenching

- 842 NPQ<sub>m</sub>, maximum NPQ level in a NPQ vs *E* curve
- 843 PAR, photosynthetically active radiation
- 844 PSII, photosystem II
- 845  $q_E$ , energy-dependent quenching
- 846  $q_I$ , photoinhibitory quenching
- 847 *t*, time during recovery following light stress
- 848 XC, xanthophyll cycle
- 849

850 Table 2. Extent of photoinhibition and efficiency of photoprotection (%), calculated as  
 851 percentage of  $\Delta F/F_m'$  recovery after 10.5 min. Relative contributions of vertical  
 852 migration and of the xanthophyll cycle to overall photoprotection (%), as calculated  
 853 from the reduction of the  $\Delta F/F_m'$  recovery in samples treated with Lat A and with Lat A  
 854 and DTT, respectively, relatively to control samples. Mean and standard error of three  
 855 replicates. Numbers within parenthesis indicate results obtained when considering 6 and  
 856 15 min of recovery, respectively.  
 857

	May	October
Photoinhibition	12.3 ± 0.55 (16.6, 11.7)	22.0 ± 2.79 (33.7, 17.0)
Recovery	87.7 ± 0.55 (83.4, 88.3)	78.0 ± 2.79 (66.3, 83.0)
Vertical migration	10.6 (24.0, 3.6)	14.3 (17.0, 11.7)
Xanthophyll cycle	10.1 (6.4, 13.2)	7.2 (7.3, 5.8)
Others	79.3 (69.5, 83.2)	78.5 (75.7, 82.5)

858



859 Figure legends

860

861 Fig. 1. Light-response curves of ETR (A) and NPQ (B) measured in May and October  
862 2010. Mean of six replicates. Vertical bars: one standard error. Numbers represent the  
863 mean values of model parameters estimated for light-response curves measured for each  
864 individual sample.

865

866 Fig. 2. Variation of migration inhibition with the concentration of added Lat A solution.  
867 Mean of three replicates. Vertical bars: one standard error. Line represents the fit of  
868 exponential decay model.

869

870 Fig. 3. Inhibition of NPQ as a function of concentration of added DTT solution. NPQ  
871 induced upon exposure to  $400 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ . Mean of three replicates. Vertical  
872 bars: one standard error. Line represents the fit of exponential decay model.

873

874 Fig. 4. Light stress-recovery experiment. Variation of PSII quantum yield,  $\Delta F/F_m'$ ,  
875 during sequential exposure to low light (pre-stress,  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ), light stress  
876 under high light (high light,  $1200 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , 180 min) and recovery under low  
877 light (recovery,  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , 10.5 min) for controls and for samples treated  
878 with migration inhibitor Lat A and with migration and xanthophyll cycle inhibitors (Lat  
879 A + DTT), collected in May 2010. Mean of three replicates. Vertical bars: one standard  
880 error.

881

882 Fig. 5. Images of PSII quantum yield,  $\Delta F/F_m'$  (false color scale), as measured in the  
883 sediment samples used in the light stress experiment described in Fig. 4 at the end of

884 first low light exposure (pre-stress,  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ), at the end of high light  
885 exposure (high light,  $1200 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , 180 min) and following recovery under  
886 low light (recovery,  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , 10.5 min). Three replicated areas of interest  
887 for each treatment.

888

889 Fig. 6. Images of fluorescence level  $F_s$  (false color scale) as measured in the sediment  
890 samples used in the light stress experiment described in Fig. 4. at the end of first low  
891 light exposure (pre-stress,  $55 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ ), and after recovery following end of  
892 high light exposure (high light,  $1200 \mu\text{mol quanta m}^{-2} \text{s}^{-1}$ , 180 min; recovery,  $55 \mu\text{mol}$   
893  $\text{quanta m}^{-2} \text{s}^{-1}$ , 10.5 min). Three replicated areas of interest for each treatment.

894

895 Fig. 7. Recovery of PSII quantum yield,  $\Delta F/F_m'$ , during relaxation following light stress  
896 for control samples and for samples treated with migration inhibitor Lat A and with  
897 migration and xanthophyll cycle inhibitors (Lat A + DTT). Lines represent the  
898 exponential model described by Eq. (6) fitted to average  $\Delta F/F_m'$  values. Detail of Fig. 4.

899

900 Fig. 8. Efficiency of photoprotection, as percentage of recovery after 10.5 min low light  
901 following high light exposure, in May and October, for controls and inhibitor-treated  
902 samples. Mean of three replicates. Vertical bars: one standard error.

903